The Risk Analysis Controversy

An Institutional Perspective

Editors:
Howard C. Kunreuther and Eryl V. Ley

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Risk Analysis has generated considerable controversy in recent years as to its meaning with respect to societal decision making. The papers and discussions in this book highlight different aspects of the risk debate. In particular, confidence in expert statements on risk has diminished. There has also been an increasing recognition of the difference between analysis of the risk associated with an event and people's preferences and values. This volume does not provide answers to the dilemmas facing society but rather raises a set of questions which need to be considered by policy makers and researchers concerned with societal problems involving risk.

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Proceedings of a Summer Study on Decision Processes and Institutional Aspects of Risk held at IIASA, Laxenburg, Austria, 22-26 June, 1981

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Howard C. KUNREUTHER
Department of Decision Sciences
Wharton School
University of Pennsylvania
Philadelphia, PA 19104

Eryl V. LEY
International Institute for Applied
Systems Analysis
A-2361 Laxenburg
Austria

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Preface

The first summer study at IIASA brought together a cross-section of individuals from different disciplines and nationalities. All the participants have had an interest in the role of risk analysis given the institutional arrangements which guide decision making for new technologies. This book contains edited versions of the papers presented at the meeting as well as a transcript of the discussions which took place. It provides the ingredients for a broader framework fcr studying the problems associated with technology and society where risk is representative of a much wider set of concerns than simply the probability and consequences of a hazardous accident.

The Bundesministerium fuer Forschung und Technologie has an interest in promoting risk and safety research because of these new developments in society over the past ten years. In particular, there has been a diminished confidence in experts' statements on risk and a realization that many of the events which are being examined are not subject to detailed scientific analysis. There has also been an increasing recognition that distinctions must be made between analysis of the risk associated with an event and people's values and preferences. Another important development is the concern by the public that they participate more fully in the decision process on these issues. These concerns were articulated in both the papers and the open discussions at the summer study. The volume does not produce any definitive answers to the dilemmas facing society on how to deal with these new developments. Rather, it raises an important set of questions which need to be considered while at the same time providing a catalog of research needs. These suggested research topics reflect several of the objectives of the current program on risk at the Bundesministerium fuer Forschung und Technologie. In particular, there has been an interest in research on potential costs and benefits associated with new technologies. There was also considerable discussion related to the interaction between technology and society regarding attitudes toward risk, another theme of the current research program. The summer study offered an opportunity for an international exchange of ideas. I hope this volume stimulates future interchanges which address the important issues associated with risk and societal decision making.

Dr. Werner Salz
BMFT
June 1982

Acknowledgement

This book presents a set of papers and discussions from the first IIASA Summer Study on Risk on the theme of "Decision Processes and Institutional Aspects of Risk". The participants in this study represent a cross-section of people from different countries and different disciplines - all of whom have recently been involved in risk research.

The meeting was designed as a forum for discussion on the state-of-the-art of research into the descriptive aspects of risk from an institutional perspective. Its objective was to produce a better understanding of the role that prescriptive techniques such as risk analysis can play in resolving conflicts.

Accordingly, the meeting was structured to encourage an interchange of ideas - the morning sessions being devoted to the more formal presentation of papers with the afternoon sessions reserved for open discussion and small group discussions. We would like to thank the people who chaired these four groups: James Dooley, Oleg Larichev, Dorothy Nelkin, and Paul Schoemaker. The Summer Study was jointly organized by all IIASA researchers involved in risk activities. In this respect, we would like to thank Hermann Atz, John Lathrop, Joanne Linnerooth, Christoph Mandl, Giandomenico Majone, and Michael Thompson for their helpful suggestions regarding the structure of the meeting. We are grateful also to Noel Blackwell for her assistance during all stages of the organization and operation of the meeting. In addition, we would like to thank Valerie Jones and Susan Riley for their contribution to making possible the rapid and accurate preparation of the manuscript. We should like to thank Chris Whipple for providing useful comments and suggestions on all the papers during a visit to IIASA prior to the Summer Study.

We would further like to acknowledge the support of Alec Lee, Area Chairman of Management and Technology, Roger Levien, then Director of IIASA, and C.S. Holling for his continued support of risk activities.

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INTRODUCTION

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Howard Kunreuther and Eryl Ley

International Institute for Applied Systems Analysis, Laxenburg, Austria

SETTING THE STAGE

The term risk analysis has generated considerable controversy in recent years as to its meaning and importance with respect to societal decision making. The papers and especially the discussions included in this volume illuminate different aspects of this risk debate. The participants represent diverse disciplinary backgrounds, but all of them have an interest in the decision process and institutional aspects of risk.

The five-day meeting held during the early part of the summer of 1981 was an integral part of a two-year study at IIASA on "Liquefied Energy Gases (LEG): Siting Decisions", supported by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany. It formed the basis for much of the research and discussions that subsequently took place among researchers at IIASA concerned with problems of risk. We therefore labeled the meeting a summer study to indicate its intended spillover effects. The problems of interest are those which have potential economic benefits to individuals and society, but also have environmental, health, and safety risks associated with them. The siting of large-scale technologies such as energy facilities is a representative example.

Several features of such risk problems can be underscored. First there are many different individuals and groups in society who are affected by a particular decision, each of which has its own goals and objectives, databases and constraints. Each party is also likely to focus on several attributes (e.g., risk to life, environmental risk, costs) and assign different relative importance weights to each of these components.

A second feature of most of these problems is that there is a limited statistical database on which to determine the risk associated with a specific project or activity. Wynne points out that there is a myth of an ideal objective scientific knowledge to deal with policy issues surrounding these problems, while the reality of the situation is that probabilities and losses associated with different events are very ill-specified. As a result, each interested party can interpret data as it sees fit to estimate different risks, and to justify its position.

A third feature of risk problems is the dynamic and sequential nature of the decision process. Different interested parties enter the debate at different stages of the process depending upon the relevant issues being discussed. Allison (1971) points out that at each stage of the process the different parties have different degrees of power and responsibility, as well as conflicting preferences. In order to determine how a particular decision emerges, it is necessary to identify the various issues which were deemed important, to indicate what bargains and compromises were agreed upon, and "to convey some feeling for the confusion".

The sequential nature of the process is also due to the limited time and attention that can be devoted by any subset of the participants to a whole set of different issues and deadlines facing them. As Simon (1967) succinctly put it:

> "...influence over the direction of attention of the political organs is a principal means for effecting action. The notion of power as a tug-of-war between alternatives yields to a notion of power as influence on a sequential decision process, in which actions must be generated as well as chosen and in which attention is a scarce resource" (p108).

These three features of societal problems considered during this Summer Study required us to focus on how institutions and decision processes impact on the treatment of risk. A useful background to this is an understanding of the different meanings attached to the word "analysis". Raiffa in his paper indicates that the US National Academy of Sciences Committee on Risk and Decision Making devoted considerable attention to the role that different types of analysis can play with respect to problems involving risk.

Analysis can simply mean the *assessment* of the risks related to an activity. Vaupel (1981) indicates that the need for this type of analysis arises because various facts uncovered by natural social science research are often insufficient or not well enough established to remove uncertainty. This type of analysis involves the synthesis of disparate and indirectly relevant evidence, both objective and judgmental, in order to assess the probability distribution estimates for the factors of primary concern in the decision problem. Experts with backgrounds in statistics and decision analysis are often called in to undertake these types of assessments. The papers by Mandl and Lathrop and by Lathrop in this volume, focus on this definition of analysis.

Analysis can signify an attempt to understand how the exisiting institutional structure deals with problems involving risk. In this interpretation of analysis one has to specify the different interested parties and their roles, the impact of different legislation and legal constraints as it affects the interaction among these parties, and the different cultural biases and styles between groups or between countries dealing with specific problems. The three papers by Wynne, Ronge, and Thompson and Wildavsky address these issues.

A third descriptive definition of analysis is an understanding of the actual decision making process for dealing with problems where risk is involved. This involves questions on how information is processed by each of the interested parties, the resulting conflicts which emerge in the policy debate, and the way in which final outcomes evolve. The papers by Kasperson and Gray, Dooley and Oseredko, Larichev and Mechitov investigate the decision process in real case study situations.

In a prescriptive context, analysis can mean the types of policies that are proposed for dealing with specific outcomes. In particular, the main theme of the papers and discussions was methods whereby one can provide better information for making decisions, the role of standards and regulations, and also of developing compensation and insurance schemes. The papers by Drake and Long and Fairley concentrate on issues of policy design.

Finally, the word analysis can refer to ways of improving the decision process in order to resolve conflicts. Here one considers mechanisms for resolving conflicts due to disparate evidence (e.g., differences between risk assessments) as well as ways to improve group decision processes. The paper by Kleindorfer and one of the lively interchanges during the discussions were devoted to this definition of analysis.

We will now elaborate on each of these five meanings of analysis, interweaving, where appropriate, the ideas presented in the papers as well as the discussions among the conference participants.

RISK ASSESSMENT

Due to the lack of statistical data and standards that assessments must meet in order to be used as evidence, experts have few guidelines for restricting how they undertake risk assessments. Such broad degrees of freedom have created considerable problems for societal decision making processes.

Oseredko *et al*. indicate that in pipeline siting decisions in the USSR, experts only provide qualitative estimates of many of the parameters and such approximations are influenced by their past experience with a particular feature or attribute.

In their study of a number of different risk assessments, Mandl and Lathrop show how experts use different definitions of risk for the same problem. For example, some estimates of risk focus on a probability of a disaster or accident occurring, and no mention is made of the consequences of the event. The other extreme is that a risk assessment might focus on a maximum credible accident without assigning any probability to its occurrence. Even if all experts were using the same definition of risk, each of them might make a different set of assumptions as to how to estimate the probability or consequence of an event. Hence, two experts focusing on the same situation and using the same definition of risk may arrive at radically different conclusions as to whether it is above or below some specified acceptable level. For these reasons, there was general agreement by the participants that political and social processes greatly influence consideration of risk and that risk should not be looked at in a vacuum.

For example, private consulting firms who undertake risk analyses can have a built-in bias telling the contracting party what they want to hear. Hence the estimates may reflect the different goals and objectives of the relevant interested parties. Linnerooth investigates the implication of several different risk assessments with conflicting estimates concerning the siting process for an LEG terminal in California. She points out that these types of analyses are designed to persuade or support a party argument rather than simply to report results in a statistically meaningful manner.

Finally, we should point out that risk assessments are affected by external events such as accidents. For example, Kasperson and Gray note that following the Three Mile Island accident the Nuclear Regulatory Commission substantially shifted its risk research program toward higher probability/lower consequence events. Similar changes also occurred in the electric power research institutes program in the US.

INSTITUTIONAL ARRANGEMENTS

The focus of attention concerning institutional arrangements was on how analysis is utilized for coping with specific problems in the context of the structure of society. When one looks at risk in this context, it is no longer determined by estimating certain parameters, but rather by a social process. Risk in this sense is viewed as a function of the way different groups in society feel about the problem and interact with each other. In their paper, Thompson and Wildavsky stress the importance of different cultural styles as they affect the group interaction process. Each of the interested groups or parties perceive risk as they want to see it, independent of its physical measurement.

An illustration of how different groups react to the same risk is provided by the analysis of the institutional response to the TMI accident (Kasperson and Gray). The US Nuclear Regulatory Commission was anxious to maintain the *status quo*, despite the fact that the Kemeny Report (the Report of the President's Commission after TMI, 1979) recommended a number of substantial changes in its organizational structure. On the other hand, the electrical utilities who managed the operation of the nuclear power plant used the accident as an opportunity to modify their existing operations. Here two parties analyzed the same situation from their own perspectives and responded to the disaster very differently.

During the meeting considerable attention was devoted to different cultural styles of risk across countries. For example, the USSR attempts to resolve differences between groups through some form of compromise (Oseredko *et al.*), whereas the United Kingdom has more of a hierarchical and consensual style (Wynne), and the US style of societal decision making is more adversarial in nature (Linnerooth). In West Germany, traditional political processes of compromise may have broken down, so that institutions are not functioning in the way they have been in the past (Ronge). Thus, we cannot assume that standard risk analysis techniques that were useful to justify decisions in the past will be able to iron out differences today in West Germany.

DECISION MAKING PROCESSES

This view of analysis stresses the limited ability and desire of decision makers to collect information on which to base their preferences. Interested parties thus attempt to *satisfice* rather than optimize (Simon 1967). For this reason, there is a tendency to use simplistic rules for dealing with particular problems.

This situation is particularly acute after a crisis or accident when many actions have to be taken in a very short space of time (Dooley).

An example of the use of simplified decision rules is provided by Oseredko *et al.* in "The Siting of Pipelines in the USSR", who point out that simple pairwise comparisons were made on separate attributes across alternatives rather than weighting all of the components simultaneously through some type of multi-attribute utility function. One reason for using this type of simplified rule in societal decision making is that the data on which to estimate different attribute values are not very good so that decision makers are hesitant to use sophisticated techniques. In addition, when there are limited alternatives, as in the pipeline case, pairwise comparisons are relatively simple to make. Given that time is an important constraint in these problems, these types of heuristics may be appropriate for the given situation.

Another critical feature of the sequential decision making process is the importance that accidents and random events play. The small statistical database coupled with systematic biases of individuals dealing with uncertainty (Tversky and Kahneman 1974) increase the importance of these exogenous events. Frequently, a disaster jolts the interested parties into action and leads to new regulations or standards to "prevent" future accidents. Kasperson and Gray illustrate this point by detailing new siting regulations which were promulgated after TMI with respect to population density near a nuclear power plant. Drake and Long provide a number of examples of new codes and standards that were triggered by specific accidents and, subsequently used for siting, designing, and operating liquefied natural gas (LNG) and liquefied petroleum gas (LPG) facilities.

In his paper, Wynne points out that human error or incompetent staff are frequently blamed for the cause of a specified accident, whereas in reality, the event may have been due to lack of relevant information and/or faulty organizational procedures. He provides illustrations of these phenomena using examples from the Windscale fire of 1957 and the TMI accident.

A pervasive problem regarding the societal decision process is the conflict among the different interested parties. The analyses utilized by each of the parties to defend their objectives are generally not based on tested assumptions, nor are they easily challenged in hearings or public enquiries. The resolution of these conflicts will depend on the nature of the problem, the degree and timing of public participation, as well as the relevant style of risk management.

Recently, the Risk Group at IIASA has developed a framework of the decision making process for problems such as the siting of facilities based on new technologies. This multi-attribute, multi-party (MAMP) approach considers the role of many interested parties in this specific concern (Kunreuther *et al.* 1982). It emphasizes the potential for conflict emerging among the interested parties as a result of their different objectives, mandates, and information sources. Linnerooth illustrates the use of the MAMP framework in the context of the siting decision of an LNG terminal in California.

POLICY DESIGN

Market-based solutions for dealing with risk are of limited usefulness in dealing with the types of societal decision making problems covered in this summer study. One reason is that the lack of a good statistical database to estimate risk makes it difficult to determine the expected costs and benefits associated with different programs.

Kleindorfer suggests three additional reasons why such policies will not work well. The first relates to the fact that these problems are classified under the heading of public goods or public bads where individuals are involuntarily exposed to certain risks. A second factor that we have already alluded to is the information collection and processing difficulties facing all interested parties. Thirdly, at the level of the firm, the catastrophic loss potential associated with particular risks makes it difficult for enterprises to obtain protective measures such as insurance.

For these reasons, social institutions for dealing with these types of problems have emerged. Therefore a critical factor is a thorough understanding of the political and social processes associated with particular problems. We will now briefly review the policies which were proposed in the papers and discussions during our meeting. The potential success of any of these proposals depends on the problem context, the existing institutions and decision processes of the relevant interested parties. We will provide examples of where certain programs have worked well in specific countries.

Providing better information. One way that analysis can help to improve decision making is to provide better information to all the parties who are affected by particular programs. One very positive example of this is in Sweden, where the government financed a program to inform the public about energy and nuclear power. The program involved 8000 study circles each consisting of approximately ten members who came together to discuss those energy-related questions they felt to be most important. The expectation on the part of the Swedish government was that this type of interchange would create a more favorable attitude toward government policy. However, the reports from these groups suggested that there was a continued uncertainty and ambivalence which resulted in lack of consensus on the issue of nuclear power (Nelkin and Pollack 1979).

Another way of providing information to different parties is through certain types of decision aids which can be used to help determine the relative merits of different alternatives (e.g., whether to site a facility at location A, B, C, or not at all). Lathrop feels that one can broaden traditional risk analysis from looking only at an expected number of fatalities, to one covering a broader set of attributes (e.g., expected health effects, catastrophic potential and unequity of impacts). He contends that this information can be incorporated through an expanded multi-attribute utility model so that the decision maker has a better appreciation of the social and political factors that may impact on final outcomes. Although this approach may be useful for a single decision maker, it still does not address the problems of conflict resolution when the different parties have not been able to reach a consensus.

In their papers, Dooley and Kleindorfer both recommend computer-aided decision support systems which will enable policy makers to determine the impact of different policies on physical phenomena under a set of scenarios that they create. For example, assume the policy maker was interested in the consequences of a fire to an LNG storage tank which was proposed for a given location. Based on models of vapor cloud dispersion he could investigate the potential destruction and fatalities under different assumptions with respect to the way the wind blows. Furthermore, he could place the LNG terminal at different points within the community or at different sites to investigate the potential catastrophic impact under different wind conditions. This type of interactive analysis enables different interested parties to see the effect of alternative assumptions and physical models (e.g., vapor cloud dispersion models) on outcomes.

Developing standards and regulations. Another class of policies relates to specific codes and standards which make structures safer or which impose restrictions on where projects can be located. These types of regulations serve many different interested parties simultaneously. Residents, for example, may feel safer if a facility is sufficiently far away from their homes. At the same time, the government may wish to avoid the higher prices of a potentially catastrophic accident in a densely populated area. As Drake and Long point out, industry is also frequently in favor of certain standards and regulations because it prevents the less responsible firms from damaging the industry's reputation. One of the open questions with respect to standards and regulations is how to estimate the potential costs and benefits of these measures to the different interested parties. In addition, there is then a need for a regulatory body to monitor, control, and enforce these measures.

Instituting insurance policies and compensation measures. The principal purpose of these programs would be to force those parties (e.g., industry, government) who stand to benefit from particular programs also to bear an appropriate share of the costs should there be damage to the environment or losses to property and life.

Insurance programs and compensation schemes directly address the distribution of gains and losses from specific programs. Such distribution questions are critically important in political decision processes. As Robert Behn (1981) argues:

> "In contrast to the analyst, the politican is most interested in distribution. Political influence is exercised not by individual citizens but through the intermediation of organized constituencies, as an elected official or political appointee of one, the policy politician is responsive to constituencies—not to the analysts' abstract notion of aggregate public welfare. The politician is deeply concerned about how much his constituents will benefit and how much they will pay."

One example of an institutional response in this direction is the self-regulation measures adopted by the public utilities following the TMI accident. Kasperson and Gray point out that the utilities have cooperated to create an insurance pool to protect themselves against the potential extraordinary cost which would accrue to any utility following a future major nuclear accident. Fairley recommends that producers who benefit from specific projects be made liable for all the costs they impose upon others. He points out that this can take the form of self-insurance, commercial insurance, industry risk pooling (as in the TMI example) and/or government-managed compensation funds. The previous history of societal risk bearing in most countries suggests that these schemes would be difficult to implement if there are catastrophic risks which tax the reserves of private industry. The Fairley proposal does suggest the importance of allocating responsibility prior to a disaster rather than determining who will pay after the event occurs.

Much of the opposition to the proposed high-risk projects comes from relatively small groups of individuals, often residents of the area, who feel that they would suffer losses in property values and would have to bear the costs of health and environmental risks. O'Hare (1980) has characterized this general problem as "not in my backyard". He has proposed a particular type of compensation scheme whereby each community considered as a potential site, determines a minimum level of per capita compensation, and it would be willing to make a legal commitment to have the project in their backyard if the compensation is paid. The applicant would include such compensation as relevant in calculating the siting costs associated with locating the facilities in community A, B, or C. The final decision would then be made by the applicant taking into account the amount of compensation he would have to pay residents in each of these three localities.

Whether or not such a compensation scheme is a useful policy description depends on the specifics of the situation and the cultural differences in risk management style. In this connection, it would be interesting to ask what types of payments would have been required to please the citizens of Oxnard, California, so that an LNG terminal could have been located there. What would the Sierra Club require in payments for them to support a site which might have adverse environmental effects? As indicated in the papers and discussions at the meeting, these questions can only be answered in a real world problem context. They do reflect an increasing concern of social scientists and policy analysts in dealing with windfalls or wipe-outs from specific accidents which involved the public sector. Kunreuther and Lathrop (1982) point out that the final outcome is likely to represent a balance between the political restraints and economic criteria. They refer to a quote by Wildavsky (1981) which states:

> "The criterion of choice in politics and markets is not being right or correct as in solving a puzzle, but agreement based on interaction among partially-opposed interests" (p131).

DESIGNING ANALYSES FOR IMPROVING PROCESS

Wynne points out in his paper that there is a myth that consensus between different interested parties is possible because there is only one objective truth.

He contends that the reality is quite different since there is no single scientific truth. If consensus occurs, it is due to default rather than agreement. Much of the discussion at the meeting revolved around the question "How do we improve the decision process given that there is not a single scientific truth? We will now briefly summarize the major points coming out of the papers and the discussion.

Establishing Credibility of Analyses

In general, existing institutions in most countries are inadequate to deal with problems of conflicting evidence and polarized expert opinion with respect to questions such as risk assessments. One of the recommendations of the CORADM Report is that one should report honestly on the basis for disagreements among experts in the assessment process and then have policy makers determine what to do with the data in their evaluation process (Raiffa). The committee pointed out that experts will disagree due to their different experiences, their different paradigms, and the different types of information they utilize.

One way of dealing with this problem is to establish rules of evidence where one can better understand the differences in experts' risk analyses. Lathrop and Linnerooth (in press) suggest a set of guidelines establishing these rules of evidence. In particular, they stress the importance of defining the risk being assessed, clarifying the assumptions and error bounds, and indicating the conditional nature of specific analyses which were undertaken.

A principal problem which currently exists in implementing these guidelines is the lack of an institutional mechanism for reviewing different risk assessments. Ackerman *et al.* (1974) point out that the traditional approaches such as legal responses, agency hearings and judicial reviews have inherent limitations with respect to evaluating these conflicting assessments. Such evaluations are especially difficult for classes of problems where there are no statistically based measures of risk. These authors propose the establishment of a review board to examine different assessments. Under their proposed procedure members, all of whom would be trained in subjects fundamental to technical analysis, would provide a written report evaluating the impact of specific assessments for specific issues (e.g., population risk, environmental impact). Particular attention should be given to identify the empirical basis of the set of findings and to determine how well the analysis is grounded in scientific theory.

Group Procedures for Facilitating Collective Action

When different interested parties disagree on a preferred set of alternatives for specific projects, there is a need for each to understand the other side's decision. Kleindorfer points out that this is particularly important when there are conflicts of values (e.g., the importance of safety or environmental impact on a project) or conflicts of fact (e.g., different risk assessments). In his paper he outlines a number of approaches for dealing with this problem. Particular attention is given to strategic planning models when one tries to mesh an ideal state with the *status quo* through scenario generation.

It may also be possible to involve the different participants in role-playing activities. Holling and his colleagues at the Institute of Resource Ecology have conducted workshops on role-playing where each of the participants specifically takes on the role of one of the relevant actors in a societal problem. Prior to the workshop, each participant interviews a particular individual whom he is representing so that he can understand his objective and relevant information being considered in evaluating different alternatives (see Holling 1981).

Institutions for Resolving Conflicts

There was considerable interchange in the discussion on different proposed review mechanisms for helping to resolve conflicts among different interested parties. There was general consensus among the group that the type of procedure is critically dependent on the specific problem being considered and the social and cultural environment. For example, reference was made to the Canadian experiment in which the Berger Commission was created to assess the Mackenzie Valley Pipeline controversy. As part of this project, intervener groups were given financial support to develop their case. The Dutch Science Shops were also cited as an example of a public enquiry which evaluates the reaction of the interested parties who are affected by projects that impact on the environment.

These examples are elaborated upon in the discussions which appear in Chapter 5. Finally, we should point out that to understand risk decision making one has to consider the cultural milieu. Thompson and Wildavsky in their paper put forward a theory as to why different types of people in the same situation react differently. One of the stimulating features of the Summer Study was the different reactions of the participants (from seven different countries both East and West) when we discussed various issues.

ORGANIZATION OF THE PAPERS

The first paper by Linnerooth outlines a descriptive framework of the decision making process for problems such as siting facilities. The approach, developed here at IIASA is a multi-attribute multi-party (MAMP) framework of choice in a dynamic setting. It considers the potential for conflict emerging between interested parties as a result of their differing objectives, mandates, and information sources. On the prescriptive side the approach explores the roles that analyses, including risk analysis, and decision theory can play in providing a more systematic basis for making decisions. The framework is illustrated in terms of a specific problem, that of the LNG siting decision in California, USA.

Raiffa, in his paper, describes the work of the US National Academy of Sciences Committee on Risk and Decision Making (CORADM). The objectives of this committee were very similar to those of our Summer Study. Much of the attention of the committee was spent on the role of analysis in dealing with problems which have adverse effects on health, safety, and the environment. In particular, the paper addresses the difficulty of decomposing risk assessment from risk evaluation, a theme which is stressed in other papers as well as in the dicussions.

Chapter 2 deals with "Risk Assessment in a Problem Context". The first paper by Mandl and Lathrop examines the assessment of risk to life in catastrophic accidents due to a large-scale technology (LNG) facility. Two primary goals are to present and compare various procedures of risk assessment and to quantify and compare risks at four facilities. The paper concludes that there are disagreements between the experts as to how to quantify risk, which models to use, and what to include and exclude in risk assessment. This is due to new technology (limited data), new techniques of risk assessment for LEG terminals (new approach), as well as the different needs of the client.

Kasperson and Gray, in their paper, report on the response and changes which occurred after TMI and the impact of the Kemeny Report on nuclear safety. Each of the interested parties reacted to the accident and report in different ways, reflecting their own goals and objectives. The authors point out that the media had considerable coverage of the Kemeny Report prior to its being issued as well as immediately thereafter. However, they exhibited lack of sustained analysis and the subsequent societal response. Industry undertook a number of reforms in managing nuclear power plant safety even before the recommendations of the Kemeny Commission. In contrast, the Nuclear Regulatory Commission's response to both TMI and the Kemeny Report has "been more delayed and uneven". The paper concludes that the long-term response to TMI and the report may be to further self-regulation in nuclear power.

Dooley's paper was stimulated by the organizational and institutional response to the Missassauga, Ontario, accident where 24 cars of a train derailed, 19 of which carried hazardous material. It looks at the characteristics of crises and then suggests ways of improving decision making. In particular, Dooley points out that decision making in a crisis seems to be described by Simon's procedural rationality model in which individuals have limited time to deal with the situation and sparse information. Decision makers will take actions based on past experience in similar situations.

Oseredko *et al.* describe the site selection process for locating gas pipelines in the USSR where there are many different attributes to be considered. Each of the interested parties in the debate considers a subset of these attributes so that at the outset there is no consensus on which one of the several alternatives to choose. The paper illustrates the sequential nature of the decision process, the use of heuristics for arriving at a final state through compromise, and the limited role that experts play in arriving at a final solution.

The final paper in Chapter 2 by Drake and Long, discusses the development of codes and standards used for siting, designing, and operating hazardous facilities such as LNG and LPG plants. Drake indicates the importance of unexpected accidents in triggering regulations and points out that standards will continue to evolve as accidents indicate weaknesses in present requirements.

Chapter 3 focuses on "Institutional Aspects of Risk". Ronge, in his paper, indicates that the traditional political processes of compromise in bargaining have broken down and hence one has to re-evaluate the role that analysis plays in the societal decision making process. In particular, the author focuses on West Germany and points out that parties that lose in the policy debate frequently resort to violence. He offers as reasons for these changes the ecological movement, the "small is beautiful" philosophy leading to opposition of large technologies, and the general antipathy to social institutions. The paper concludes that risk research needs a framework grounded on theoretical principles which incorporates political processes.

The following paper, by Wynne, is concerned with myths regarding the operation of institutions and the use of scientific rationality in risk assessment. Society is operating under the myth that there is objective scientific knowledge which can be used to deal with policy issues associated with risk. The reality is we cannot achieve this ideal. By striving to reach it we may create more problems than we solve. The paper argues that there is a need to study how scientists, organizations and institutions function in the context of the political process so that we can replace the set of current myths with a more realistic picture of the world.

Chapter 3 ends with "A Proposal to Create a Cultural Theory of Risk", by Thompson and Wildavsky, who attempt to answer the question as to why different types of people facing a similar societal problem react in different ways. A cultural theory of risk is developed which characterizes five different groups on the basis of the intersection of two dimensions: groups (the extent to which an individual is involved in social groups) and grids (the extent to which an individual is involved in hierarchical arrangements). Each of the five resulting cultural categories has its own rationality which is likely to be contradictory. Risk debates are likely to differ between cultures because of different constellations of groups in each culture. On the basis of this theory, one can give policy makers insights into why there are profound disagreements over risk, and under what situations one can hope to resolve conflicts between parties.

Chapter 4 is concerned with "Decision Processes and Prescriptive Aspects of Risk". The principal theme of Lathrop's paper is that there are two perspectives on risk: the technical and psychological, each of which looks at the societal and decision making problem in different ways. The technical perspective focuses on a single index, the expected number of fatalities from a given alternative. The psychological perspective looks at a variety of different factors in evaluating the risk. At the prescriptive level, the paper proposes an expansion of a multiattribute utility function so that it recognizes political realities in social concerns which affect risk management.

In his paper, Kleindorfer indicates the information and process difficulties associated with market-based solution and regulatory mechanisms for solving societal decision making problems. The key challenge in risk management is to find ways of reconciling conflicts between the parties because of the different assumptions, goals, and objectives, as well as the knowledge base on which each group operates. The paper proposes the use of group processes for reconcilling differences building on the work of Ackoff *et al.* on strategic planning. The approach relies on scenario generation towards an ideal state which requires stating the necessary assumptions which each group has made to achieve this ideal state. By coupling this approach with specific methods (e.g., Saaty's analytic hierarchy approach, computer-based decision support systems, role playing) one may be able to get the decision maker to see differences in the assumptions. In this way interested parties may be able to achieve consensus through compromise solutions.

In the concluding paper, Fairley argues for market-based solutions to problems of societal risks so that risk producers are liable for the costs they impose on others. By shifting the responsibility for catastrophic accidents from society to producers, the author feels that risk producers will undertake thorough risk assessments since they have a stake in the accuracy of the data. In this way risk assessments will focus on a number of other attributes besides loss of life, such as injury and property damage.

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Siting an LNG Terminal in California: A Descriptive Framework

Joanne Linnerooth

International Institute for Applied Systems Analysis, Laxenburg, Austria

1. BACKGROUND

Liquefied natural gas (LNG) is, as the name suggests, a gas that is liquefied for purposes of transportation. To liquefy natural gas, its temperature is reduced to -160^{0}C, at which point the volume of the gas is reduced to approximately one-six hundredth of its original volume. Presently, there are 16 receiving plants in the world, primarily in Japan, in Western Europe, and in the US. A typical tank has a volume of 80 000m^3; there are usually from two to four of these tanks at a receiving terminal. The early ships had a capacity of something around 27 000m^3, present ships as high as 130 000m^3. It was estimated that in 1981 there would be at least 57 LNG carriers operating in the world with a combined capacity of over 5.21 million m^3.

The capital costs of a typical operation include the costs of the export terminal, the receiving terminal, and the ships. The cost of a typical export terminal is around $750 million; a receiving terminal with four tanks costs something in the order of $150 million; and three methane tankers, a minimal number, add another $450 million. This totals more than a billion dollars (Office of Technology Assessment 1977). The throughput of a typical plant, as calculated from Point Conception (see Mandl and Lathrop 1981), is approximately 15 000 megawatts (MW) of electricity. This is approximately equivalent to the throughput of 15 nuclear power plants. In sum, the import or export of LNG is a highly capital-intensive and energy-intensive operation.

In the event of a ship or terminal accident, a significant amount of LNG could be spilled, which would "boil off" into a methane cloud. Since the dispersion characteristics of methane clouds are poorly understood there is a great deal of uncertainty involved in predicting accident consequences. Yet, the present state of knowledge indicates that at some very low probability an LNG accident could result in a cloud covering several miles before igniting. Depending on the population density of the area covered by the cloud, the possibility exists, albeit at a low probability, for a catastrophic accident.

A liquefied energy gas terminal, therefore, promises to yield benefits to society, but only at a cost of potential catastrophic accidents. The siting of these large-scale facilities presents a formidable challenge to political risk management processes. There are two features of these problems that make them particularly difficult to resolve. First, the gas consumers who benefit from the terminal do not always bear the risks, which fall on a small group of people living in the vicinity of the terminal. The problem is how to distribute the costs and benefits. Hence, there is the potential for conflict among the interested parties. A second feature of the siting problem is the absence of a database that provides conclusive statistical evidence on the likely performance of the new

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technology and the probability distribution associated with potential accidents. Each of the interested parties may thus provide different estimates of the chances and consequences of certain events. There are *no* objective measures to settle these differences.

The IIASA Risk Group is investigating how decisions with these features are taken. For this purpose, the siting of LEG terminals in four countries—the FRG, the Netherlands, the UK, and the USA—have been selected as case studies. The approach taken at IIASA builds on the notion that a good understanding of how societies make siting decisions, i.e., the institutions involved and the uses made of scientific expertise, is necessary to improve upon these processes.

2. THE DESCRIPTIVE FRAMEWORK

In this section, I will briefly discuss the framework used to compare the siting process in the four countries under study, and will illustrate this framework in the context of the siting process in the United States. The framework emphasizes the involvement of many interested parties and the diverse concerns, or attributes, of these parties. Hence we have labeled it the multi-attribute, multi-party (MAMP) approach. In developing this structure, we have been greatly influenced by the concepts discussed by Braybrooke (1974) where he looks upon the political system as a machine or collection of machines for processing issues.

2.1. Rounds

The decision process can be separated into different rounds which we label by capital letters, A, B,... A round is simply a convenient device to illustrate a change in the focus of discussions. This new focus or direction can be triggered by (1) a key decision taken (or a stalemate reached due to conflicts among parties), or (2) a change in the context of the discussions due to an unanticipated event, the entrance of a new party, or new evidence brought to the debate. Rounds are simply a convenient way of segmenting the decision process; they are not unique and can be simultaneous or overlapping.

The problem in each round is defined by a set of issues, decision constraints and procedures. Braybrooke (1974) refers to an "issue-circumscribing" phase where the alternatives for discussion are bounded by generally accepted, though not necessarily irrefutable, facts and values, e.g., "it is technically feasible to import LNG to California" or "California needs LNG". As we have already noted the problem is also formulated or defined by the decisions from earlier rounds. Clearly the problem-defining process will have an effect on final outcomes through this latter type of bounding constraint.

2.2. Problem Formulation

A round of more or less official discussions is initiated by a formal or informal request. Informal discussions may be initiated simply by such actions as a request for information on the part of one of the parties or a request for preliminary discussions. Because the particular form of how the round is initiated may further define or limit the bounds of the discussion, the careful scrutiny of their wording is important. For example, it may make a difference in the decision process if the question is framed as "is there a site which is appropriate?" or "which of the sites x, y, and z is appropriate?" Braybrooke (1974) refers to the first question as a "which-question" and the second as a "whether-question". Which-questions demand more complicated considerations and detailed thinking, while whether questions can be approached with simpler rules of thumb and heuristics.

2.3. Interaction

To understand a particular pattern of institutional choice it is necessary to analyze a set of policy actors, their interactions with one another at different stages of the process, and the information available to them. A party's evaluation of an alternative is based on its estimation of the levels and values of each attribute resulting from that option, the value of each of those levels, and the relative importance given to each attribute. Another party might have different estimates of the effects of an option, different costs and benefits resulting from those effects, or may assign a different relative importance to each of the attributes. Because of any of these differences one party may rank alternatives differently from another.

The interaction among the parties is represented by the *main arguments* each brings to the debate in support of or in rejection of each of the alternatives at hand. Those arguments may relate to only one or two attributes. It is *not* suggested here that the arguments presented for or against a particular proposal necessarily reflect a concern of the party making the argument. For example, a party opposed to a site because of its concern for environmental quality may present an argument using seismic risk as the main reason to reject the site. The argument may be selected to maximize the effectiveness of the argument, not to reflect the actual concern of the party. The argument reflects a *strategy* on the part of the actor in support of or opposition to the proposal. The strategy of the actors can reveal a number of underlying motives and desires of those concerned and may be essential in understanding the interpretation and use of scientific evidence, including risk analyses.

2.4. Concluding a Round

The round is concluded by a decision, a stalemate, a change in information (changing the focus of the debate and hence initiating a new round), or an unanticipated event aborting the discussions and requiring a new round of inquiry. Each decision can, in turn, be described by the trade-offs implicit in the choice made. These trade-offs may not be explicitly recognized by the decision maker, or not explicitly analyzed in the process of making the decision.*

3. APPLYING MAMP: THE SITING OF THE CALIFORNIA LNG TERMINAL

In the late 1960s, faced with projections of decreasing natural gas supplies and increasing need, several California gas utilities began to seek additional supplies. In 1974, Western LNG Terminal Company (Western), which was formed to represent the LNG interests of the gas utilities, applied for approval of three LNG import sites on the California coast: Point Conception, located on a remote and attractive part of the coast; Oxnard, a port city; and Los Angeles, a large harbor metropolis. The LNG would be shipped from southern Alaska, Alaska's North Slope, and Indonesia. At the time of writing, Point Conception, the one site remaining under active consideration, is still pending approval. This section describes the interested parties, procedures, decisions, and events of this lengthy process (for a more complete review see Linnerooth 1980, Lathrop 1980, Kunreuther *et al.* 1981).

3.1. Interested Parties and Relevant Attributes

To structure the siting process we need to have a good understanding of the different concerns of the interested parties. In the California case, there were

*The distinction between a "decision maker" and a decision resulting from a process is an important one since the person responsible for the decision often cannot be identified (see Allison 1971, Majone 1979).

Table 1. Principal party-by-attribute matrix for LNG siting in California.

		Principal parties*							
		Applicant	Government					Interest groups	
			Federal	State			Local		
Attributes		Utilities P_1	FERC P_2	CCC P_3	CPUC P_4	Legis. P_5	municip. P_6	Sierra Club P_7	Local citizens P_8
RISK									
Supply interruption	X_1	•	•		•	•			
Population	X_2		•	•	•	•	•	•	•
Earthquake	X_3		•	•	•	•			
ENVIRONMENTAL									
Air quality	X_4		•		•	•		•	
Land use	X_5		•	•	•	•	•	•	•
ECONOMIC									
Profit consideration	X_6	•							
Price of gas	X_7		•		•	•			
Local economic benefits	X_8						•		

*Key to party acronyms, abbreviations:

FERC: Federal Energy Regulatory Commission, or in the first two rounds of the process, its preceding agency, the Federal Power Commission.
CCC: California Coastal Commission.
CPUC: California Public Utilities Commission.
Legis: California State Legislature
Municip: Municipal government.

Source: Kunreuther *et al.* (1981).

three categories of concern which are relevant: risk aspects, economic aspects, and environmental aspects. Each of these concerns can be described by a set of attributes. Table 1 depicts an interested party/attribute matrix showing the main concerns of each of the relevant groups over this seven-year period.

The attributes listed have been selected to reflect the nature of debates in the process, that is, to reflect the attributes as perceived by the parties in the debate, rather than to characterize in some logical analytical manner the alternatives. For example, population risk (X_2) involves the risk to life and limb to neighbors of the LNG terminal due to accidents including those induced by earthquakes. Earthquake risk (X_3) which involves both population risk and supply interruption risk due to earthquakes, is included as a separate attribute since it was handled as such in the process.

The filled cells in Table 1 indicate which parties pay particular attention to which attributes. Naturally, many of the parties care about all the attributes listed. However, either because of the incentives directly felt by the party or because of the role the party plays in society, each party makes its decisions based upon a particular subset of the attributes. For example, while the applicant is certainly concerned with environmental quality and risks to the population, its primary responsibilities and concerns are earning profits for shareholders and delivering gas reliably to consumers. Its actions are apt to be motivated by concerns for profits and gas supplies, and constrained by political and legal limits set by other parties' concerns for safety and the environment. Likewise, the Sierra Club cares about reliable gas supplies, but receives membership dues for being primarily concerned with environmental quality. Consequently, in a situation where a proposed action increases the reliability of gas supply at the expense of environmental quality it is reasonable for the applicant to favor the proposal and the Sierra Club to oppose it. These differences in primary concerns may determine a great deal of the behavior of the political decision process, and explain how that process is apt to differ from the single decision maker postulated by normative evaluation approaches. The important message of Table 1 does not lie in the details of exactly which cells are filled, but lies in the generally great differences in the columns of the table. That is, the different parties in the process care about different subsets of the attributes.

The applicant, Western LNG Terminal Associates, was a special company set up to represent the LNG siting interests of three gas distribution utilities: Southern California Gas Company, Pacific Gas and Electric, and El Paso Natural Gas Company. As domestic gas supplies seemed to be diminishing in the late 1960s, the gas utilities perceived an increased risk of supply interruption, which could be mitigated by additional supplies such as LNG. Quite naturally, the applicant was primarily concerned with profitability (X_6) and secure supplies of gas (X_1).

At various government levels there are five principal parties. The Federal Energy Regulatory Commission (FERC) in the Department of Energy is the principal body at the federal level which determines whether a proposed LNG project is in the public interest and should be allowed. In making its judgment it considers primarily the following attributes: risk factors (X_1, X_2, and X_3), environmental guidelines as reflected in air quality (X_4) and use of land (X_5), and the expected LNG price (X_7).

At the state level, the California Coastal Commission (CCC) was created in 1976, and has the responsibility for the protection of the California coastline. Its primary concerns with respect to LNG siting are with the use of land (X_5) and the associated risks (X_2 and X_3) from building a terminal at a specific site. The California Public Utilities Commission (CPUC) is the principal state body involved in power plant issues and is primarily concerned with the rate-setting process. Hence, it focused on the provision of energy to California residents and the need for gas (X_1) and the proposed price of the product (X_7). In addition, it has responsibility for evaluating the impact that a proposed facility would have on the environment and safety. The California state legislature is ultimately responsible for the outcomes of any siting process. It determines which state and local agencies have final authority to rule on the feasibility of a proposed site. In addition, it can set standards to constrain any siting process. Hence the concerns of the legislators range over economic, environmental and safety attributes, as shown in Table 1.

At the local level, the city councils evaluate the benefits of a proposed terminal in their jurisdiction in terms of the tax, business revenues, and jobs (X_8) it promises to provide. The councils try to balance this positive feature with the impact that the facility would have on land use (X_5) and risk to the population (X_2). Finally, the public interest groups, represented by the Sierra Club and local citizens' groups, are primarily concerned with environmental and safety issues.

3.2. The Decision Process

The siting process in California (which is not yet terminated) can be characterized by four rounds of discussions as shown in Table 2, which provides a summary of how the problem was defined, the initiating event, and how the discussions were concluded. The remainder of this subsection discusses in more detail the decision process within each of the rounds. The main elements of round's A, B, C, and D are described in Tables 3, 4, 5, and 6 respectively.

Table 2. Summary of rounds in California LNG siting case.

ROUND A		DATE
Problem formulation:	Should the proposed sites be approved? i.e., Does California need LNG, and if so, which, if any, of the proposed sites is appropriate?	
Initiating event:	Applicant files for approval of three sites.	September 1974 (34 months)
Conclusion:	Applicant perceives that no site is approvable without long delay	July 1977
ROUND B		
Problem formulation:	How should need for LNG be determined? If need is established, how should an LNG facility be sited?	
Initiating event:	Applicant and others put pressure on state legislature to facilitate LNG siting.	July 1977 (2 months)
Conclusion:	New siting process set up that essentially assumes a need for LNG, and is designed to accelerate LNG terminal siting.	September 1977
ROUND C		
Problem formulation:	Which site should be approved?	
Initiating event:	Applicant files for approval of Point Conception site.	October 1977 (10 months)
Conclusion:	Site approved conditional on consideration of additional seismic risk data.	July 1978
ROUND D		
Problem formulation:	Is Point Conception seismically safe?	
Initiating event:	Regulatory agencies set up procedures to consider additional seismic risk data.	
Conclusion:	(Round still in progress).	

Round A began in September 1974, when the applicant filed for approval of three sites on the California Coast—Point Conception, Oxnard, and Los Angeles—to receive gas from Indonesia. The application raised two central questions which defined the problem addressed in Round A: Does California need LNG, and if so, which, if any, of the proposed sites is appropriate?

The agenda for discussion was more narrowly defined at this stage. The wheels of the process were set into motion, not by a broadly based energy policy question initiated in Washington, but by a proposal from industry for three preselected sites. The importance of this process—where the initiative was taken *first* by industry—in preselecting the agenda for debate cannot be overemphasized. The initiating proposal framed the problem as "Should the proposed LNG sites be approved?" and *not* "Should California have an LNG terminal in view of the alternatives, costs, risks, etc?" Setting the agenda in this manner did not preclude the "need" question from entering the debate, but it did ensure that the question was only considered in the context of a siting application.

Table 3 also specifies the relevant interested parties who were involved in the interaction phase of round A. Those parties which had formal decision power are marked with an asterisk. There were four primary attributes which were utilized in the ensuing debate among the parties. The need for LNG or the risk of an interruption in the supply of natural gas (X_1) supported the locating of a terminal in at least one of the three proposed sites. While environmental land use considerations (X_5) suggested a non-remote site (Los Angeles and Oxnard), the risks to the population (X_2) argued for siting the terminal in a remote area (Point Conception). Finally, concerns about earthquake risk brought about opposition to the Los Angeles site, which was found to be crossed by a significant fault.

Table 3. Elements of round A.

Problem formulation:	Should the proposed sites be approved? i.e., Does California need LNG, and, if so, which, if any, of the proposed sites is appropriate?				
Initiating event:	Applicant files for approval of three sites.				
Alternatives:	Point Conception:	A^1			
	Oxnard:	A^2			
	Los Angeles:	A^3			
	Any combination of:	A^1, A^2, A^3			
Interaction:	Involved parties		Attributes used as arguments		
	Applicant	P_1	X_1		
	FERC*	P_2	X_1		X_3
	CCC*	P_3		X_2	
	City councils*	P_6		X_2	X_5
	Sierra Club	P_7		X_2	X_5
	Local citizens	P_8		X_2	X_5
Key decisions:	(1) CCC concerns over population risk implies that A^1 is preferred over the other two sites. (2) FERC would not approve A^2 because the seismic risk is greater than a prescribed acceptable level.				
Conclusion:	Applicant perceives a stalemate, i.e., that no site is approvable without long delay.				

*Interested party with responsibility for decision(s).

The interaction phase of round A (see Table 2) indicates the attributes used as arguments by each of the major involved parties. It is important to distinguish this listing of attributes from that in Table 1. While Table 1 specifies which attributes are of *primary concern* to each party, Table 3 specifies which attributes were *used as arguments* by each party. Thus while the applicant is concerned with both profit considerations and supply interruption risk, its arguments in support of each site stressed supply interruption risk.

Two key decisions were made during round A. First, the CCC, concerned about the catastrophic potential of LNG, implied that they were likely to favor Point Conception over the non-remote sites due to concerns over population risk. Specifically, the CCC advised Western to pursue at least one site in a remote area since they would deny approval to any non-remote site which was not considered safe. Second, the FERC indicated disapproval of the Port of Los Angeles as an acceptable site because a recently discovered earthquake fault increased the seismic risk above a prescribed acceptable level.

The round was concluded with a possible stalemate, at least as perceived by industry (Ahern 1980). Los Angeles would not receive federal (FERC) approval, Oxnard might not receive state (CCC) approval, and Point Conception would face difficult approval challenges at the county and state (CCC) levels because of its adverse land-use impacts.

The stalemate of round A formulated the problem for round B. It was clear to all the parties involved that it was difficult, if not impossible, for the applicant to gain approval for a site under the existing siting procedure in California. In particular, there were possibilities of vetoing proposals at either the federal, state, or local level, as evidenced by the respective reactions to the three proposed sites. Rather than trying to operate within the existing constraints of the process, the interested parties in the process frequently tried to change the rules of the game (Majone 1979).

Table 4. Elements of round B.

Problem formulation:	How should need for LNG be determined? If need is established how should an LNG facility be sited?				
Initiating event:	Applicant and others put pressure on state legislature to facilitate LNG siting.				
Alternatives:	Consider offshore sites: B^1 Consider remote onshore sites: B^2 Consider non-remote onshore sites: B^3 One-stop licensing B^4 Licensing agency: CPUC = B^5, CCC = B^6, CEC = B^7* Any consistent combination of B^1 through B^7.				
Interaction:	Involved parties		Attributes used for arguments		
	Applicant	P_1	X_1		
	CCC	P_3		X_2	X_3
	CPUC	P_4	X_1		
	State legislature**	P_5	X_1	X_2	
Key decisions:	(1) Initial legislation introduced which included B^1, B^2, and B^5. (2) Final legislation passed which incorporated B^1, B^4, and B^5.				
Conclusion:	Passage of LNG Siting Act of 1977 (S.B.1081) which defined a custom-tailored siting procedure for LNG. Some features: — CCC nominates and ranks sites in addition to the one applied for — CPUC selects a site from the CCC-ranked set, not necessarily the top-ranked site.				

*CEC = California Energy Commission

**Interested party with responsibility for decision(s).

This behavior relates to the process described by Braybrooke (1978), where he points out that the issues are frequently transformed over time. Round B is a good illustration of this process. The problem was redefined into two new questions: How should need for LNG be determined? If need is established, how should an LNG facility be sited? The round was thus initiated when pressure to change the siting procedure was brought to the state legislature by the utility companies, the business community and the labor unions in California. Table 4 depicts the relevant alternatives which formed the basis for the debate on the elements of proposed legislation.

The industry and business interests saw the inevitable problem of obtaining local approval for a project in the national interest, but with costs to the local community. So the utility companies battled for a bill (S.B.1081) which would vest the CPUC with one-stop licensing authority, precluding any interference from local communities. The environmental and local interests, on the other hand, objected to a one-stop licensing process and favored a bill which required remote siting.

The resulting legislation was a compromise between the environmentalists, who supported consideration of offshore sites, and those who saw an urgent need for an LNG facility to assure energy and jobs. The CPUC was chosen over the more conservation minded CCC or the California Energy Commission as the agency with state permit authority, pre-empting local governments. As a bow to the conservationists, the CCC was given the mandate to choose and to rank possible sites, and to pass these rankings on to the CPUC. It was agreed that the site would not be offshore, as some environmentalists wished, nor could it be in a populated area, as the gas utilities wished. Indeed, an unpopulated area was strictly defined. There could be no more than an average of 10 people per square mile within one mile of the terminal, and no more than 60 people per square mile within four miles of the terminal.

The passage of the Siting Act of 1977 (S.B.1081) opened up a new procedure for finding an acceptable site and led to round C with the following problem formulation: Which site should be approved? The round was initiated by the CCC which, after considering 82 sites meeting the remote siting constraint, ranked the top four sites, Camp Pendleton, Rattlesnake Canyon, Point Conception, and Deer Canyon, in that order, on the basis of seismic, soil, wind and wave conditions, rough cost, and coastal resource considerations.*

These four alternatives form the background for the interaction among the interested parties in round C, as shown in Table 5. The CCC passed these rankings on to the CPUC which chose, by process of elimination, Point Conception, on the grounds that the two higher-ranked sites would involve unacceptable delay and would cause unacceptable risk to transients (i.e., campers, swimmers, etc.) at the nearby beaches and public parks. The CPUC, however, could only conditionally approve Point Conception subject to the utility company's ability to show that earthquake faults discovered in the area presented an acceptable risk to the terminal.

At the federal level, the FERC staff determined that the risks of both Oxnard and Point Conception were acceptably low, so that Oxnard should be preferred on land-use grounds; however, the FERC, choosing to avoid a federal-state confrontation, ruled in favor of Point Conception. After an appeal by the environmental and local interests, the Washington, DC Court of Appeals remanded the case back to the FERC on the ground that not all available seismic risk data were considered by the FERC in its ruling. This decision concluded round C.

Round D is still in progress at this time. As shown in Table 6, the initiating proposal is determined by the activities in round C which frame the alternatives as simply whether or not to declare the Point Conception site seismically safe. Only two parties, the FERC and the CPUC are currently active in the process, and they are considering only one attribute—the seismic risk at Point Conception. A final decision will depend upon whether the new studies show this risk to be above or below some acceptable level.

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*Point Conception was included in the candidate set because S.B.1081 required that the applied-for site be included.

Table 5. Elements of round C.

Problem formulation:	Which site should be approved?
Initiating event:	Applicant files for approval of Point Conception (the only site of the original three meeting the remote siting constraint of S.B.1081).
Alternatives:	(Sites nominated by CCC plus applied-for site) Camp Pendleton: C^1 Rattlesnake Canyon: C^2 Point Conception: C^3 Deer Canyon: C^4

Interaction:

Involved parties		Attributes used for arguments			
Applicant	P_1	X_1			
FERC*	P_2	X_1			X_5
CCC	P_3			X_3	
CPUC*	P_4	X_1	X_2		
Sierra Club	P_7			X_3	X_5
Local citizens	P_8				X_5

Key decisions:	(5) The CCC has the following preference: $C^1 > C^2 > C^3 > C^4$ (6) The CPUC approval conditional on whether or not the seismic risk is acceptable. (7) The FERC consider C^3 acceptable. (8) Court requires FERC to consider additional data to determine whether or not seismic risk at C^3 is acceptable.
Conclusion:	FERC and CPUC to consider additional seismic data.

*Interested party with responsibility for decision(s).

Table 6. Elements of round D.

Problem formulation:	Is Point Conception seismically safe?
Initiating event:	FERC and CPUC set up procedures to consider additional seismic risk data
Alternatives:	Declare Point Conception safe: D^1 Declare Point Conception not safe: D^2

Interaction:

Currently active parties		Attribute considered
FERC	P_2	X_3
CPUC*	P_4	X_3

Key decisions:	None yet. Future hearings are to determine whether or not seismic risk is acceptable for Point Conception.

*Interested party with responsibility for decision(s).

4. INTERPRETATION OF THE MAMP MODEL: THE ROLE OF RISK ANALYSIS

A great deal of attention has been paid recently to the topic of technological risk assessment for problems such as the siting of facilities (see Conrad 1980, Schwing and Albers 1980). It is of interest to examine, in the context of the MAMP framework, the role that risk assessments have played in the California LNG case.

The sequential nature of the decision procedures, as clearly demonstrated by the increasing concreteness of the problem formulations through the four rounds of discussions in California, limits the possibilities for comprehensive analyses. The risk studies were carried out, not as an input to a broad energy analysis in California, but to support a more narrowly defined problem (Should site x or site y be approved?). Since round A in California was *not* defined in these narrow terms (the question of whether the terminal was needed was yet to be resolved), the analyses were ill-suited to address fully the issues on the table. In some sense, then, analyses designed to address the question of safety were prematurely introduced into a process that had not resolved higher-order questions of energy policy. Though they served to focus the debate on the safety question, they could not offer (nor were they intended to offer) a panacea for the resolution of the siting question.*

During the course of the LNG debate in California, six studies assessing the safety risks of the proposed terminals were conducted by the utility and local, state, and federal government agencies (for a critical review of these studies, see Mandl and Lathrop 1981). Several studies are of particular interest. The applicant commissioned a consulting firm, Science Applications Inc. (SAI), to do a study and the FERC produced its own risk assessment. Both reports showed very low numbers on various probabilistic measures of risk (expected fatalities per year and individual probability of fatality per year). These numbers were interpreted to mean that the risk was acceptable. A risk assessment produced by the consulting firm Socio-Economic Systems (SES) for the Oxnard municipal government suggested similarly low probabilistic measures of risk (though expected fatalities were 380 times higher than the applicant's assessment), but they interpreted the figures as unacceptably high.

One explanation for these different interpretations lies in the format for presenting the results. The SAI study described maximum credible accidents (MCAs) without accompanying probabilities. Opposition groups interpreted these results as evidence that the terminal was *not* acceptably safe. The municipal government originally in favor of the site, began to waver in its support, probably influenced by the apparent uncertainty of the risk and the strength of the opposition groups (Ahern 1980). In sum, the risk assessments did not provide a single, coherent assessment of acceptability of the risk of an LNG terminal; their results were subject to interpretation depending on party positions (Lathrop 1980). In fact, the risk assessments were used both to promote and to oppose terminal applications.

In reviewing the technical differences between the assessments leading to these conclusions, Lathrop and Linnerooth (1982) have shown that there are many degrees of freedom left to engineering and analytic judgment, including how to characterize risk, what formats to use for presentation, what gaps to fill with assumptions, which of several conflicting models to use, how to portray the degree of confidence in the results, and what contingencies to leave out of the analysis.

This analytic freedom helps explain the differences between the above three Oxnard risk assessments. It can push the risk measurement in any direction. Very conservative assumptions can drive it up; omissions of inconvenient aspects such as terrorism can drive it down. Clear presentations of expert disagreements can decrease the confidence in the results; and so on. The final result may have as much to do with the predilections of the analyst as with the physical characteristics of the site or technology.

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*It is not surprising, then, that round A ended in a stalemate. The second round, where the state legislature took center stage, narrowed the problem (by resolving the question whether California needed a site) to one more receptive to technical risk studies.

This finding takes on special significance when viewed in the context of the policy process. The MAMP model has illustrated that the risk assessments, though intended to advise a client on the safety of the proposed terminal, were typically used to support a party argument. For this reason, clear incentives exist for the analysts to present their results as persuasively as possible, which explains the tendency on their part to omit discussions on the uncertainty of their results and to choose presentation formats that present their case as strongly as possible.

5. SUGGESTIONS FOR FUTURE RESEARCH

In this paper, I have attempted to give a flavor of the work of the Risk Group by describing the decision process in the USA in the context of the MAMP framework. The MAMP framework should be viewed as a starting point for undertaking research which can improve the political process with respect to problems such as the siting of facilities. We have seen that formal risk analyses, especially risk assessments, are subjective exercises undertaken to support a specific party's arguments. Furthermore, the importance of these analyses will depend on the nature of the sequential decision process, the relevant interested parties which interact, and the type of conflicts emerging.

Given these descriptive observations, several research areas appear to be promising avenues for the future. In a recent paper Nelkin and Polak (1979) indicate the inadequacy of existing institutions to deal with problems of conflicting evidence and polarized expert opinion with respect to questions such as risk assessments. As a way of dealing with this problem, they advocate the need to establish rules of evidence as a basis for making better decisions. Lathrop and Linnerooth (1982) provide a suggested set of guidelines with respect to establishing rules of evidence. In particular, they stress the importance of defining the risk being assessed, being clear on assumptions and error bounds as well as indicating the conditional nature of specific analyses which are undertaken.

There is a need for more field research which attempts to apply these criteria or others to a specific set of problems. One of the difficulties which currently exists is the lack of an institutional mechanism for evaluating the different risk assessments produced by different parties. Ackerman *et al.* (1974) point out that the traditional approaches such as legal responses, agency hearings and judicial reviews have inherent limitations with respect to evaluating these conflicting assessments. The problem is especially difficult for the siting of new technologies where there are no objective measures of risk. Private consulting firms frequently undertake these analyses but have a built-in bias in telling the contracting party what they want to hear.

With respect to the more direct consequences of siting a new facility O'Hare (1977) has proposed a compensation system to deal with opposition to proposed sites from certain interested parties. For example, suppose residents of a community are concerned with suffering losses in property values as well as safety and environmental risks if the project is sited near them. O'Hare proposes that each community determines a minimum level of per capita compensation for it to be willing to make a legal commitment to having the project in its backyard if the compensation is paid.

From the above suggested topics it should be clear that there is considerable research on risk which needs to be undertaken of a prescriptive nature. The purpose of our cross-country comparisons of LEG siting decisions is to provide data on how the political process appears to work in practice and the differences across countries. The MAMP framework described in this paper has been found to be a useful framework for making comparisons among countries. The challenge for the future is to capitalize on our understanding of process to try and improve political decision making.

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Science and Policy: Their Separation and Integration in Risk Analysis

Howard Raiffa

Graduate School of Business Administration, Harvard University, Boston, USA, and Chairman, Committee on Risk and Decision Making (CORADM)

The Committee on Risk and Decision Making (CORADM) was commissioned by the Division of Technology Assessment and Risk Analysis (TARA) of the US National Science Foundation to give advice on their research program in risk analysis. CORADM is an *ad hoc* committee in the Assembly of Behavioral and Social Sciences (ABASS) of NAS/NRC, and our report will be submitted to ABASS and TARA at the end of 1980.

The Committee members felt that if we are to report on research priorities for TARA we should first step back and reflect on how our society generates and copes with risk. Thus we have decided to prepare an extensive prologue to the report on research suggestions for TARA, and I should now like to discuss the stage reached in our deliberations on that prologue.

CORADM is primarily concerned with the adverse effects of risks to health, safety, and the environment. The following list illustrates a set of problems, which is far from exhaustive, that motivates our concerns:

Three Mile Island
Chemical waste
Oral contraceptives
Occupational exposure to benzene, asbestos, vinyl chloride, cotton dust, coke-oven emissions
Alcohol consumption and cigarette smoking
Accidental or intentional nuclear war
CO_2 and atmospheric warming
Extinction of plant and animal species
Depletion of the ozone layer
Health effects of dietary factors
Acid rain
New passive restraint standard
Fluoridation
DC-10s
Air pollution (sulfates and small particulates)
Decline of new prescription drugs
Natural hazards (earthquakes, floods, etc.)
Low-level radiation
Nuclear high-level wastes

I will now outline what our committee *currently*—and I stress currently because we are still in a state of flux—is thinking about in terms of a prologue or a general report. After describing the structure and purpose of CORADM, the report will outline the macro-perspectives of risk by looking at the rising tide of public concern and document this by means of opinion polls, legislative and agency activity, public and private sector investments, media publicity, and increased litigation. Using time series of different indices such as infant mortality, premature death (i.e., death before 65), longevity, accidents, disabilities, sick days, birth

*This paper is an edited transcript of the talk given at the Sixth Symposium on Statistics and the Environment, October 1980.

defects, etc., the report will attempt to take stock of how our society is faring at the present time. These studies will be concerned not only with aggregate values, but also with the smaller-scale differences between various segments of our society. For example, there are still inequalities between blacks and whites, and between the US and other countries, and these represent potentials for improvement.

We will try to point out some of our greatest worries and potential problem spots, but, as is to be expected, committee members have some disagreements on this topic. Next we try to rationalize why public concern about risk has increased.

In the second main section of the report we discuss processes for managing and coping with risks. The word management often evokes different responses, so perhaps the term "risk management" should be defined more clearly. "Risk" is used differently in various disciplines such as in finance, economics, insurance, decision theory, engineering, etc. Risk management in its broadest sense involves the identification, estimation, assessment, monitoring, evaluation, and control of risk, including preventive, reactive *ad hoc*, and unorganized processes to deal with them. Institutions for this purpose include courts, legislatures, administrative agencies, business enterprises, labor unions, research institutions, citizen groups, and educational institutions, as well as individuals. Risk analysis itself can be subdivided into the assessment of uncertainties; and evaluation, i.e., policy analysis (other than assessment) for risk management.

Before discussing ways of coping with risks we look at ways in which they are generated in our society; i.e., self-imposed risks, co-generated risks, risks arising from productive activities or business and government, natural hazards, and risks that arise from the very institutional framework of our society. In this section we also discuss the slippery distinction between voluntary and involuntary risks.

Policy instruments for coping with risks can include, for example, information, incentives/disincentives, prohibitions, liability, transfer rights to generate risks, mediation and arbitration, insurance policies, regulation, etc. Most of these are self-explanatory, except perhaps for mediation and arbitration: for example, it is possible that in certain circumstances labor unions and businesses could jointly agree on means to control risks and then to obtain a formal stamp of approval on these contracts by government.

We next look at the various federal agencies that have to cope with risk and the different statutes that govern them. Statutes can be classified according to those that look at risks only (e.g., the Delaney Clause); those that try to reduce risks up to technological feasibility; and those that attempt to balance adverse consequences with benefits broadly interpreted. In practice, these statutes are not administered literally so that the distinctions are even more blurred than they first appear.

We look at what is happening in the courts, their levels of activity and different philosophical approaches, and how some commentators view their role in risk management. In addition to a discussion of public perceptions of risk and how they are formed, we want to discuss the problematic issues such as (i) what roles do (and should) perceptions play, and (ii) the thin line between education and indoctrination.

The most extensive part of our report concerns the roles of risk analysis, which may be summarized as follows:

- Should keep in mind complex, socio-economic-political interactive processes for coping with risk
- Most decisions based on common sense "ordinary" knowledge, with little formal analysis
- Analysis can help with incremental choices
- Analyses are often multi-purpose for multiple audiences
- Analysis cannot eliminate judgments about uncertainties and values
- Analysis can raise the level of discourse
- Analysis can generate creative alternatives
- Poor analysis may be worse than none
- Analysis should be iterative: it should improve over time

Analysis can be used and misused as a political weapon
Analysis can be used and misused in the adversarial process
Need for peer review
Need for more and better analysts

Analysis can be subdivided into two categories, which can be called "in the large", and "in the small". An example of the former could be the case of an in-depth analysis done for an administrator of an agency who must decide (no action is a decision!) on what to do about a potentially troublesome chemical. It does not have to be an administrator or a chemical; the idea is that there is a high-level, (relatively) unitary decision maker who has a reasonably well defined problem. Possible solution settings are:

(a) Generation of policy alternatives (a checklist of things to think about)
(b) Consequences (impacts, costs, benefits)
  Health effects: how many? how much? who are they? how voluntary? how identifiable? etc.
  Non-health effects: to nature; to economic and business activity; to sociopolitical activity; to international relations
  Feedbacks of non-health effects on health effects
(c) Uncertainty analysis: assessment of uncertainties; natural science, behavioral science
  Being precise about degree of imprecision
  Volatility
  Disagreements
(d) Analysis for the dynamic decision process

Factors involved in the generation of policy alternatives include

Analysis can help generate creative alternatives
Sequential choices with intervening information
DM can sometimes collect information (e.g., experimentation)
Interdependence of problems (precedents)
Irreversibilities (physical, political, managerial—strict and partial)
Decisions about locus of action to be taken (e.g., level of government, decentralization through the market, etc.)
Institutional decision network (who has to decide what and when? Who has to be convinced, pressured, influenced, etc.)

The consequences of risk analysis can be summarized as follows:

Health effects:

1. How many people are (will be) affected?
   (a) in the entire population
   (b) in sensitive groups
2. How much are they affected?
   (a) mortality
   (b) morbidity
   (c) severe pain and suffering
   (d) psychological discomfort
   (e) anxiety
3. Who are they?
   (a) age distribution
   (b) income distribution
   (c) race/ethnic group
   (d) sex
   (e) occupation
   (f) geographical location
   (g) quality of life/health status

4. When will they be affected?
   (a) now
   (b) with some time lag
   (c) future generations
5. How voluntary/involuntary is the risk?
6. How "catastrophic" is the risk? (clustering of fatalities over time and space)
7. How "identifiable" are the victims (*ex ante* and *ex post*) and how "accountable" will the decision maker be?

Non-health effects:

1. Aesthetics
2. Effects on nature
3. Economic costs (and to whom)
4. Effects on economic growth, productivity, and innovation
5. Effects on business competition
6. Effects on other countries
7. Effects on distribution of incomes
8. Effects on public satisfaction with government

Secondary, tertiary, and general equilibrium considerations; net health effects: feedback fron non-health effects on health (e.g., 3, 4, 5, 7).

Next we turn to uncertainty analysis, and this will be given more detailed attention below. There next follows a category of activities which can be listed under the heading "the dynamic decision process".

Analysis for choice Peer review of analysis Adversarial inputs Commitment to first steps Public announcements Adversarial documents	} Legal analysis

Influencing and persuading others
Educating others
Monitoring
Evaluating
Experimenting
Accumulating information
Guiding
Re-analyzing
Commitments to second steps
⋮

Another factor in the assessment of uncertainty, which we call "risk assessment" can be singled out for further discussion, as follows:

Why decompose?
Linkages between assessment and evaluation
Effective reporting of uncertainties (false precision or imprecision)
Special cases of assessments:
  rare catastrophic events
  carcinogenicity
  large systems (e.g., energy policy)
Need for judgmental synthesis in assessment of uncertainties:
  separation of facts and judgments about uncertainties
  separation of judgments about uncertainties and values
Criteria for effective reporting

Prudence in reporting *versus* prudence in action
Assessments by groups:
  spectrum of opinion
  why experts disagree; structuring
  vulnerability to external attack
Need for independent, credible assessment groups
Protection of scientific institutions; right to refuse to report
What to do if decomposition is uncomfortable

Figure 1 illustrates the decomposition of risk assessment and evaluation. Our report will treat at length the difficulties involved in this decomposition of tasks, and its advantages; if tasks are to be decomposed they still have to be linked and there is usually a lot of dysfunctional slippage in the linkages.

The uncertainties to be assessed can be roughly divided into two categories: those that fall within the natural science domain, and those in the behavioral or managerial science domain. Let us now turn to natural science uncertainties. Is a given chemical carcinogenic, for example? If so, what is its severity? What about exposures? What about health effects?

We next consider the effective reporting of uncertainties and the use of quantitative probabilistic reporting. We worry a lot about the false precision that comes with the use of numbers, and what to do about it, as well as the false sense of imprecision that comes with the use of qualitative reporting, such as with the use of such semi-quantitative terms as rarely, not unthinkable, beyond a shadow of doubt, not so often, sometimes, the preponderance of evidence shows, with some exceptions, etc. However, there are some advantages of probabilistic reports, as follows:

Less likely to be misinterpreted
Probabilities can be combined with other probabilities
Probabilities can be combined with losses and utilities—meshes with other factors
Probabilities can be compared (comparative risks)
Probability numbers are precise enough to be attacked

After discussing some special assessment problems we arrive at the conclusion that assessment is complex; only rarely do scientific facts speak for themselves. These disparate facts, theories, empirical findings, etc., have to be synthesized and made comprehensible for use in the policy making process (see Figure 2). This synthesis is required because:

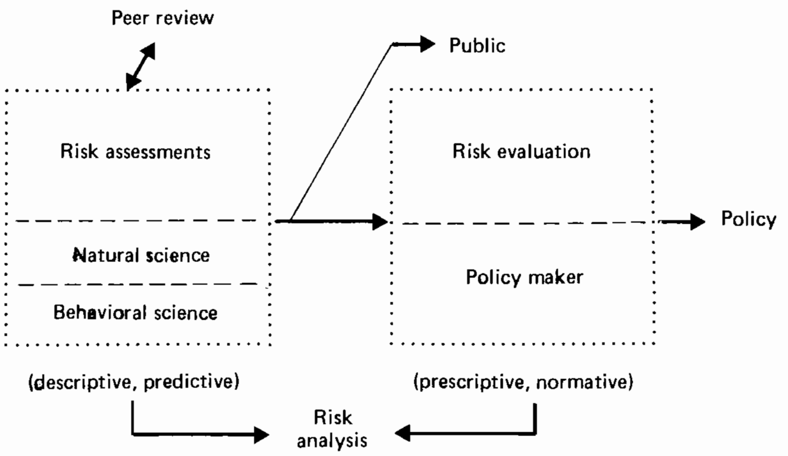

Figure 1. The decomposition of risk assessment and risk evaluation.

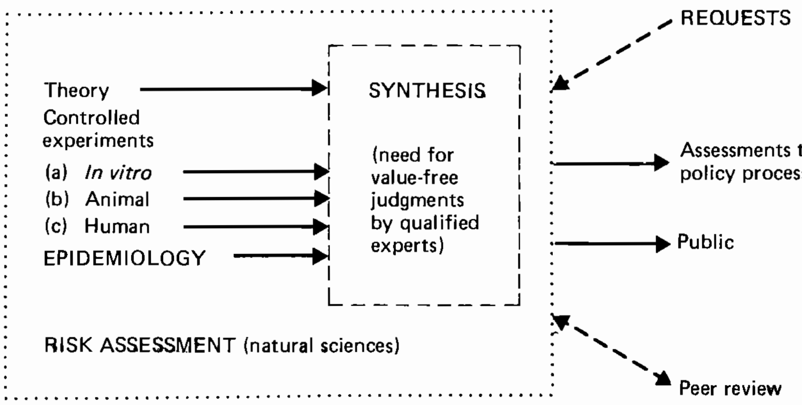

Figure 2. Synthesis of information for use in the policy making process.

Information comes from several sources, often conflicting, often messy;
Information is often very indirectly relevant;
Recitation of the set of indisputable facts may not be enough; may be useless to a nonexpert policy maker;
Judgments by experts may be indispensable for synthesis; but separation of fact and judgment, including value-free judgment, should be clearly demarcated.

The criteria for good reporting can be summarized as follows:

Inclusive—should synthesize relevant information (theory, experimental data, epidemiological data, etc.)
Free from the values of policy values—report should not prejudge policy conclusions; values appropriate to policy evaluation should not influence assessments of uncertainties
Comprehensive and meaningful to clients—informative and relevant
Useful in the decision process—use of proxy variables
Honesty and prudence

I would now like to dwell on the last criterion: honesty. This sounds nice, but there is a tension between honesty and prudence that should be clarified (see Figure 3), using an example from a business setting. A businessman wants to know how much of a given item he should stock. He does not know what the demand for that item will be, but he does know that if he stocks too little that will be profit foregone (a loss of underage); if he stocks too much he will have an excess and there will be profit foregone (a loss of overage). He asks his expert(s) to assess a probability distribution of demand, and then knowing this, and the comparative per unit losses of overage and underage, he can balance those expected losses and arrive at a decision. In the case where the underages are more serious than overages it is prudent to stock a quantity in the right tail of the assessed distribution. If the assessors of the uncertain demand purposely translate their assessed distribution to the right in the name of prudence, because they feel that it is more serious to underestimate than to overestimate, and if the businessman also compensates, then they may be overcompensating and the resulting action may be imprudent.

Probabilistic reports should not prejudice policy issues and purposely report with a prudent bias. Cascading prudent reports could result in imprudent actions, and there is a danger of double-counting competing risks. Such reporting should be honest, and not attempt to second-guess policy choices. Probabilistic reports about diverse consequences to health, for example, are very often slanted to be

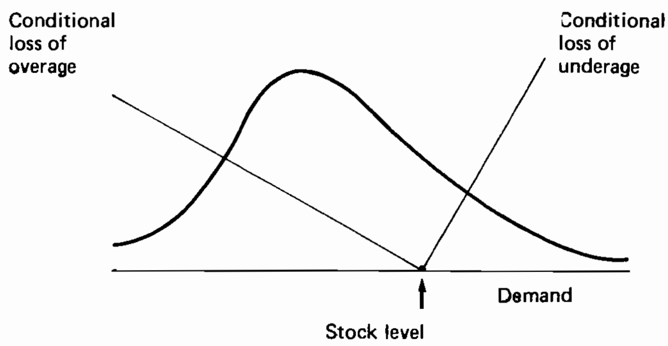

Figure 3. Prudence in reporting: an illustrative example. Optimal stock level is at a high fractile; the probabilistic assessment should not be distorted.

conservative. I believe that it is better to report honestly, and that prudence should, more appropriately, be accounted for in the evaluation process, rather than in the assessment process.

We will now look at assessments by groups. It is no secret that experts disagree; there are reputable scientists who hold fringe opinions at both ends of the spectrum—sometimes they are just plain wrong, and occasionally they are right. It is important that these fringe opinions are heard, but they should not be overweighted just because they are different. The media seek to inform and to interest their readers, so there is always a tendency for them to over-represent the tails of the distributions. Theory states that experts should agree, but they often do not, for the following reasons:

- Slippage in vocabulary
- Different experiences and difficulties with articulation
- Imprecise overlap of information
- Different paradigms
- Cognitive biases (anchoring, etc.)
- Elicitation biases
- Effect of role
- Personal interactions and reinforcements
- Conscious biases:
  - to help mankind — to compensate for adversarial purposes
  - to help oneself — money, not to curry disfavor of peers, colleagues, friends, children

When experts disagree it is important not to suppress their differences; and these differences, if they are to be understood and properly reflected in the policy process, should be structured. Do the experts agree on what they disagree about? Do they agree on what further analyses (modeling, data collection, etc.) would be desirable to bring their views into closer harmony? Attention should be given to meaningful ways to report disagreements; an eye should be kept on ways users of reports react, and should react, to such reports.

Many assessments (such as of adverse effects to health and the environment) are clear-cut and no elaborate quantitative analyses are required because the facts speak for themselves. When we concentrate discussions on those assessments that present difficulties, we should not lose sight of the fact that many are routine and that a little analysis without controversial judgments may go a long way. Some given chemical may be clearly carcinogenic, substitute chemicals may exist, and the given chemical may not yet be on the market. That's easy. Another easy case is where the chemical is given a clean bill of health.

While the bulk of cases studied may be routine, there are plenty of important ambiguous cases where the facts (about uncertainties) do not speak for themselves. Facts, theories, ambiguous experimental findings, uncontrolled epidemiological findings, etc., all must be synthesized by experts for policy analysis and decision by nonexperts. Experts, when they look at a given set of facts, might disagree and might organize their deliberations about such disagreements, but suppose that after considerable internal discussion a risk assessment group comes to a consensus on a synthesis of facts and judgments about uncertainties, and then reports this consensus to a risk evaluation group. This risk assessment will also be made public and reviewed by other experts, some of whom will not like the policy implications of the report. Those external reviewers may attack the conclusions and try to find vulnerable spots in the report; and what is more vulnerable than an only partially supported judgment? It may be the case that some members of the risk assessment group have consciously (and therefore inappropriately) biased their inputs, while others might have fallen prey to subtle subconscious biases. Such weaknesses should rightfully be adversely criticized.

External reviewers with strong *policy* viewpoints will often attack risk assessments when the implications are not congenial to their preferred policies. To be effective, those attacks should be concentrated on potential weaknesses of the synthesis process. Even if a member of the risk assessment group has meticulously tried to subdue his or her potential subconscious biases, this might not actually be perceived as being the case by an outsider; and even if it is perceived to be the case, the adversarial outsider might win debating points by casting suspicion on the integrity of the insider.

It is not easy for a risk assessment group, in a highly charged controversial domain, to fulfil its mission responsibly even if its assessments are to be privileged documents only for the eyes of the policy maker and his discreet staff. But when these assessments have to withstand the barbs of those with strong policy convictions the task becomes doubly difficult. It takes courage and an impeccably neutral committee member to say what he or she actually believes in a controversial case because that member henceforth will be branded as an exponent of a cause. There is a tendency for individuals, who jealously want to be perceived as neutral, to soften their true opinions and to bend over backwards to be fair to the other side. Thus another bias enters the scene.

There are lots of idealistic, dedicated scientists who are motivated to seek the "scientific truth", wherever that may lead them, and who are more than willing to engage in academic interchanges to seek out collective wisdom. They may realize that they are prey to subconscious behavioral biases and they might be consciously eager to monitor their actions to avoid egregious conflicts of interest. It is important to encourage scientific groups to foster a tradition of openness and honesty in reporting. Such groups would, if created, deserve acclaim, and financial support should be properly laundered in ways to bring a minimum of external pressure. I am not recommending anything as grandiose as the scientific court of respected elders, but hope that many panels and committees can be founded in universities, in consulting firms, in industry, in scientific academies, and in government agencies that take pride in their scientific integrity and work hard to fulfil their responsibilities. Something is wrong when the membership of prestigious committees, created to report on some natural science uncertainties and not on policy issues, must be structured to yield a balanced portfolio of policy viewpoints rather than a balanced portfolio of scientific and methodological skills.

The scientific community must understand the dilemma we are in. It is imperative both for the progress of science and for better decision making that scientific reports be openly available and subject to peer review. But this puts a burden on assessment groups that must mold together science and judgment. Science cannot simply stand aloof from all the policy needs of our society, but when it gets involved it should expect to be attacked and should carefully prepare its defenses. There is some safety when a multiplicity of scientific institutions engage in these controversial activities and more groups within existing institutions should be created and suitably financed to undertake such studies. Occasionally it may be desirable for some such group simply to say that it is not ready to give its opinions on some controversial topics.

Even the Supreme Court prefers not to consider some legal issues because they are currently too divisive, just as the members of a risk assessment group may do. The reluctance of the Supreme Court to delve into some issues is justified by its grander role in society. Why should it jeopardize its mission by getting trapped into a morass of emotional conflicts when society is not ready for reasoned arguments. A similar argument can be made on behalf of science. When the scientific facts do not speak for themselves, when judgments are suspect, or when advocates are ready to pounce on all sides of an issue, then occasionally scientists and methodological experts should say that they are simply not ready to make pronouncements in this field under the auspices of such and such an institution. Scientists are individuals, of course, have the right, and some would say the obligation, to speak out. However, here I am making a distinction between scientists as individuals, and scientists who speak on behalf of scientific institutions.

This leads to a final point: what should be done if the decomposition of risk assessment from risk evaluation cannot be comfortably achieved? Analysis has to be much less formal and presumably the principal decision maker will need to get integrative advice that mixes facts, judgments about uncertainties, and opinions about values.

We now come to risk analysis "in the small", which can be summarized as follows:

- Analysis does not have to be "grandiose"
- Analysis for individual (small) actors (within a complex system) can be simple
- Sometimes a little analysis can go a long way
- Analysis may be too difficult and not worth doing
- General-purpose analyses can help many users (one reason why assessments of uncertainties should be isolated)
- Analysts should understand the way society copes with risk and be prepared to help "in the small" as well as "in the large"
- Analysis may not only help to "solve" problems, but also to devise new ways of thinking about old problems, and to generate new ones

The important message here is that analysis, if it is tailor-made for specific individual purposes, need not be horrendously intricate. Often a little analysis can go a long way, because, for example, a given actor may be severely constrained in his choices; many attributes of concern that one can think of *a priori* may yield roughly equivalent outcomes; and only one or two uncertainties may be of prime importance.

Next we come to value controversies, and here, as elsewhere, our intention is to identify some key problems rather than to solve them. The following list is far from complete.

Value controversies

- Trade-offs of incommensurables:
  - Expenditures for life saving
  - Allocations with fixed budgets
  - Size of budget
  - Shadow prices of life saving by agencies
  - Should shadow prices be uniform?
  - American lives versus lives of others (foreign aid)
- Trade-offs within domain of health
  - Mortality/morbidity/psychological well being
  - Lives, ELYs, QUALYs, EDRAs
- Temporal trade-offs
  - Discounting (of lives?), intergenerational trade-offs; lives of "others" today versus lives of Americans in the far future
- Efficiency equity
  - Project-by-project equity, cyclical equity, income redistribution

Identifiability and accountability: probabilistic identifiability, *ex ante* and *ex post*
Protection of most sensitive groups with self-imposed sensitivities (e.g., air pollution and the heavy smoker, people living in the flood plains, etc.)
Clustering of deaths over space and time (e.g., 500 deaths at once, versus 600 isolated deaths)
Paternalism: arguments for and against
Libertarian views on imposed risks
"Man" versus "nature"
Rights of the fetus
⋮

We start off with the popular controversy: dollars or lives. It is interesting to estimate the marginal cost of life-saving activities in the various federal agencies. The values range from tens of thousands to tens of millions of dollars per life saved. Most commentators who are bothered by the idea of placing a dollar value on anyone's life will nevertheless feel it important to examine how a given budget would be efficiently spent on saving lives. I have parenthetically included in the above list a remark about saving foreign versus US lives because we have the policy option of doing something dramatic to save foreign lives (e.g., those starving in the Sahel).

But we also have problems of trade-offs within the domain of health; such as between mortality, morbidity, and states of psychological well being. Instead of counting only numbers of lives saved, we might want to look at expected life years (ELYs) or quality-adjusted life years (QUALYs) saved. Various mortality states might be commensurate in terms of equivalent days of restricted activity (EDRAs). How these trade-offs are, and should be, made involves controversial value judgments. The remaining value controversies can also not be ignored in important policy settings.

The final sections of part III of the CORADM report (Roles of analysis) have hardly been discussed by the committee. Section 6, entitled "Analysis in the adversarial process" includes one topic that has been repeatedly pointed out to us by environmentalists, namely, that resources for anlysis are unevenly distributed across adversarial groups. For instance, business is most highly endowed, and environmental and public interest groups have little resources. The situation may not be that unbalanced because a lot of academic researchers are antagonistic to business, and many are willing to work for a cause. Nevertheless, there is a perceived imbalance, and some environmentalists recommend that government agencies should support the analytical capabilities of groups that are challenging the "system".

For example, Wash 1400 (the Rasmussen Report) was a mammoth multi-million dollar study that was comforting to the nuclear industry. Scientific groups that did not like its findings attacked it and looked for flaws—and they found many. Should that study, to be credible, have been undertaken at the outset by two independent groups? Or should funds have been set aside for external peer reviews that would not have been designed to be adversarial? I have my own opinions on these questions, but our committee has not yet debated them. The trouble is that there is too much debate, and the more we probe, the more we find fine points on which to disagree.

The prologue of our report to TARA can be outlined as follows—as perceived today, but not necessarily as of tomorrow. All this comes before our research recommendations to TARA.

PROLOGUE TO THE REPORT TO TARA

Chapter 2

RISK ASSESSMENT IN A PROBLEM CONTEXT

Comparing Risk Assessments for Liquefied Energy Gas Terminals – Some Results

Christoph Mandl and John Lathrop

International Institute for Applied Systems Analysis, Laxenburg, Austria

1. INTRODUCTION

1.1. Purpose, Background and Scope

One of the most challenging problems in decisions concerning the deployment of novel, large-scale technologies is the assessment of the risk to the surrounding population. In particular cases, such as nuclear reactors or liquefied energy gas (LEG) facilities, the political process involved may tend to focus on one particular form of that risk, i.e., the risk to life from catastrophic accidents. This paper examines several different assessments of that type of risk with two main goals in mind:

(i) To present and compare the various procedures of risk assessment as applied to liquefied energy gas (LEG) terminal siting, and in doing so to clarify the limits of knowledge and understanding of LEG risks.

(ii) To quantify and compare the risks at four LEG terminal sites: Eemshaven (Netherlands), Mossmorran (UK), Point Conception (USA), and Wilhelmshaven (West Germany).

In the last decade a new technology for transporting and storing natural gas has become increasingly important for the overall energy supply of industrialized countries. The central idea of this new technology is to reduce the temperature of natural gas below -162°C, at which point natural gas becomes a liquid with one six-hundredth of the volume of the gas. The advantage of liquefied natural gas (LNG) is that it can be transported and stored efficiently in tanks due to its high energy per unit volume. Only in liquefied form can natural gas be transported via ships at reasonable cost.

However, due to the extremely low temperatures of LNG it is necessary to build special ships, special terminals to transfer LNG to and from the ships, and special tanks on land to store LNG. Cost considerations have made it necessary to plan and build LNG vessels and LNG terminals of considerable size; a typical vessel can contain 125 000m^3 LNG. At LNG terminals up to 60 000m^3 LNG is transferred per day and terminal storage tanks are planned to contain up to 500 000m^3 LNG. It is therefore not surprising that this high concentration of LNG at the site of a terminal has created concern that there might be potential negative effects, particularly to the environment and to the local population.

This paper in fact covers a broader category of terminals than those handling LNG. One of the terminals examined is to handle liquefied propane and butane. While LNG is stored at -163°C at very low pressure over ambient, liquefied propane and butane are stored at much higher temperatures and pressures, leading to significantly different behaviors during spills. However, all three substances involve essentially the same accident scenarios, though with different parameters and probabilities of detonation. Consequently, propane and butane have many of the same risk assessment features and problems as LNG. Since all of these substances, liquefied methane, propane, and butane, are called liquefied energy gases (LEG), the terminals examined in this study will be referred to as LEG terminals. Although there are many aspects involved in assessing the advantages and disadvantages of an LEG terminal at a specific site, the risk to the local population has turned out to be a crucial question. Because of the lack of historical data on accidents at LEG terminals, the frequency of such accidents as well as their consequences to people cannot be readily estimated. Therefore, over the past seven years attempts have been made to quantify the risk to the local population for different planned LEG terminals, using different techniques and models, with different results.

It is the purpose of this paper to review carefully the risk assessments undertaken for four LEG terminals in four countries, to discuss their plausibilities, explain their differences, compare their risk estimates and draw conclusions concerning their usefulness and limitations. Where necessary and appropriate we also expand some of the risk assessment reports. While this is not the first comparison of LEG risk assessments (see, e.g., HAZEL-REV; see references for explanation of acronyms), it is the first that we know of to compare assessments from different countries.

Because LEG terminal risk assessment is a new technique, there is still some disagreement among experts as to how to quantify risk, which models to use, what to include in a risk assessment, and what to exclude. Clearly, no pretense is made that this report provides complete or final answers concerning comparative risks or risk assessments. Rather, it describes some initial attempts to address important problems in the field of risk assessment.

1.2. Risk, Probabilities, and Consequences

Before it is possible to quantify risk, we must define it. It will become apparent in this section that different people mean different things when they talk about risk. Therefore our definition (actually a set of definitions) cannot be descriptive but rather will be prescriptive.

Ideally, if one adopts the axioms of rational choice under uncertainty, the evaluation of any decision alternative should consider the probability distribution over the consequences resulting from the alternative, which may be expressed in a space of several dimensions (see, e.g., LUCE-GEN). Yet the concept of risk singles out a subset of those dimensions for special analysis. The term is typically applied to particular uncertain costs, diverting attention from other costs and uncertain benefits that could be just as important for evaluation. In the case of LEG importation, for example, several dimensions are of concern for site selection and facility design. Of those, several involve uncertain costs, such as financial losses to the applicant if anything goes wrong (delay in application approval, loss of source contract, ship accident); environmental losses due to accidents or even routine disruption; fatalities and injuries due to accidents; property losses due to accidents; and losses to consumers from natural gas supply interruption if anything goes wrong (these could include unemployment and health effects in an extreme winter). While all of these uncertain costs could be and are referred to as risks, and all of them could be analyzed by techniques of risk assessment, in fact the term risk assessment in the context of LEG typically refers only to assessments of uncertain loss of life due to accidents. That is the scope for all risk assessments reviewed in this paper.

The best way to develop a definition of risk is to start by quoting some of the definitions from the risk assessment literature.

SAI-USA: "Risk is the expected number of fatalities per year resulting from the consequences of an accidental event".

CREM-UK: "Risk is the probability of an injurious or destructive event, generated by a hazard, over a specified period of time".

BATTE2-OTH: "Group risk is defined as 'the frequency at which certain numbers of acute fatalities are expected from a single accident'. The risk to society as a whole is defined as 'the expected total numbers of acute fatalities per year resulting from accidental events in the system'".

Surveying the set of risk assessments reviewed in this study, one can identify two extreme definitions of risk. One extreme, given by the risk definition of CREM-UK considers probabilities of destructive events only, and does not look at the consequences these events can have. Such an approach only makes sense for comparison or evaluation in the very limited case when all destructive events have equally valued consequences, and risk is defined as the probability that any one of the events will occur in a given time interval. It would be clearly meaningless to label two facilities equally risky if they had equal probabilities of an accident, but where an accident in one facility would have much more serious consequences than an accident in the other facility.

At the other extreme, risk can be, and sometimes is, viewed as the worst possible event (with the most serious consequences). Again we would argue that comparing this kind of risk is not meaningful because it omits the probability of an event and thus the relevance of such a worst possible event. We thus find that the definitions of risk described by Keeney *et al.* (KEEN-OTH) are the best prescriptive definitions:

(i) *risk of multiple fatalities:* probability of exceeding specific numbers of fatalities per year;
(ii) *societal risk:* total expected fatalities per year;
(iii) *group risk:* probability of an individual in a specific exposed group becoming a fatality per year;
(iv) *individual risk:* probability of an exposed individual becoming a fatality per year.

Each of these definitions addresses a different aspect of the political perspective of risk.

Risk of multiple fatalities is typically displayed as a complementary cumulative probability distribution: the probability per year that the number of fatalities will exceed x shown against x. Such a curve, sometimes called a Rasmussen curve, contains information not available in the individual probabilities: the effect of correlations between those probabilities. A Rasmussen curve addresses the sensitivity to catastrophe found in the political perspective of risk. Consider two facilities that cause equal numbers of expected fatalities per year: in one facility those are bunched into very rare catastrophes, and in the other they are spread over common small accidents. The former facility may encounter greater political opposition due to sensitivity to catastrophe.

Expected fatalities per year is appropriate for particular types of analysis, such as cost-benefit or risk-benefit analysis, where social preference is assumed to be linear in terms of number of lives lost.

The third definition (the probability of an individual in a specific group becoming a fatality per year) could be used to address the sensitivity toward equity found in a political perspective of risk. This measure enables one to determine in some sense how much of the risk is being borne by neighbors, campers, boaters, etc. This definition also allows separate determinations of occupational and non-occupational risks, two risks which are often treated quite differently in political and social processes.

Risk, according to the fourth definition (the probability of an exposed individual becoming a fatality per year), is simply an average over the group risks measured by the third definition. This measure is somewhat troublesome because it is dependent on the definition of exposed population. If "exposed" is defined as having an individual probability of fatality of greater than 10^{-12} per year, the individual risk will be averaged over a region extending not too far from the facility. If, on the other hand, "exposed" is defined with a cut-off probability of 10^{-30} per year, the individual risk will be averaged over a much larger region, and will be much lower. In spite of this shortcoming, individual risk is a measure that allows a convenient comparison of the measured risk and more routine risks the individual may face (e.g., the risk due to smoking, driving, etc.). While such comparisons do not fit into a decision or choice framework, they do provide readily understandable benchmarks for scaling the risk of a facility.

1.3. LEG Terminal Risk Assessment as a Decision Aid

Given the orientation of this paper, it is easy to forget that a risk assessment is not an end unto itself, but is in fact only one element of the complex process of LEG facility siting and design. More importantly, a risk assessment is supposed to be a decision aid for one or more of the decisions that must be made within that process. An understanding of where a risk assessment fits within an LEG siting and design process is essential to the understanding of the adequacy and worth of a risk assessment as a decision aid. One aspect of that process is of particular importance here: risk to life is only one dimension of concern for the decisions involved. Other dimensions include cost, land use, environmental quality, air quality benefits of natural gas, and dependence on foreign sources. There are also other important dimensions involving risk: supply interruption risk due to shortage, embargo, accident, earthquake, or bad weather preventing berthing.

Given the many decisions involving risk dimensions that must be made, it would seem that there are several roles for risk assessment in LEG facility siting and design. Yet the processes studied in our research have narrowed that role down to a single application: in one dimension, risk to life and limb; at one level, siting or design (depending on the country). There are several effects of this narrowing. To begin with, it diverts analytical effort and political attention away from those questions not addressed by risk assessment. For example, supply interruption risk could be a significant factor.

A second effect of the narrow role given to risk assessment is that the level at which it is applied affects how it is conducted. When risk assessment is part of the site selection process, a particular facility design is assumed, and analytical effort concentrates on such things as shipping traffic and local population density as site-specific inputs in a calculation of population risk. When risk assessment is part of the facility design process the site is assumed to be fixed, and the analysis considers the sizes, arrangements and specifications of components of the facility. In that case technical variations on the design are considered in terms of incremental reductions of risk.

There is a third effect of the narrow role assigned to risk assessment. Once a site is selected, given the political realities of the situation, the question of the overall acceptability of the risk is more or less settled. If a risk assessment is applied at the design level, it may consider various modifications to reduce the risk in the most cost-effective way. However, given its scope and charter, the assessment is highly unlikely to find that the site cannot be made acceptably safe with current technology and so should be abandoned. On the other hand, if a risk assessment is applied at the site selection level, it would at least be feasible to rule that none of the sites in the current choice set is acceptable.

Risk assessment does not exist in a vacuum. It is a decision aid in a much larger process. Any understanding of current assessment, and any suggestion for improvement, requires an understanding of that larger process. As this section has pointed out, that larger process controls the role and nature of risk assessment in very basic and important ways, even though the assessments may be carried out as strictly independent studies.

2. REVIEW OF RISK ASSESSMENT REPORTS

Table 1 gives a comprehensive overview of the most important risk assessment reports available to us, including not only those prepared for the four sites—Eemshaven, Mossmorran, Point Conception, and Wilhemshaven—but also a few others of particular interest. Some comments on the row headings of this table might be helpful.

(a) *Parts of the system considered.* Not all reports consider all the main parts of an LEG terminal, namely the vessel, transfer, and storage tanks. In particular, for Wilhelmshaven there are two types of report, one dealing only with vessel operation and LEG transfer, and the other dealing only with the storage tanks.
(b) *Concept of risk.* As discussed in Section 1.2, there is no unique definition of risk. Each report should therefore be quite specific on what type of risk is analyzed.
(c) *Estimation of probabilities of events.* One crucial part of risk assessment is the estimation of probabilities, unless only the consequences are considered. It is therefore necessary to see how this problem is solved in different reports. Two techniques can assist in performing this task for fixed plants. The *event tree* is a technique for developing a logical sequence of events (failures) resulting in unwanted consequences (accidents), and can help to avoid overlooking possible accidents. Having identified the possible events (failures), the goal of *fault tree analysis* is to identify and determine the probability of a "top-level event" (typically a specific accident) that would be the result of a sequence of basic events (failures) of the system. However, these techniques are not appropriate for estimating probabilities of accidents such as ship collisions. Two methods for estimating those probabilities are discussed later.
(d) *Estimation of consequences of events.* It is necessary for the consequences to be stated in terms a decision maker is concerned with. For this reason, and because of the definitions of risk typically assumed, most reports estimate the consequences in terms of the number of fatalities a certain event could cause.
(e) *Estimation of risk.* Different estimations are given depending on the definition of risk employed. In some cases no estimation is given at all.
(f) *Final findings.* The ideal result of a risk assessment report should be the quantification of the risk in comparison with risks from other sources such that the decision-making process can determine whether the risk from an LEG terminal is high or low compared with other risks. The ideal comparison is between risks from alternatives actually faced in the decision-making process: site A against site B, site A against no site, risk mitigation I against risk mitigation II, etc. Such a risk comparison is the risk assessment result of most direct usefulness to the decision process. In any case, it should be kept in mind that decisions concerning the acceptability of the risk from an LEG terminal involve social value trade-offs and perhaps political considerations that go beyond the mission of the risk assessment and the legitimate authority of technical risk assessors. It follows that the final finding of a risk assessment should impart information to the decision maker for him to use as a basis for his decision without making that decision for him.
(g) *Uncertainties in final findings.* Due to the lack of experience with LEG accidents there remains a substantial amount of uncertainty about the accuracy of the estimations of probabilities and consequences of events. Different reports handle this problem differently: some ignore uncertainties completely, some give conservative estimations, some perform sensitivity analysis, and some give error bounds on the quantified risk.
(h) *Single event with highest risk.* If mitigating measures to reduce the risk are undertaken it is interesting to know which event bears the highest risk, as it is often the case that the highest-risk event offers the most cost-effective opportunities for mitigation.

When evaluating the reports one should keep in mind that the differences between the reports that become obvious from Table 1 can at least partially be explained by the fact that they were prepared and used for different decision processes and therefore each report was developed in a way suited to the particular decision process it was to serve.

Table 1. Comparison of reports on issues.

Issues		TNO1-NL	ACTION-UK	CREM-UK	ADL-USA	FERC-USA	SAI-USA
a	Parts of system considered	Vessel, transfer, storage tank	Vessel	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel	Vessel, transfer, storage tank
b	Concept of risk	Risk of multiple fatal-ities and group risk	Group and individual risk	Probability of an injurious or destructive event	Multiple fatalities risk	Societal, group, and individual risk	Risk of multiple fatal-ities, group & individual risk
c	Estimation of:						
c1	probabilities of events	Yes, quantitative	Yes, quantitative	Only in terms of low, very low, etc.	Yes, quantitative	Yes, quantitative	Yes, quantitative
c2	event tree analysis used	Yes	No	No	Yes	Yes	Yes
c3	fault tree analysis used	No	No	No	Yes	No	Yes
d	Estimation of consequences of events	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, but only physi-cal cons. (eg, spill size); no estimation of fatalities	Yes, quanti-tative in terms of fatalities	Yes, quanti-tative in terms of fatalities	Yes, quanti-tative in terms of fatalities
e	Estimation of risk	Societal & indi-vidual risk low cf. other man-made risks	Individual risk high cf. other man-made risks	No estimation of expressed fatalities; only of probabilities of events	Yes, quantitative	Yes, quantitative	Yes, quantitative
f	Final finding	Societal and individual risk low cf. other man-made risks	Individual risk high cf. other man-made risks	No reason to doubt that installations cannot be built and operated in such a manner as to be ac-ceptable in terms of community safety	Pt.Conception suitable with respect to vessel traffic safety. Risk is very low.	Risk compar-able to risks from natural events & thus on an accept-able level	"The risk is extremely low"
g	Uncertainties in final findings	Not mentioned	Not mentioned	Not mentioned	Sensitivity analysis	Disagreement among experts is mentioned	Sensitivity analysis
h	Single event with highest risk	Grounding of LNG tanks	Not identified	Not identified	Not identified	Not identified	Not identified

Table 1. Continued.

Issues	BROTZ-D	KRAPP1,2,3-D	WSD-D	BATTE-OTH	HSC-OTH	KEEN-OTH	SES-OTH
a	Vessel, transfer	Vessel	Vessel	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel, transfer, storage tank	Vessel, transfer, storage tank
b	Not defined	Not defined	Not defined	Multiple fatality, societal, and group risk	Multiple fatality and group risk	Multiple fatality, societal group and individual risk	Multiple fatality risk
c1	Only in terms of very low	Yes, quantitative	Only in terms of very low	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative
c2	No	No	No	Yes	Yes	Yes	No
c3	No	No	No	No	No	No	No
d	Yes, but only physical cons. (eg, spill size); no estimation of fatalities	No estimation given	Some quantitative statements in terms of few and many fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities	Yes, quantitative in terms of fatalities
e	No estimation given	No estimation given	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative	Yes, quantitative
f	With regard to consequences & their probability there is no danger, cf. relevant laws	No final findings	Risk is not insignificant	Risk about the same as that from the gas distribution network	Risk only acceptable if suggested mitigating measures are undertaken	Risk less than those that the population near terminal is exposed to presently	Level of safety cannot be specified accurately
g	Not mentioned	Not mentioned	Mentioned	Considered, & error bounds given	Not mentioned	Sensitivity analysis conducted to examine effects of variations of 2 parameters	Considered, & error bounds given
h	Not identified	Not identified	Not identified	Rupture of transfer pipeline with delayed ignition	Not identified	Not identified	Not identified

3. ASSESSMENT AND COMPARISON OF LEG TERMINAL RISK

In this section the probabilities and consequences of different events (failures) will be discussed. The procedure follows the line of the reports SAI-USA and BATTE2-OTH. After giving a technical description of the four LNG terminals the rest of this section is divided into three distinct parts. First, estimations of the probabilities of failures are considered, then the estimation of the size of a vapor cloud and its ignition probability as a result of the failures, and finally the consequences to the local population. The primary purpose of this section is to present the results from risk assessment reports in a comparable manner and to discuss important differences in estimates of probabilities and consequences between the reports in terms of the underlying assumptions of the models used and their plausibility.

However, as we have already shown in Section 2.1, not all reports are easily comparable. Some do not consider all the events discussed, while others do not quantify either the probabilities or the consequences of events. Therefore, this section cannot and will not be a complete comparison for all events.

In Table 2 we give a brief description of the planned terminals at Eemshaven, Mossmorran, Point Conception, and Wilhelmshaven. As can be seen, Mossmorran is a different type of terminal from the others. Not only is it an export terminal, but the exported gases are mainly propane and butane, while LNG consists mostly (approximately 90 percent) of methane. As far as one can tell from the available risk assessment reports, the technical layouts of the different terminals are much the same. Not only are the LEG vessels similar (except in size) or even the same, but also the storage tanks and the transfer systems are very much alike.

3.1. Events: Their Probabilities and Resulting Spill Sizes

One of the most difficult questions in risk assessment is the identification of possible events or failures and the estimation of their frequencies or probabilities. By definition it is almost impossible to obtain enough historical data to estimate the probabilities of a low-probability event. Rather, one has to build models and rely on data from other presumably similar systems. Another important part of the problem is the identification of events that have never occurred before that would have serious consequences. This problem was acknowledged in the Lewis Report (LEWIS-REV), where it was stated that:

> "It is conceptually impossible to be complete in a mathematical sense in the construction of event-trees and fault-trees; what matters is the approach to completeness and the ability to demonstrate with reasonable assurance that only small contributions are omitted. This inherent limitation means that any calculation using this methodology is always subject to revision and to doubt as to its completeness."

We therefore do not and cannot claim that the events considered here are a complete set of possible events. However, it can be said that this set of events includes all events that were thought of in the risk assessment literature, e.g., TN01-NL, SAI-USA, ADL2-USA, BATTE2-OTH. The two major failures of concern are vessel accidents and storage tank ruptures, both of which are discussed below.

Philipson (PHIL-GEN) describes two methods typically used to establish estimates of the probabilities of vessel accidents:

(i) *Statistical inference*. Estimates are computed using historical data, first for a larger class of ships, such as oil tankers, and then modifying the estimates to account for the anticipated differences in LEG ships and their operations at the specific harbor. This is done, for example, by employing judgment and by assessing the proportion of past accidents that would not have occurred if various capabilities of the system had been in place.

Table 2. Description of terminals and sites.

	Eemshaven	Mossmorran	Point Conception	Wilhelmshaven
Type of terminal	Import	Export	Import	Import
Type of transferred material	LNG	Propane/butane (liquefied) and gasoline	LNG	LNG consisting of 90% methane, 5% ethane, propane/butane
Average transfer per day (in m^3 liquefied or MW)	18 500 m^3 ≃4 900 MW	13 400 m^3	Initial: 58 500 m^3 ≃15 500 MW current plan: 41 000 m^3 ≃10 900 NW	56 500 m^3 15 000 MW
Maximum capacity of ships	125 000 m^3	60 000 m^3 propane/butane 10 000 m^3 gasoline	130 000 m^3	125 000 m^3
Number of ships per year	54	80 for propane/butane 9 for gasoline	190	170 ships of 125 000 m^3 264 ships of 10 000 m^3
Number and capacity of storage tanks	2x120 000 m^3	4x60 000 m^3 propane/butane 2x31 000 m^3 gasoline	2 later 3 with 77 500 m^3 each	6x80 000 m^3
Number of people living within 2 km of terminal	60 (12 people/km^2)	approx. 350 (50 people/km^2)	projection for 1990: 14 (2.2 people/km^2)	0 but recreation area within distance
Number of people living within 5 km of terminal	858 (28.9 people/km^2)	approx. 8000 (200 people/km^2)	projection for 1990: 98 (2.5 people/km^2)	5900 (151 people/km^2)
Number of people living within 10 km of terminal	9800 (85 people/km^2)	approx. 100 000 (470 people/km^2)	data from year 1977: 129 (0.9 people/km^2)	43 000 (275 people/km^2)

(ii) *Kinematic modeling.* In SAI-USA ship collisions are analyzed by assuming ship motions to be random in a zone of interest corresponding to the short interval of time preceding an accident. A kinematic model provides the expected number of collisions per year under this assumption for a harbor with specific characteristics of configuration and traffic. A calibration to the actual average conditions of seven harbors is then made by scaling the model to fit actual past collision frequencies in these harbors.

The estimation of the probabilities of various spill sizes due to the six different types of events considered in the reports are given in Table 3. It should be mentioned that the estimates given in Table 3 are not always taken directly from the reports. In some cases the estimates were adjusted to take additional data into account. SAI-USA used more ships with larger tanks than currently planned, so the probabilities and spill sizes were reduced accordingly. FERC-USA only considered spill sizes of 25 000 m^3 in their report, although they stated the data for smaller sizes as well. These data were considered in generating Table 3. KRAPP1,2,3-D produced a variety of different results using different accident reduction factors, ranging from 1.0 to 0.05. Because the latter factor was not based on any stated reasoning, we used the factor 1.0, which was used in KRAPP1-D.

The most interesting findings from this comparison of assessments were:

(a) compared with the probability of collision, grounding and ramming, the other events are rather unlikely (except for the internal failure in ACTION-UK);
(b) the differences in probabilities of spills between the three reports for Point Conception are substantial (between 10^{-3} and 10^{-6} for 10 000-25 000 m^3 spills);
(c) although the traffic patterns at Eemshaven, Mossmorran, and Wilhelmshaven are quite different, they all come up with a total spill probability of the order of 10^{-3}, but spill sizes differ and are not defined for Wilhelmshaven.

The event that could create the largest spill is the rupture of a storage tank. In the literature, it is assumed that one of the following events can cause a rupture: severe winds, airplane and missile crash, meteorites, earthquakes, internal system failure, and accidents at other chemical plants nearby.

The estimate of TNO1-NL is taken from historical data of a peak-shaving LNG plant. CREM-UK only qualify the probability as "remote", without reference to how this qualification was produced. ADL2-USA and SAI-USA derive their estimates from historical data on weather conditions, earthquake frequencies, and frequencies of airplane crashes. The probabilities for internal system failure—due to matallurgical failures—were derived through a technical analysis, considering the material and the variations of the temperature of the material causing fatigue or stress. BROTZ-D estimates the probability of an airplane hitting one of the six tanks from historical data from the FRG.

All storage tanks are placed within containment basins capable of holding all the contents (in liquefied form) of the tanks. All credible failure scenarios assume that these containment basins will not break and therefore all spills remain within these basins.

Only SAI-USA considers probability of rupture of more than one tank at a time, due to a common cause. The maximum credible spill is then considered as a rupture of all three storage tanks (each consisting of 77 500 m^3) at a time. SAI-USA adjust their probabilities to the fact that the tanks are empty approximately 40 percent of the time.

Major findings on storage tank rupture probabilities are:

(a) The probability of a storage tank rupture is estimated for all sites (except Mossmorran and possibly Wilhelmshaven, where not all reports are available for comment) of being of the order of 10^{-5} per year.

(b) As a conservative assumption the spill size is generally assumed to be at least the complete contents of one tank. However, CREM-UK only assume 15 percent of the contents of one storage tank to be spilled.
(c) There are no major differences in the estimates, except between ADL2-USA and SAI-USA. For example, the SAI probability of a spill due to objects crashing into the tank is 4×10^{-7}, while the ADL estimate is 10^{-5}. Elizabeth Drake (of ADL) has pointed out that this difference is due to changes in missile launch plans at the nearby Vandenburg Air Force base between the times the two reports were written (personal communication 1981).
(d) Common-cause failures causing more than one tank to rupture are only considered by SAI-USA.

3.2. Physical Consequences of LEG Spills

We have so far discussed the probabilities of different spill sizes resulting from failures of parts of the system. Before we can quantify the number of fatalities certain spill sizes could cause, we have to discusss what happens to the spilled LEG and how it can cause fatalities.

There seems to be agreement that only ignition and consequent rapid burning or detonation of the spilled LEG can have consequences to life and limb, because of thermal radiation and blast effects. LEG will immediately start to vaporize after a spill, resulting in a vapor cloud. This vapor cloud will then travel downwind and disperse. If there is no ignition, all parts of the cloud will eventually reach the lower flammability limit of concentration, below which it cannot be ignited. To estimate the effects it is therefore necessary to estimate the size of the vapor cloud, the downwind travel distance of the part of the cloud that retains a concentration above its lower flammability limit and the probability of ignition.

We will first discuss the size of the vapor cloud, which depends on the spill size, on meteorological conditions, and on whether the spill is on land or on water. We will then discuss estimates for the ignition probabilities at different sites and for different events.

3.2.1. Vaporization and Dispersion of LEG After a Spill

Among all topics of LEG risk assessment the question of how LEG behaves after a spill has attracted the most scientific interest. So far, empirical data include only information for spills up to 50 m^3 for an LNG spill on land, and up to 200 m^3 for an LNG spill in water. The prediction of the behavior of large spills has therefore had to rely on theoretical models, which are not easy to validate. Predictions differ for large spills but produce good estimates of the observed spills. The predicted downwind distances after a spill at sea, taken from the different reports, are listed in Table 4. It should be noted that these predictions are valid primarily over water, where the landscape does not influence vapor cloud dispersion in a specific way. One could expect that vapor cloud dispersion is faster over rough landscape, except in the case of propane and butane vapor, which could accumulate in low areas due to their high density.

The differences between the reports are substantial. While SAI-USA and BROTZ-D predict relatively short distances, ADL2-USA and FERC-USA are comparable in their prediction of large distances. It is also worth noting that the distance increases with decreasing wind speed in FERC-USA while for SAI-USA the distance decreases with decreasing wind speed.

Although possibly larger in size, spills on land are generally considered less dangerous than spills on water. The first reason for this assumption is that spills on land are confined because the storage tanks are surrounded by dikes, which are generally considered not to rupture. The second reason is that the vaporization rate of LEG on land is slower than on water.

Table 3. Estimation of LEG vessel failures.

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA	BROTZ-D	KRAPP1,2,3-D
(1) Probability of collision that can lead to a spill per ship approaching the LEG terminal	$2.8x10^{-5}$			$5x10^{-4}$	$1.3x10^{-8}$	—	$4x10^{-5}$
(2) Probability of grounding that can lead to a spill per ship approaching the LEG terminal	$2.5x10^{-4}$	$1.5x10^{-5}$ includes (2) and (3)		$4x10^{-4}$	0	—	$7x10^{-5}$
(3) Probability of ramming that can lead to a spill per ship approaching the LEG terminal	—			$3x10^{-4}$	0	—	$3x10^{-7}$
(4) Probability of missile or airplane crash causing one spill per year	—	—	See (14)	—	$4x10^{-7}$	$8.3x10^{-5}$	—
(5) Probability per year of a meteorite falling on a specific area of 1 m^2	—	—		—	$3.3x10^{-13}$	—	—
(6) Probability of internal system failure	—	$3.2x10^{-3}$		—	$1.0x10^{-11}$	—	—
(7) Number of ships per year	54	80	190	190	190	432	432
(8) Deck-size of ship in m^2 (maximum)	12 000	6600	12 000	12 000	12 000	12 000	12 000
(9) Length of stay of loaded ship in the vicinity of the terminal (years)	—	—	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-3}$
(10) Size of one tank (maximum) in m^3	25 000	12 000	25 000	25 000	25 000	25 000	25 000

Table 3. Continued.

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA	BROTZ-D	KRAPP1,2,3-D
(11) Probability of different spill sizes given (1)							
0< ≤ 1 000 m^3	0	0		0.02	0		
1 000< ≤10 000 m^3	0	0		0.026	0		0.05
10 000< ≤25 000 m^3	0.56	0.25	See (14)	$2.3x10^{-2}$	0.22	—	spill size
25 000< ≤50 000 m^3	0.44	0		0	0.025		not defined
50 000< ≤75 000 m^3	0	0		0	0		
(12) Probability of different spill sizes given (2)							
0< ≤ 1 000 m^3	0	—		0.0024	—		
1 000< ≤10 000 m^3	0.33	—		0.0057	—		0.009
10 000< ≤25 000 m^3	0	—		$3.9x10^{-3}$	—	—	spill size
25 000< ≤50 000 m^3	0	—		0	—		not defined
50 000< ≤75 000 m^3	0	—		0	—		
(13) Probability of different spill sizes given (3)							
0< ≤ 1 000 m^3	—	—		0.0034	—		
1 000< ≤10 000 m^3	—	—		0.0065	—		0.1
10 000< ≤25 000 m^3	—	—	See (14)	0	—	—	spill size
25 000< ≤50 000 m^3	—	—		0	—		not defined
50 000< ≤75 000 m^3	—	—		0	—		
(14) Total probability of different spill sizes per year*							
0< ≤ 1 000 m^3	0	0	0	$2.3x10^{-3}$	0		
1 000< ≤10 000 m^3	$4.5x10^{-3}$	$1.1x10^{-3}$	0	$3.3x10^{-3}$	0		$3.8x10^{-3}$
10 000< ≤25 000 m^3	$8x10^{-4}$	0	$7.4x10^{-5}$	$2.5x10^{-3}$	$8.9x10^{-7}$	—	spill size
25 000< ≤50 000 m^3	$7x10^{-4}$	0	$3.2x10^{-6}$	0	$9.9x10^{-8}$		not defined
50 000< ≤75 000 m^3	0	0	$6.5x10^{-9}$	0	0		

* = [(1)(11) + (2)(12) + (3)(13) + (5)(8)(9)] (7) + (4) + (6)

Table 4. Maximum downwind distance of a flammable vapor cloud following an instantaneous spill of LNG onto water.

Report	LEG spill size (m^3)	Atmospheric stability	Wind speed (km/h)	Downwind distance (km)
BROTZ-D	20 000	A-F	All wind speeds	2.3
		During night only	All wind speeds	3.5
TNO1-NL	25 000	D	—	3.3
		E,F	—	10.0
ADL2-USA	25 000	A	25.0	1.0
		D	21.0	7.0
		E	19.8	10.0
		F	10.8	20.0
FERC-USA	30 000	A	25.0	0.5
			16.0	0.5
			9.0	0.6
		D	25.0	4.2
			16.0	4.9
			9.0	5.9
		E	25.0	7.8
			16.0	9.2
			9.0	11.3
		F	25.0	18.1
			16.0	21.6
			9.0	27.1
SAI-USA	37 500	A,D,F	54.0	6.0
		A,D,F	25.0	3.5
		A,D,F	11.0	2.0
		A,D,F	0.0	1.0
ADL2-USA	50 000	A	25.0	1.0
		D	21.0	9.0
		E	19.8	15.0
		F	10.8	25.0
SAI-USA	88 000	A,D,F	11.0	2.5

3.2.2. Ignition of Vapor Clouds

Ignition probability is composed of two parts. The first is the direct ignition by the event that caused the spill. As can be seen from Table 5 these probabilities, depending on the different events, are generally high because it is assumed that an event that causes a tank to rupture could also create enough frictional heat to ignite the resulting vapor cloud.

The second part is the probability that the vapor cloud is ignited by some other source given that it is not ignited immediately. Obviously this depends on the availability of ignition sources within the flammable bounds of the vapor cloud. Delayed ignition will in general have larger consequences, because the vapor cloud increases in size and travels downwind. Therefore, for most spill locations a high immediate ignition probability will reduce the overall risk. In this respect TNO1-NL and ACTION-UK are more conservative in their estimates than

Table 5. Probabilities of immediate ignition following different events.

Event causing the ignition	TNO1-NL	ACTION-UK	FERC-USA	SAI-USA	BATTE2-OTH	KEEN-OTH
Vessel tank rupture caused by:						
collision	0.65	0.66	0.9	0.9	0.8	0.9-0.99
grounding	0.1	—	0.0	—	0.3	—
ramming	—	—	0.9	—	—	—
missile/airplane	—	—	—	0.9	0.9	—
meteorite	—	—	—	0.0	—	—
internal failure	—	0.9	—	0.0	—	—

the other reports. Certainly, the ignition probability can be site-dependent. For example, KEEN-OTH points out that the immediate ignition probability is estimated at a high value because collisions at the specific site studied would generally involve larger vessels carrying dangerous cargoes (such as chlorine). Because historical data on LNG spills are lacking, the estimated ignition probabilities can not be validated.

FERC-USA, SAI-USA, BATTE2-OTH, and KEEN-OTH use the same model for delayed ignition probability. They assume that each source of ignition has the same probability p of igniting the vapor cloud. Thus the probability P_n that the vapor cloud will have been ignited within n seconds becomes $P_n = 1 - (1 - p)^n$. Additionally, all assessments using this model assume that each person (or that every fourth person) is a source of ignition, because (s)he will use facilities (e.g., car, oven, light) that are actual sources of ignition. The differences between the reports are the judgmental estimates of the probability p (Table 6).

Table 6. Ignition probabilities per person in case of delayed ignition.

	FERC-USA	SAI-USA	BATTE2-OTH	KEEN-OTH
Probability p that each person within the vapor cloud ignites the cloud	0.0025	0.1	0.01	0.01-0.1

Any of the assumed values of p can be either conservative or nonconservative depending on the number of people (and thus ignition sources) within the reach of the vapor cloud. The estimate of FERC-USA, for example, is less conservative for Point Conception than the estimate of SAI-USA because there are not more than 130 people living within 10 km of the LNG facility. Thus the FERC-USA estimate implies that there is a substantial probability that the vapor cloud will not be ignited at all, while the estimate of SAI-USA implies that the vapor cloud will be ignited with very high probability. On the other hand, using the model for Wilhelmshaven with 43 000 people living within 10 km of the LNG site, the FERC-USA estimate implies that the vapor cloud will be ignited, but only after covering more populated area than that predicted using the SAI-USA estimate.

3.2.3. Fatalities Caused by Ignited Vapor Clouds

Effects from ignited vapor clouds can be twofold: thermal and blast effects. There is no doubt that thermal effects exist, but it is an open question whether blast effects due to a deflagration or detonation can occur at all with methane and, if so, whether the peak overpressure created by a deflagration or detonation will be significant enough to cause damage. TNO1-NL considers blast effects to be the only serious danger, and thermal effects are of comparatively minor importance. CREM-UK considers both thermal and blast effects, as is logical since the Mossmorran terminal handles butane, propane, and ethylene, which are known to explode in certain mixtures with air. ADL2-USA only considers thermal effects, because an explosion (either deflagration or detonation) of methane is considered very unlikely. FERC-USA and SAI-USA again only consider thermal effects. BROTZ-D considers both thermal and blast effects. In NMAB-REV it is concluded that the possibility of explosions of LNG vapor clouds cannot be ruled out completely, although empirical evidence for such a possibility does not exist.

One first step to estimate the percentage of fatalities within certain distances from the vapor cloud is to state the level of thermal radiation and peak overpressure above which fatalities can be expected. Here one has to distinguish between primary and secondary effects. Primary effects are fatalities directly caused by thermal radiation and peak overpressure; while secondary effects are fatalities caused by fires created from thermal radiation by collapsing buildings as a result of peak overpressure.

All reports available to us consider only primary thermal and secondary blast effects. BROTZ-D maintains that primary blast effects can be ruled out, because the required peak overpressure has never been observed. Secondary thermal effects, however, are a possibility for people sheltered from direct radiation, but are very difficult to estimate. One way to include secondary thermal effects is to assume a low radiation level as a threshold level for fatalities.

Blast effects do not play a significant role in the risk calculations in most of the assessment studied. The only report relating blast effects to fatalities is TNO1-NL, and BROTZ-D does not consider them at all. The treatment of thermal effects varies markedly among the assessments. The distance from the center of the fire to the lower fatality level is about twice as large in ADL2-USA as in FERC-USA and SAI-USA. CREM-UK and BROTZ-D do not give a lower fatality level.

The major findings of a comparison of fatality calculations among the assessments can be summarized as follows:

(a) The reports differ on the major cause of fatalities. While TNO1-NL assumes all fatalities to be caused by secondary effects of vapor cloud explosions, ADL2-USA, FERC-USA, and SAI-USA assume fatalities to be caused by thermal radiation. CREM-UK and BROTZ-D do not consider fatalities as a result of ignited vapor clouds.

(b) There is also some difference in the radiation levels above which there will be fatalities. ADL2-USA adopts the most conservative assumptions on this topic among the reports.

(c) The effects of LNG and LPG vapor clouds can be quite different. For example, it is known that LPG vapor clouds can explode, while the possibility of an unconfined LNG vapor explosion has not yet been determined.

(d) The ignition of an LNG vapor cloud can have effects on nearby plants with possibly high secondary effects on the people living or working near the plants. Except at Point Conception there are chemical plants near all the other LEG terminals. CREM-UK and BROTZ-D considered this point and concluded that effects on the chemical plants nearby do not increase the overall risk significantly. In TNO1-NL it is pointed out that in the case of a detonation a nearby NH_3 storage tank could collapse with inadmissible consequences (the lethal dose of NH_3 would reach tens of kilometers).

3.3. Assessment of Population Risk

In many of the assessments the various numbers discussed so far are combined to aggregate estimates of population risk. These estimates of the societal risk, the individual risk and the risk of multiple fatalities are given in Table 7. No estimates of the risks were given in CREM-UK and BROTZ-D.

Not surprisingly, Point Conception has the lowest risk among the three sites. However, as discussed above, different reports consider quite different events. The probabilities also vary for the same event and the same site between different reports. It should also be noted that the estimate of SAI-USA was given for an LNG terminal with more storage tanks and larger ships than the one currently planned. Although we adjusted the estimates in earlier sections accordingly to make them comparable with ADL2-USA and FERC-USA, this was not done in Table 7. Therefore, the risk of the smaller LNG terminal currently planned, as estimated by the SAI-USA analysis, would be lower than that stated in Table 7.

Table 7. Estimates of risks for the different sites.

	TNO1-NL	ACTION-UK	ADL2-USA	FERC-USA	SAI-USA
Societal risk (fatalities per year)	$4x10^{-2}$	—	$7x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Individual risk (probability of fatality per year)	$\leq 7x10^{-6}$	$7x10^{-4}$	$\leq 9x10^{-8}$	$8x10^{-7}$	$1x10^{-8}$
Number of people at risk	$\geq$5000	?	$\geq$80	15	90
Risk of multiple fatalities: probability that number of fatalities per year is equal to or greater than					
1	$3x10^{-3}$	—	$1x10^{-6}$	—	$6x10^{-7}$
10	$1x10^{-3}$	—	$1x10^{-8}$ $6x10^{-7}$	—	$3x10^{-11}$
100	$5x10^{-6}$	—	∅	—	∅
1000	$5x10^{-6}$	—	∅	—	∅
5000	$3x10^{-7}$	—	∅	—	∅

4. CONCLUSIONS

The major findings of this report can be summarized as follows.

(a) There is no unique concept of risk that is used throughout all the risk assessment reports examined in this study. Many of the important differences between the reports stem from the different risk concepts used. Some reports do not even define their underlying risk concepts. However, there is a concept of risk that involves several measures, each based on both probabilities of failures and consequences of failures, that we judge to be superior to other less comprehensive risk concepts, and that we have adopted in this study.

(b) The possible failures of the system, the probability of those failures, and the estimation of their consequences to life and limb differ between the reports. Not all the differences can be explained by differences between the terminals and sites; some must be viewed as resulting from the limited knowledge and understanding of LEG risks. In this respect too little reference is made to remaining uncertainties in the estimation of risk in most reports.
(c) Given the differences between the reports there is no relative tendency for each report individually to over- or underestimate the risk. Rather, each report is more conservative on certain topics and less so on others, as compared with the other reports. Thus no report can be singled out as producing a more conservative estimate of the risk (with respect to all parts of the total risk) than any of the others.
(d) On a relative risk scale it can be said that, of the four sites, Point Conception presents the lowest societal risk (because of very low population density), Mossmorran and Wilhelmshaven present the highest relative risk (because of high population density and more vessel traffic) and Eemshaven is in between.
(e) Although risk is an important dimension of the decision to import LEG and to choose a specific site for the terminal, it should not be forgotten that other dimensions such as reliability are important too. Any decision regarding LEG importation and terminal siting should involve comparisons with alternative options. As part of that process the risk of LEG should be compared with the risk of other options.
(f) Whatever flaws the LEG risk assessments may have, they are clearly superior to less systematic ways of identifying possible system weaknesses and informing the decision-making process on the topic of risk.

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Societal Response to Three Mile Island and the Kemeny Commission Report

Roger E. Kasperson and Arnold Gray

Center for Technology, Environment and Development, Clark University, Worcester, Massachusetts 01610, USA

1. INTRODUCTION

The accident at the Three Mile Island nuclear power plant on 28 March 1979 was by common consensus the worst to occur in the history of commercial nuclear power generation in the United States. It is not surprising, therefore, that the accident provoked a series of assessments of its meaning as to the safety of nuclear power. Prominent among these was the President's Commission on the Accident at Three Mile Island, popularly known as the Kemeny Commission.

The commission labored for six months, eventually taking some 150 formal depositions, interviewing hundreds of individuals, hearing testimony under oath from numerous witnesses, and collecting sufficient material to fill 300 feet of library shelf space. In its work, the commission was supported by a budget of $1 million and a substantial staff. Its final report, issued in October 1979, received undoubtedly more media coverage and congressional attention than any other document on nuclear power safety.

The report is one of a genre of risk assessments. Unlike the Reactor Safety Study (WASH 1400) or the Risk Assessment Review Group Report (the Lewis Report) which relied heavily upon expert assessment dealing with the quantitative probabilistic assessment of risk, the Kemeny Commission inquired into the larger issues of nuclear safety as indicated by a particular accident. Because of the significance of the crisis event and the direct responsibility of the Commission to the President, the report had a unique opportunity to contribute to the shaping of nuclear safety in the United States.

This paper inquires into the response of various segments of society, particularly the mass media, industry, and the regulators.

2. A NOTE ON METHODOLOGICAL ISSUES

Assessing the impact of the Kemeny Commission Report on nuclear safety policy requires the isolation of the report from the numerous other risk assessments conducted after the accident, from the accident itself, and from the ten congressional subcommittees that had held hearings on the subject by the first anniversay of the Three Mile Island (TMI) accident. This cannot be done. In fact, the Nuclear Regulatory Commission (NRC) quite explicitly and systematically integrated the various report findings in order to fashion a coordinated response. In addition, a number of safety problems were quite evident in the accident itself, and it is futile to determine which source stimulated a particular response.

Within these constraints, however, there are some opportunities. A substantial part of the industry and governmental response occurred well in advance of the publication of the Kemeny Report some seven months after the accident; more of it presumably would have occurred even in the absence of the commission. Also, several post-accident evaluations and congressional inquiries appeared prior to the report and thus provide a benchmark from which to assess its particular contributions. Finally, there was not a complete overlap in these reports so that some of the individual findings and recommendations of the Kemeny Report can be distinguished and assessed as to impacts.

3. NEWSPAPER COVERAGE OF THE KEMENY REPORT

In regard to media coverage, the Kemeny Commission Report represents a special case among nuclear risk assessments. First, it came in the wake of the TMI accident, the top news story of the year. Consequently, the commission operated under a spotlight of media attention from the time it was created by President Carter until it published its report some seven months later. Second, unlike the Rasmussen and Lewis Reports, the Kemeny Report was intended to investigate the problems that led to an *actual* event and then to make recommendations on how best to avoid any similar occurrences in the future.

3.1. Pre-report Coverage

Interest in the Kemeny Commission was intense well before the report actually appeared. A total of 31 articles and three editorials on the Commission's activity were published prior to its release on 31 October, more than the total number of articles listed in the *New York Times Index* after its release. This well developed interest in the commission's investigatory work is apparent from Figure 1. Since further references to the Kemeny Report were included in articles on related topics, (e.g., the Rogovin Commission) after publication, the column inch counts suggest that pre- and post-Kemeny coverage was roughly equal.

The creation of the Kemeny Commission was first reported in the *New York Times* on 6 April 1979, after President Carter's announcement that a presidential commission of experts would be convened in order to "investigate the causes of this accident and ... make recommendations on how we can improve the safety of nuclear power plants". The first articles on the commission that tended to "paint a picture" of the TMI accident, and nuclear power in general, appeared on 20 May. The commission had just held its first day hearing testimony from residents of Middletown, and the article emphasized the emotionalism of the session: "Citing estimates that a few additional cases of cancer might develop as a result of the accident... a resident asked, his voice rising with emotion: 'Who'll be the ones? Myself? My son? My wife?'" As the testimonies were given, first with the control room operators, then with NRC officials, Babcock and Wilcox, executives, and Pennsylvania state officials, an image of mismanagement, carelessness, ineptitude, and complacency emerged. The reader of the *New York Times* could not easily come away from these articles with anything but a generally pessimistic view of nuclear power in America.

With the evidence in and the jury in deliberation, the press was left to wait for the verdict. Following up on rumors and strategically placed leaks, the *New York Times* focused much of its attention upon an anticipated moratorium of some form. Apart from this issue, the preliminary findings alluded to in the press did, for the most part, show up in the actual Kemeny Report. Key among them were:

(i) The NRC had a major attitudinal problem and was preoccupied with licensing. It would be recommended that the NRC be reorganized as an executive agency.
(ii) There must be an approved licensing plan.
(iii) There should be periodic relicensing of nuclear power plants.
(iv) Operator training should be upgraded with increased government regulation and better (possibly standardized) design for control rooms.

None of these findings or recommendations, however, received the same amount of attention that the moratorium issue received.

3.2. Post-report Coverage

The Kemeny Report ultimately included 81 specific findings and 44 recommendations. Of the 81 findings, only 13 were reported in the *New York Times* (see Table 1). Of the 44 recommendations, only eight were covered. The treatment, in short,

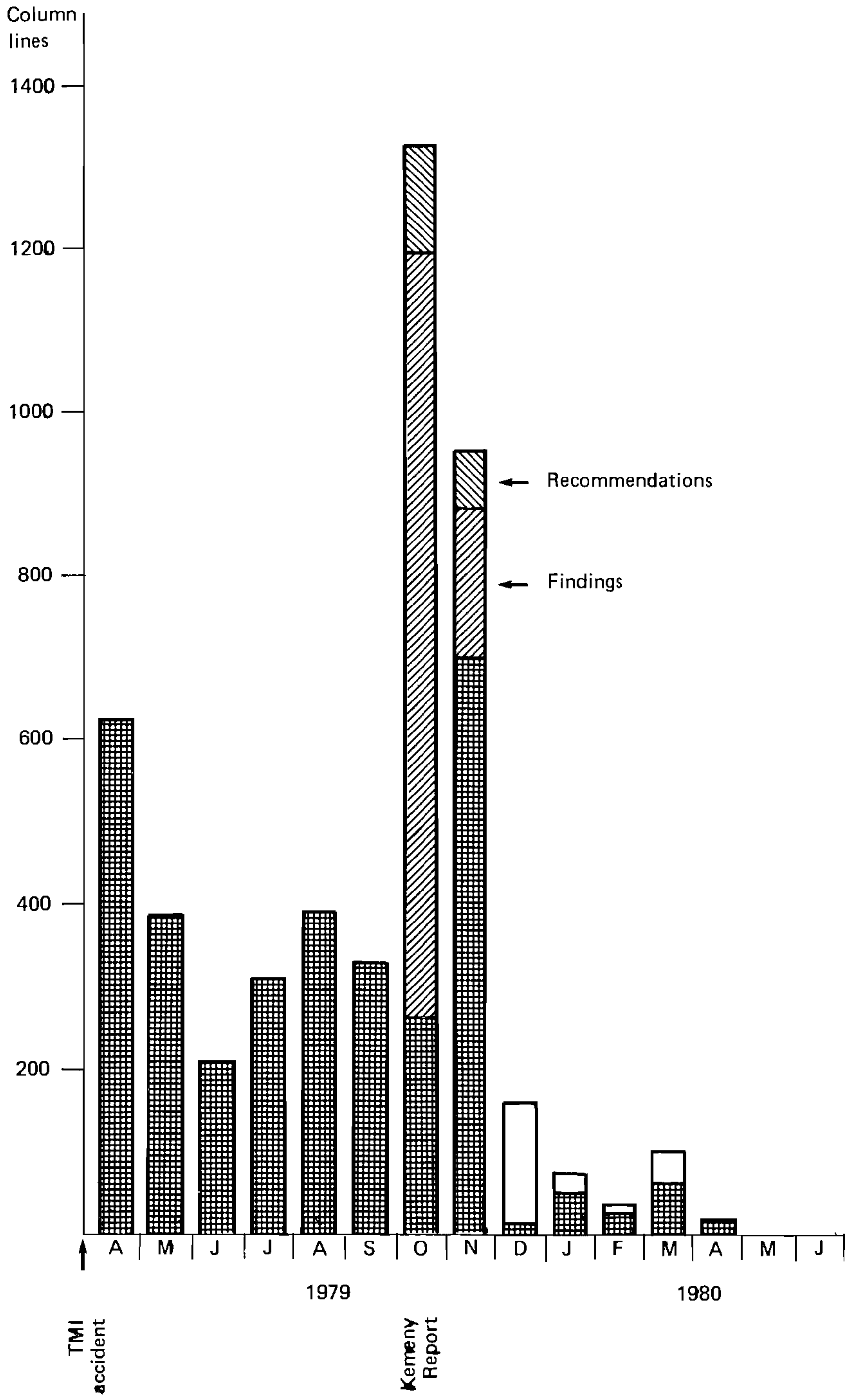

Figure 1. Column lines of Kemeny Commission general coverage, findings, and recommendations in the *New York Times*.

Table 1. Findings and recommendations from the Kemeny Commission Report as reported in the *New York Times* (in print lines).

	1979			1980					Total no. of
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Totals	articles
Recommendations									
A1—Reorganize NRC	70	30	119	9	—	—	—	212	13
A2—Establish executive oversight committee	6	—	8	—	7	—	—	21	3
A5, F1—Broaden utility responsibility in emergency	—	3	—	—	—	—	—	3	1
A7, A8, A11e, F1—Upgrade licensing procedure	50	30	21	—	—	—	—	106	9
C1—Improve operator and operating procedure	22	—	—	—	—	—	—	22	3
Findings									
Overall conclusion	136	24	15	—	—	—	—	175	9
A1, 2, 8, 12—assessment of significant events	249	—	—	—	—	35	—	284	7
H4, 10—Public right to know	159	104	—	—	—	—	—	263	6
G8, 12—NRC	117	12	3	—	—	4	—	136	9
E5—Utility and supplier	107	20	3	—	—	—	—	130	7
B16, 4—Public health and health effects	54	14	—	—	—	—	—	68	5
F1—Operators and operating personnel	38	—	—	—	—	—	—	38	3
Attitudes: personal and institutional	78	—	—	—	—	—	—	78	3

was highly selective, emphasizing what the *Times* found important. Those findings and recommendations that were covered, however, were covered extensively. The finding that "fundamental changes are necessary if those risks are to be kept within tolerable limits", deemed *the* central finding by the *Times*, was reported no less than nine separate times during the post-report period. Two recommendations in particular dominated the overall coverage: the reorganization of the NRC and the upgrading of licensing procedures. In fact, the proposal to reorganize the NRC (not adopted) received more coverage than the remaining 40 or 50 recommendations. Even the recommended upgrading of licensing procedures was discussed primarily in terms of the moratorium issue—an issue, we should note, that while not a recommendation, received more coverage than any of the actual Kemeny recommendations or findings.

Coverage of the report rapidly fell off the *Times* reporting agenda, although analysis of the coverage is difficult because attention shifted to specific issues rather than the report itself. A gleaning of the *Times Index* suggests that attention shifted toward transient conditions at various nuclear plants, problems surrounding Indian Point, economic problems of the nuclear industry (including fines, cost over-runs, delays), and the political struggles between pro- and anti-nuclear forces rather than the important but less conspicuous responses within industry and government dealing with the generic safety issues raised by TMI. Throughout 1980, for example, there was no substantial discussion of the NRC's *Action Plan* (NUREG 01600), the single most important governmental response to emerge from the accident and the Kemeny Commission Report.

4. SCIENTIFIC PRESS COVERAGE

The coverage of the Kemeny Report in *Science* and *Nature* was quite different from that of the *New York Times* although, in several respects *Science* and *Nature* also differed from one another. *Science* carried three articles on the Kemeny Commission before the report release, treating the make-up of the committee and its budget and constraints, the ending of the licensing moratorium, and the iodine-131 problems. *Nature* mentioned the Kemeny Commission only twice prior to the report and referred to completely different issues: the California study of TMI, and a news brief on the dissolution of the citizens' panel.

Both *Science* and *Nature* published only one article to cover the report's findings and recommendations. Both provided extensive coverage of the report, although *Science* was somewhat more specific and comprehensive. Neither of the two, however, included a *verbatim* listing of either the findings or the recommendations. The *Science* article, under the heading "Kemeny Report: Abolish the NRC", referred to 23 specific findings, nine recommendations and two criticisms of omitted recommendations. The report was criticized for "not [going] the extra step and [demanding] fundamental changes" and also for not asking for a licensing moratorium.

The reporting in *Nature* was less complete, treating eight findings, five recommendations, plus a section on the happenings of the accident. *Nature* did go on, however, to discuss immediate reaction to the report by pro- and anti-nuclear groups. The critics had charged that the report's "bark may ... turn out worse than its bite". The nuclear industry interpreted the report's message as "proceed with caution". *Nature* later published an article (17 January 1980) that challenged the latter view.

In terms of post-Kemeny coverage, the two journals presented only one major article (*Science*, 21 December) specifically addressing responses to the report. Briefer treatments did appear as well. On 8 February 1980, *Science* dealt with the Rogovin Report, noting the agreement of the two reports on the need to reorganize the NRC. A second article covered the NRC's review of reactor design in view of the Crystal River accident. While the Kemeny Report was not mentioned *per se*, there was discussion of safety recommendations that had been included in the report.

Nature carried three post-Kemeny articles. The first covered the congressional debate over the moratorium issue, noting that the report did not recommend a licensing moratorium, and the second included a discussion of nuclear safety, with attacks authored by Dr Russell Peterson (a former Kemeny Commissioner). An alternative view was presented by Nobel prizewinner Dr Rosalyn Yalow. Finally, in an article (19 June) entitled "What (if any) future for nuclear power?", *Nature* criticized the Kemeny Report for its lack of criticism and its minimal impacts.

Overall, the scientific press, as indicated by coverage in *Nature* and *Science*, achieved a more balanced and analytical treatment than the *New York Times*, but again the follow-up coverage of responses was insufficient to provide the reader with an informed treatment of what the report eventually meant for nuclear power.

5. INSTITUTIONAL RESPONSES

To assess institutional responses to the accident and the Kemeny Report, we can identify 12 key areas of recommendation from among the 43 specific ones made by the commission. For each key recommendation, the major societal responses are noted, major unresolved issues specified, and our overall assessment of the response is provided in Table 2.

The Kemeny Commission reached a number of biting judgments concerning the primary institutions responsible for the assurance of nuclear safety, the most notable of which were as follows.

(i) *The Nuclear Regulatory Commission.* "with its present organization, staff, and attitudes, the NRC is unable to fulfil its responsibility for providing an acceptable level of safety for nuclear power plants" (p56).

(ii) *The Advisory Committee on Reactor Safeguards.* The Committee is the only body independent of the NRC staff which regularly reviews safety questions, but the Committee "has established no firm guidelines or procedures," its members are "part-time and have a very small staff" and it relies heavily upon the NRC staff for follow-up of concerns.

(iii) *The Utility.* The utility (Met Ed) failed in a number of important cases "to acquire enough information about safety problems, failed to analyze adequately what information they did require, or failed to act on that information" (p43). "It did not have sufficient knowledge, expertise, and personnel to operate the plant or maintain it adequately" (p44).

To deal with these institutional deficiencies, the commission recommended a broad set of changes involving the NRC, the Advisory Committee on Reactor Safeguards, and industry.

The Kemeny Commission found that the NRC lacked sufficient organizational and management capability to ensure safety, a judgment supported by the Rogovin Report. Unfortunately, the commission recommended the rather shopworn suggestion of agency reorganization, in this case a change from an independent regulatory commission to an executive branch agency with an administrator, as the most prominent means of redress. The Kemeny Report was the first accident post-mortem to call for this change, though it subsequently also found favor in the Rogovin Report. The recommendation was unpopular from the start: the NRC staff opposed it, all the current NRC commissioners save one also opposed it. Congress was lukewarm to the idea, and the President, sniffing congressional opposition, never supported the recommendation. Instead, he called for, and congress eventually approved, a strengthening of the chairman's role.

Two years after the accident, top leadership in the NRC remains as an outstanding problem, recently described by one of the NRC commissioners as "analogous to hitching fire horses at different points around a sled". The general weakening of reglatory agencies in the current Reagan administration does not bode well for the hope that the recent drift and indecision will halt and that coherent, effective leadership committed to safeguarding public health and the environment will emerge in the NRC. Other changes in the NRC have met with greater success and indicate some limited improvements in regulatory performance. Central to these responses has been a shift in commission resources and emphasis on monitoring and assessing operating reactors. Within four months of the accident (and well in advance of the Kemeny Report), the NRC established a new office for analysis and evaluation of operational data aimed at the serious deficiencies in learning from past reactor incidents and malfunctions apparent in the TMI accident. The NRC also established a program of resident inspectors stationed at individual power plants. The severity of licensing exams for reactor operators has also been increased, producing a rise in failure rates from 5 to 30 percent. The NRC has improved its capability for crisis management by clarifying responsibilities and improving communication with an analytical strength for existing reactors.

Table 2. Societal response to key Kemeny Commission recommendations (as of March 1981).

Recommendation	Response
Restructure/improve NRC (A1)	President does not accept Kemeny reorganization recommendations. Congress retains collegial structure with strengthened powers of chairman. Chairman designated as spokesman in emergencies. <u>Assessment</u>: basic problems of the commission referred to in report remain unresolved, restructuring is not achieved, but some improvement in emergency response and regulating of operating reactor capabilities. In September 1980, the Nuclear Safety Oversight Committee finds evidence of a "business-as-usual mindset in NRC".
Improve ACRS (A3)	NRC opposes any mandatory response to ACRS recommendations. On 11 February 1980, ACRS charges NRC "largely ignores" its input on Kemeny Commission responses. <u>Assessment</u>: no substantial action undertaken to improve ACRS. It is unlikely that the ACRS can and/or will influence change within the NRC.
Establish new oversight committee (A2)	Executive Order established Nuclear Safety Oversight Committee on 18 March 1980. Committee issues three letter reports to the President on NRC action plan, radiological consequences of nuclear accidents, and emergency response planning. <u>Assessment</u>: Committee has provided limited but useful function. Future is unclear.
Upgrade reactor operator and supervisor training (A4, C1, C4)	Nuclear Safety Analysis Center establishes computerized communication system connected to all utilities on operating incidents. NRC proposes upgrading in formal education: senior reactor operators, 60 college credits in engineering; shift supervisors, a BS degree in engineering. Utilities improve training for emergency events. No change proposed in formal education of reactor operators. Memphis State University inaugurates new training program in cooperation with utilities. Severity of licensing exams increased; failure rate rises from 5 to 30 percent. NRC declines to accredit training programs. <u>Assessment</u>: upgrading becoming evident though requirements still lag behind those in Europe.
Increase safety emphasis in licensing (A10)	NRC reorganizes licensing staff to correct weaknesses in licensing process. Increased attention to operator training, utility management, emergency planning, reactor design features, and evaluation of plant operating experience; NRC decides against Office of Hearing Counsel. 1981 licensing plan reduces role of intervenors. <u>Assessment</u>: actions to date fill a number of gaps in safety coverage, but the degree of substantial improvement unclear. NRC licensing of Sequoyah plant questions commitment to safety. Reduced role of intervenors weakens safety focus.

Table 2 continued.

Recommendation	Response
Improve safety inspection and enforcement (A11)	NRC establishes resident inspectors at power plants, requires annual evaluation of licensees, improves reporting requirements. A new NRC Office for Analysis and Evaluation of Operational Data established (prior to Kemeny Report) in July 1979. Fines for utilities increased. Bingham Amendment calls for "systematic evaluation" of all operating nuclear power plants, a possible 5-8 year effort that has evoked opposition. <u>Assessment</u>: although too early to tell, indications are of substantial improvement in inspection and regulation of operating reactors. But position of top leadership of NRC during Reagan administration will be important. Bingham Amendment will require significant new NRC resources.
Improve technical assessment and equipment (D1-D3)	Utilities initiate improvement in control room design and instrumentation. <u>Assessment</u>: substantial improvements implemented or ongoing in improved instrumentation, equipment, and monitoring.
Initiate new reactor risk assessments (D4-5, D7, E1)	NRC reorientates risk assessment research program with new attention to higher probability events, accident mitigation, and human factors. Retrospective iodine release study of TMI accident suggests possible past overestimate of consequences by factor of 10. Utilities establish improved monitoring and dissemination system of operating incidents. NRC establishes Division of Human Factors and initiates effort to define level of acceptable risk. Epidemiological studies of effects of low-level radiation initiated. EPA recommends against ten-fold reduction in occupational standard. Probabilistic risk assessment initiated by utilities at eight power plants. Radiation Policy Council established in Executive Branch. <u>Assessment</u>: significant changes instituted to give new priority to TMI-like events, to human factors, and accident mitigation. Individual plant risk assessments should improve safety performance and enlarge accident response capability.
Improve industry attitudes and performance (B1-B3, B5)	Industry establishes two new institutions: Institute for Nuclear Power Operations (INPO) with power plant evaluation and training as primary functions and Nuclear Safety Analysis Center (NSAC) with analysis of operating experience and other technical assessment its primary activities. International cooperation with NSAC makes world experience database a possibility. <u>Assessment</u>: substantial industry response: new institutions are important safety vehicles. Still unresolved are prevailing attitudes and assurance of high level of overall technical competence in individual utility management structure.

Table 2 continued.

Recommendation	Response
More remote siting of nuclear power plants (A6)	NRC proposes (NUREG 0625) upper limits on population densities around plants and making siting criteria distinct from engineered safeguards. Estimates suggest 49 of 84 currently operating plants would fail to meet criteria. Strong industry opposition. Assessment: proposal currently mired in controversy; no change to date, but new plants not currently being ordered in any event. Since no retrospective application of criteria, limited safety impact on 100-150 GWE nuclear system.
Improve emergency response and mitigation (A7-A8, E3-E5, F1-F3, G1-F4)	NRC issues new rule on emergency response plans, extending 5-mile zone to 10-mile and 50-mile radii. All operating reactors required to have emergency plans approved by April 1981. NRC installs a crisis management communications link of all power plants to NRC headquarters. New rule mandates that state be able to notify every person within 10 miles of a nuclear power plant of accident within 15 minutes and evacuate population. Proposal to distribute potassium iodide pills mired in controversy. *Nucleonics Week* survey finds confused and uncertain response by states. No notable improvement in mass media capabilities, despite an NRC pilot program. Assessment: although utilities and the NRC have improved their emergency response capabilities, the overall capacity of society to respond to a major accident remains in doubt.
Educate the public (F4, G5)	NRC plans to investigate need for literature. No program instituted to date. Assessment: no substantive response despite widespread scientific belief as to need.

Beyond these useful changes, however, is the more basic and difficult problem of attitudes and orientations throughout the professional staff of the NRC. The Kemeny Report was quite specific about these problems:

> "...we have seen evidence that some of the old promotional philosophy still influences the regulatory practices of the NRC" (p19)
> "...the evidence suggests that the NRC has sometimes erred on the side of the industry's convenience rather than carrying out its primary mission of assuring safety" (p19)
> "There seems to be a persistent assumption that plants can be made sufficiently safe to be 'people-proof'" (p20)
> "We do not see evidence of effective managerial guidance from the top, and we do see evidence of some of the old AEC promotional philosophy in key officers below the top" (p20).

The Kemeny Report was hopeful that the reorganization of the NRC would begin a change in attitudes from the top down. A coherent plan for dealing with these difficult behavioral problems has not been forthcoming, yet obviously substantial changes are critical to a strengthened regulatory performance. The behavior of the NRC since the accident suggests, not surprisingly, that the pre-accident attitudes are proving difficult to extirpate. A scant five months after the accident