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RISK ASSESSMENT METHODOLOGIES APPLICABLE TO MARINE SYSTEMS

by
B. John Garrick, PhD

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PREFACE AND ACKNOWLEDGEMENTS

This review of risk assessment methodologies applicable to marine systems has received contributions and source material from several individuals and groups. They include the National Research Council, the United States Coast Guard, PLG, Inc., and several individuals. The idea and early source material of the review came from the Committee on Risk Assessment and Management of Marine Systems of the Marine Board of the National Research Council. The author of this review served on the committee and was chair of a risk assessment methodologies panel of the committee. The panel was to address the subject of this paper, but a shortage of funds terminated the effort. Meanwhile, the Coast Guard in an effort to capture the work that had already been performed decided to support continuation of the project under a private consulting arrangement. The resulting review is therefore the sole responsibility of the author and is not to be interpreted as a National Research Council publication.

While this was to be a review paper solely the responsibility of the author, the U.S. Coast Guard did want to retain the outline and tone of what would have been an Academy report as much as possible. The result is an attempt to be quite broad in scope and to benchmark marine risk assessment activities with those of other industries.

From the National Research Council Committee, the author acknowledges the contributions of E. S. Bouchard, Dr. C. D. Massey, and Dr. M. E. Pate-Cornell. Lt. D. E. Boniface of the United States Coast Guard provided valuable guidance on the most current risk assessment activities in the Coast Guard and reviewed the draft of the paper. PLG provided access to their several studies on marine systems and source material for Appendix A. PLG staff especially helpful were W. C. Gekler and R. A. Dykes. Other private individuals making valuable contributions were Dr. S. Kaplan (to Appendix B) and Dr. S. R. Medhekar (especially to Sections 4 and 5).

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EXECUTIVE SUMMARY

A review is made of risk assessment methods and practices in and outside the marine field suitable for application to marine systems. The perspective of the review is the use of quantitative risk assessment to improve the safety of marine systems through improved decision making. Offshore platforms and ships are the marine systems considered. Comparisons of risk assessment methods and practices are made with other major industries such as chemical, nuclear, space, and defense.

The field of quantitative risk assessment has grown rapidly over the past two decades, triggered by the publication in 1975 of the seminal work, the Reactor Safety Study. As a result, the nuclear industry is the most advanced in the use of quantitative risk assessment, although specific project applications in other industries, including the marine industry, are impressive.

Marine systems have much in common with power and chemical systems, especially at the hardware level, but there are unique characteristics of marine systems that are extremely important in the consideration of risk assessment methods. These characteristics include confinement and isolation, self-containment, and extreme limitations with respect to accident recovery and emergency response. Other important characteristics include a diversity of systems in size and complexity, harsh environments, and hazardous and nonhazardous cargoes.

While the marine industry lags such other industries as nuclear and defense in the adoption of quantitative risk assessment practices, they are embracing qualitative methods piecewise into their analysis and regulatory framework. The safety case work for offshore operations contains elements of risk assessment and has led to much more rigor in their safety analyses. Specific methods have surfaced that could evolve into a general framework of quantitative risk assessment such as the methodologies for comparison of alternative production systems. With respect to ships and transportation, an example of applying risk assessment methods is the Prince William Sound risk assessment project. The United States Coast Guard and other regulatory agencies have programs for considering the role of more formal risk assessment practices but none has yet committed to risk informed or risk based regulation. The marine risk assessment projects and programs that have been performed have demonstrated the value of a systematic and deliberate process for exposing accident threats and vulnerabilities. These same projects have provided some direction and guidance on design alternatives and regulatory change.

This review has identified a number of opportunities for improving the risk assessment methods employed on marine systems. An overarching recommendation is to develop stronger ties with other agencies and industries more advanced in the use of the risk sciences in regulatory practice and industry activities. Examples of agencies are the U.S. Nuclear Regulatory Commission and the U.S. Environmental Protection Agency. Examples of industries are nuclear power, chemical and petroleum, and space and defense. The development and commitment to a general plan of direction of the marine industry in the more efficient use of in-depth risk management tools.

There are several technical opportunities for improving the use of the risk sciences in the marine field. These include the adoption of a general risk assessment framework to baseline marine risk assessment activities, expansion of the risk measures beyond just accidents and oil spills to include human health effects and environmental impacts, and expansion of the scope of the risk assessments to consider such phenomena as common cause failures, uncertainty analysis, human factors, and organizational impacts.

1. INTRODUCTION

Risk assessment has been a part of the human psyche since the beginning of time. As life becomes more complicated, driven largely by technology, it is increasingly important to understand the risks we face in order to make decisions that not only sustain life and the environment but also enhance their quality. Attendant with this increase in complexity is the need to become more explicit and quantitative in our risk assessments. The principal change in risk assessment, especially over the past two or three decades, is the opportunity to move from risk assessments that are intuitive, implicit, and qualitative, to risk assessments that are rigorous, explicit, and quantitative.

Among the complicated technological systems on which societies have a growing dependence are marine systems. For purposes of this study, we are considering marine systems that primarily have to do with shipping activities and offshore oil production systems. In particular, it is the purpose of this paper to review risk assessment methods and practices for application to marine systems. Consideration is given to both marine and nonmarine experience. Risk assessment practices in the nuclear and chemical industries are examples of nonmarine experience that were reviewed. In the marine field two activities of special interest are the Prince William Sound risk assessment project (PWSRA) and the United Kingdom safety case (both have been labeled as state-of-the-art safety assessment activities).

The emphasis in this review is on quantitative risk assessment (QRA) in order to answer the question of just how this relatively new technology can add value to the risk assessment and risk management of marine systems. Narrowing the scope to QRA methods also permits the review to be reasonably focused in terms of reaching specific conclusions.

Among the questions considered are:

- What is the general status of quantitative risk assessment?
- What are some of the unusual characteristics of the marine field?
- What risk assessments have been applied to marine systems?
- What lessons have been learned from the limited risk assessments of marine systems?
- What enhancements to risk assessment methods would facilitate their application to marine systems?

In addition to providing responses to the above questions, an attempt is made to highlight the regulatory practices of the marine field.

2. CURRENT RISK ASSESSMENT PRACTICES

While there is a lack of universality in the definition of "risk" terms, some definitions and meanings have evolved which are becoming increasingly accepted. Three important ones are *risk assessment, risk communication, and risk management.* Figure 2-1 is an attempt to highlight these definitions.

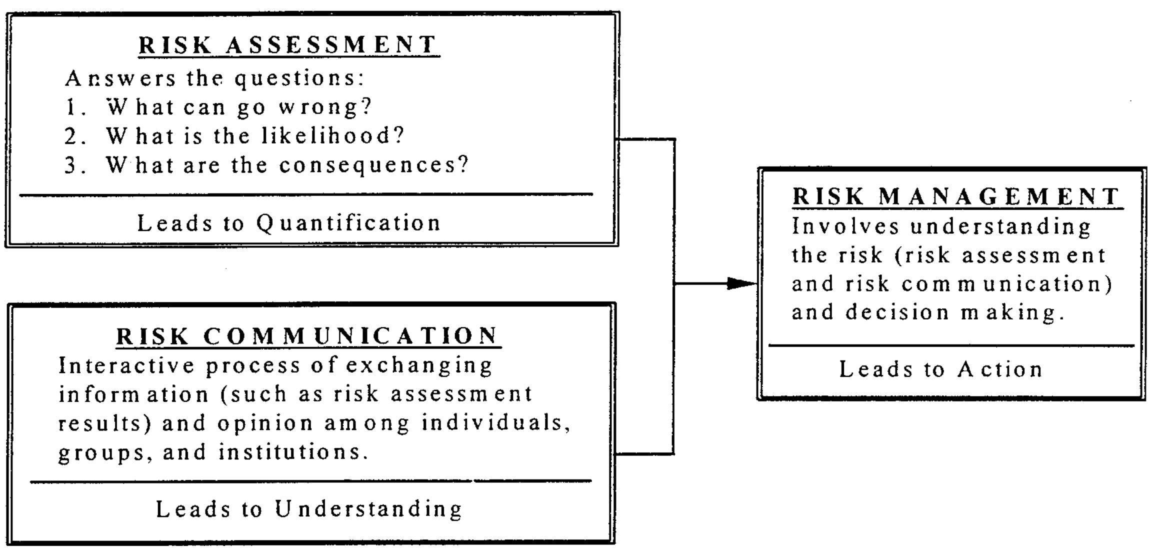

Figure 2-1. Taxonomy of Risk

The engineering community made its biggest jump in the quantitative risk assessment field in 1975 with the release of the reactor safety study (Reference 1). Leading up to the reactor safety study, there was research going on to upgrade the safety analysis of nuclear power plants (Reference 2). Following the nuclear industry, the space, defense, and chemical industries were the most active in the development and application of the risk sciences to the safety management of technological systems.

Members of the nuclear industry have been the most active practitioners of quantitative risk assessment, or probabilistic risk assessment as it is labeled in the nuclear industry. The probabilistic risk assessments performed for the Zion and Indian Point nuclear power plants (Reference 3) in 1981 and 1982 were the first such full-scope studies performed. The reactor safety study and the Zion/Indian Point PRAs paved the way for a major shift in the way safety analysis was performed in the nuclear power industry. The performance assessment of geological nuclear waste repositories is a more recent development in the application of quantitative risk assessment principles to complex and hazardous systems.

The risk assessments of nuclear power plants have provided a robust resource of methods, data, and expertise for extension of these methods to other technological systems including marine systems. Nuclear plant risk assessments have reached a reasonably high level of maturity. In addition to the United States, probabilistic safety analysis (PSA), the international term for PRA, is practiced at most nuclear power plants throughout the world. In Germany, the PSAs have had an even greater influence on the design of their plants than they have in the United States. France, Sweden, Japan, and Korea are other countries making extensive use of PSAs as the method of choice for in-depth understanding of the safety of their plants. While no country, including the United States, has totally adopted risk based regulation, there is a clear movement in that direction as all nuclear power plant licensees have been required to submit some form of a probabilistic risk assessment. The current state of affairs is often referred to as risk informed regulation.

While the space and defense industries were the cradle for many of the basic techniques employed in risk assessment, such as fault tree analysis, reliability analysis, and failure mode and effect analysis, these industries have been cautious in adopting an aggressive move towards quantitative risk assessment. In the late 1980s, NASA began to show signs of moving towards the selective use of quantitative methods with a "proof-of-concept" study (Reference 4) to demonstrate the use of QRA methods on a critical system in the operation of the space shuttle. This has been followed by numerous other studies, perhaps the most recent and significant of which is a broader-scoped probabilistic risk assessment of the entire space shuttle (References 5 and 6). The United Space Alliance, an alliance of aerospace companies contracted to operate the space shuttle, is developing a formal and reasonably rigorous risk management program (Reference 7) that is expected to contain quantitative elements. The move towards quantitative risk assessment in the space program is clearly underway albeit a cautious one.

The chemical industry is very different from the above industries in some extremely important ways. These differences have greatly influenced the chemical industry's use of risk assessment methods. Among the important differences is its extremely competitive nature resulting in cost considerations being a much bigger driver of how the industry is managed from a risk perspective. Another important difference that is a distinct advantage over the nuclear and space industries is the large experience base that exists in the chemical field. Besides the effect of new regulations, the Center for Chemical Process Safety has been a force and a valuable resource for the chemical industry's move toward the greater use of more formal safety assessment and management practices, including the use of risk assessment methods. Qualitative risk assessment plays a major role in the risk assessment practices of the chemical industry. The industry has generally adopted the concept of a process hazard analysis (PHA) program utilizing such tools as failure mode and effects analyses (FMEAs) and hazard and operability (HAZOP) studies. The HAZOP concept was developed entirely by the chemical industry. It establishes the likelihood and consequence of hazardous events using conservative methods. It also identifies the operability problems that, though not hazardous, could compromise the chemical plant's ability to achieve design productivity.

The discussion of chemical and process risk assessment practices is a logical lead into the risk assessment of marine systems as they often involve some of the same types of hazardous materials. For purposes of this review marine systems are considered to be offshore oil and gas production facilities and shipping activities. Initially, risk assessment activities of offshore facilities primarily involved the analysis of structural failure as a result of environmental threats. During approximately the past two decades there has been increased emphasis on analyzing the risk of accidents involving marine systems including ship collisions, fires, explosions, and blowouts. The pace in performing more formal safety assessments has quickened considerably just in the last decade. Several disasters have greatly elevated public interest in the safety performance of marine systems. Examples are the capsizing of the Herald of Free Enterprise (March 6, 1997), the Piper Alpha explosion (July 6, 1988), the Exxon Valdez grounding in Prince William Sound (1989), and the 1989 South Pass Block 60 accident in the Gulf of Mexico. These events and others led the way to a major change in regulations governing the design, operations, and safety management of marine systems with particular emphasis on offshore production facilities and marine transportation systems.

The maritime nations leading the way to more formal risk and safety assessments of marine systems are the United Kingdom, Norway, Australia, and the United States. The United Kingdom has pioneered the formal safety assessment (FSA) methodology (Reference 8) which advocates elements of a risk based approach. Norway requires risk assessments in petroleum activities but does not prescribe specific methods. However, the guidelines imply a quantitative risk assessment thought process. Australia requires a formal safety assessment to record the risk assessment and results but allows the flexibility of nonquantitative approaches. The United States currently has no requirement for the use of risk assessment but is in transition relative to safety assessment requirements. While in the United States safety is primarily a matter controlled by the coastal states, the Mineral Management Service (MMS), a federal agency, is encouraging operators to implement a Safety and Environmental Management Program (SEMP) based principally on the American Petroleum Institute (API) Recommended Practice (RP)2A, "Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms-Working Stress Design." Although there remains some resistance in the marine field to requiring quantitative risk assessments of marine systems, there is considerable activity that could lead to a change in the culture. Important examples are the U.S. Coast Guard's (USCG) publication of risk based decision-making guidelines (Reference 9) and the risk assessment study of the Prince William Sound (Reference 10). The reference to risk assessment in the guidelines for the application of formal safety assessment to the International Maritime Organization's (IMO) rule making process (Reference 11) is another example of increased interest in more formal risk assessment practices. Examples of other marine system safety projects that involve the use of risk assessment methods to varying degrees are:

- The United Kingdom's "Formal Safety Assessment of High Speed Catamaran Ferries" (Reference 12).

- Italy's "Formal Safety Assessment Study on the Effects of Introducing Helicopter Landing Area (HLA) on Cruise Ships" (Reference 13).

- John Volpe National Transportation Systems Center's "Scoping Risk Assessment: Protection Against Oil Spills in the Marine Waters of Northwest Washington State" (Reference 14).

- Changes in the Port State Control Program to enable the Coast Guard to more systematically determine the probable risks posed by nonU.S. ships calling at U.S. ports (Reference 15).

- New policy guidance to the Coast Guard regarding methods of risk reduction to passengers of permanently moored passenger vessels (Reference 16).

While none of these activities adopt the complete scope of quantitative methods discussed in Appendix B of this report, they clearly indicate an embracing of the risk thought process. The trend appears to be a cautious move in the direction of increased use of risk assessment methods in general and occasional use of quantitative methods in particular. There does appear to be growing support, especially in the marine transportation field, for the use of quantitative methods when actual design changes are under consideration.

A brief review of risk assessment practices in different industries allows for some qualitative comparisons of methods and programs. Appendix A presents evaluation sheets on several methods and programs in and outside the marine field. Tables 2-1 and 2-2 attempt to provide some perspective and comparisons of the methods and scope of risk assessment in selected industries.

At the quantitative level, the specific numbers in these tables would, of course, vary depending on the judgment of the individual(s) making up the tables. At the qualitative level it is believed that there would be considerable agreement among risk assessment practitioners who have worked in the various industries being compared. The assignment of the numbers was based on actual risk assessment experience in several of the industries, an informal polling of practitioners in the various industries considered, and a review of the risk assessment literature for evidence of regulations, methods, applications, and scope of analyses performed in each of the industries. Actual evidence obviously lags actual activity. In particular, it is important to note that many of the industries noted in Tables 2-1 and 2-2 are in transition in their use of the risk sciences to enhance decision making on matters of risk and safety. The maritime field is one example. Thus, it is expected that even if the tables are a reasonable representation of the relative state of risk assessment practices between the different industries, the picture will probably change quite rapidly as the literature catches up with the actual activity.

Table 2-1. Comparison of Risk Assessment Methods in Different Industries

Industry	Method		
	QRA, PRA, PSA (Quantitative Methods)	PHA, HAZOP (Qualitative Methods)	Other Methods (Primarily Qualitative)
Marine Shipping	3	2	4
Marine Offshore	6	5	8
Chemical/Petroleum	2	10	5
Nuclear Power	10	2	4
Nuclear Waste	7	5	5
Space	5	2	8
Defense	6	3	5
Legend: High Emphasis (10-8), Medium Emphasis (7-5), Little Emphasis (4-2), Under Study (1), Not Applicable (0)			

Table 2-2. Comparison of Risk Assessment Scopes in Different Industries

Scope	Industry						
	Marine Shipping	**Marine Offshore**	**Nuclear Power**	**Nuclear Waste**	**Space**	**Defense**	**Chemical/ Petroleum**
Health Effects	2	2	5	9	3	1	9
Releases	8	6	6	9	3	3	8
Facility Damage	5	8	10	3	8	8	5
External Events	3	7	10	8	5	6	3
Human Reliability	4	3	7	1	2	5	5
Organization Performance	2	2	1	1	0	0	0
Common Cause Analysis	2	2	8	0	2	3	2
Cost Benefit	2	4	3	5	0	3	2
Decision Analysis	2	5	3	6	2	3	2
Uncertainty Analysis	0	4	7	8	6	6	0
Legend: High Emphasis (10-8), Medium Emphasis (7-5), Little Emphasis (4-2), Under Study (1), Not Considered (0)							

As Table 2-1 attempts to communicate, the marine shipping industry places little emphasis on risk assessment methods, especially quantitative risk assessment. While the offshore marine industry puts more emphasis on risk assessment (with medium emphasis on both quantitative and qualitative methods), it lags behind other industries in the application of quantitative methods. And while it may seem that the use of QRA is fairly prevalent based on Table 2-1 (at least for the offshore industry), a more detailed consideration of the scope of offshore risk assessment practices, Table 2-2, reveals very limited applications when compared with the more active industries. Both marine shipping and offshore risk assessment practices appear to be very limited in such areas as human response analysis, common cause analysis, and uncertainty analysis. Offshore risk assessments tend to include more damage and external event analysis than do the risk assessments for shipping. While no industry can boast of looking at all aspects of risk assessment, the marine industry does lag behind the industry benchmarks chosen for this review.

3. CHARACTERISTICS OF THE MARINE FIELD

3.1 TYPES OF SYSTEMS

The types of marine systems are almost unlimited. They include ships of various sizes and classes with both hazardous and nonhazardous cargoes; crews of widely diverse nationalities and qualifications; and a nonstandard enforcement of safety rules and qualification standards. Marine systems also include onshore and offshore production facilities, drilling operations, refineries in some cases, pipelines, terminals, docks, tankers, barges, and all the interfacing systems, not to mention the organizations, people, communications, and emergency response infrastructures involved.

As the technology advances, the systems are also changing. Ships are getting larger and carrying less crew. Oil exploration, drilling, and recovery operations are moving further offshore into deeper waters subject to more violent forces of nature. Floating production systems are being introduced into the mix of marine systems and will involve the combining of the analysis of stationary and dynamic systems.

Marine systems have many attributes that are unique and make them stand apart from the more conventional land-based systems for which risk assessment methodologies have a long history of application. Marine systems:

- Are confined, isolated systems.
- Are self-reliant (rely on self-produced electricity, water, etc.).
- Have limited manpower and material resources.
- Have limited emergency response capabilities.

A general classification of the marine field systems may be as follows:

- Movable systems such as ships (of various sizes, propulsion, and cargo), tankers, barges, etc.
- Fixed systems such as offshore production facilities (drilling platforms, pipelines, etc.)

The movable systems such as ships have unique characteristics from a systems perspective in that the physical system is usually moving through all types of geographic areas and is exposed to a wide variety of natural phenomena and forces. In addition, there are many other features that make these systems unique from a risk assessment viewpoint. These include no time away from work for personnel on board and constant work shifts. These systems usually have very limited response capability in the event of an accident. Adding to these complexities, during their life cycles most ships transition through multiple owners, different crews with varying qualifications, varying standards of maintenance, and a variety of cargoes.

Movable marine systems are, of course, dynamic and must be modeled accordingly when considering a risk assessment. In many respects they are similar to space vehicles that encounter a variety of environments, stored energy conditions, and heavy dependence on crew and equipment in confined spaces. Experience with such systems suggests the phasing of mission operations into discrete sets that can be linked together to represent changes in system states and, therefore, be responsive to dynamic effects. The discrete sets or phases can usually be analyzed using established methods. A key in such modeling is the definition of the links that connect the discrete sets. The links take the form of inputs and outputs to each phase with the final output being the chosen measure of risk such as the likelihood of releases or health and environmental impacts or combinations. This approach, sometimes referred to as the scenario-based approach to risk assessment, is widely used in the space, chemical, and nuclear fields and should be applicable to movable marine systems. Simulation techniques are also a way to represent the dynamics of movable systems. Such techniques were employed in the Prince William Sound risk assessment project.

The fixed systems such as offshore platforms can be considered as industrial petroleum facilities located in water. The uniqueness of offshore platforms comes from a combination of factors. Offshore platforms may be floating or stationary systems subjected to extreme natural forces not encountered by land-based facilities. In the event of an accident there is the potential for a long response time with limited capability. However, for most cases, standard industrial process tools may be used for these systems. Use of such standard tools is acceptable as long as they account for the system's uniqueness – location in water, limited manpower and operating space, and the fact that prompt evacuation is not always possible.

3.2 CURRENT MARINE INDUSTRY PARADIGM FOR RISK ASSESSMENT

Highlighted below are some perceptions of the current marine industry paradigm. While these views are believed to be widely held, it is clear that not everyone within the marine industry subscribes to them.

- Marine regulators and the industry while increasing their use of risk assessment practices believe they have good safety practices. For example, most of the marine system platforms are not judged to be sufficiently complex to warrant QRA. Safety is important, but competitive forces make production a very high order of business. The approach to safety and risk management is through detailed regulation of design. Often these regulations derive from past accident experience.

- In contrast to the complicated requirement for safety cases in Europe, the Minerals Management Service, a United States' regulator, only asks for voluntary compliance with safety and environmental analyses/programs. A government supported safety program, known as facility assessment, maintenance, and enhancement (FAME), was not supported by industry members. The safety and environmental management program (SEMP) is a voluntary marine program in an industry that has no self-policing entity. Both FAME and

SEMP are highlighted in Appendix A. Since MMS resisted making SEMP a requirement, it is generally perceived that the industry and regulators believe that QRA is not needed. Under the voluntary SEMP program, safety cases or analyses are not approved but merely "accepted." While the Europeans are moving towards QRA (with respect to platform and human loss), there is less of a regulatory trend towards adopting QRA (except in structural reliability) in the United States.

- The United States marine industry is yet to be convinced of a general need for quantitative risk assessment, except for special circumstances. The special circumstances are case studies or responses to inquiries about accidents that have occurred. For the most part, they have confidence in their existing practices and procedures although the risk based decision making guidelines and the IMO guidelines suggest a possible new direction. The main benefits of QRA are additional insights on the prevention of accidents and the ability to recover from accidents should they occur. These insights take the form of a better understanding of how systems function under threatened and degraded conditions and how subsystems and components interact during such conditions. Risk assessment results have been beneficial to other industries in making good decisions about recovery from degraded conditions and minimizing accidents, should they occur. While the marine industry has developed sophisticated tools to predict platform and ship structural failure due to wave/current forces, it has not developed QRA tools for assessment of the safety and environmental aspects of the marine systems. Even the Prince William Sound probabilistic risk assessment (to be discussed later) limits its measure of risk to *oil in the water,* not environmental damage or threats to public health and safety.

- Safety/reliability data of marine systems is sparse and is not being rigorously collected. While some data exists such as the Offshore Reliability Data Handbook (Reference 17) which has excellent equipment reliability data, it mostly is only available to industry sponsors in real-time/electronic form since it is seen as a commercial advantage. While some in the marine industry recognize human factors as a critical aspect of safety (with some experts attributing 80% of accidents to human error), no quantitative data is available to support these claims. No data collection and processing system has been instituted for the explicit purpose of quantifying the risk of marine systems.

3.3 CURRENT MARITIME REGULATIONS

3.3.1 Shipping Regulations

Shipping is a heavily regulated industry. Within the United States, the United States Coast Guard traditionally regulates ship operations at the federal level. Federal regulations governing shipping generally can be found in Titles 33 and 46 of the Code of Federal Regulations and in Navigation and Vessel Inspection Circulars, which contain policy guidance on specific subjects issued by the USCG.

With the grounding of the *Exxon Valdez* in 1989, many of the coastal states established their own regimes for regulating tank vessels and, to a lesser extent, dry cargo and container ships. For example, on the West coast, California and Washington created new administrative offices to oversee regulation of the shipping industry and established extensive and stringent regulatory regimes. Alaska, which had previously regulated the shipping industry due to the history of the trans-Alaska pipeline trades, promulgated new and tougher standards. In California, the California Harbor Safety Committees developed methods to reduce navigational risk in California's major ports. The methods employed by the California Harbor Safety Committees are based on a combination of checklists and "what if" analyses.

On the East and Gulf coasts, states such as Texas, Florida, Maryland, Virginia, and Rhode Island promulgated regulations ranging from contingency planning and financial responsibility requirements to natural resource damage assessments and tug escorts. These myriad of state requirements overlap with the federal regulations and are often viewed as overly burdensome by the shipping industry, which prefers to be regulated at the federal level by the U.S. Coast Guard.

The shipping industry also is regulated by the International Maritime Organization which was established by the United Nations in 1948 to determine acceptable standards, develop international treaties relating to shipping, monitor the implementation of these treaties by governments, and keep governments up to date with advances in technology. The importance of the IMO has grown over the years, particularly as the modern shipping industry becomes increasingly globalized and regulators and industry representatives, alike, recognize the importance of providing for a level playing field through international regulation. The growing importance of IMO adds to the impact of their guidance and the use of risk assessment methods.

Regulation of the shipping industry traditionally has been governed by command and control regulation, especially the structural integrity of the vessel. Only recently, with the focus on human factors as a critical element in safe ship operations and a recognition that there are more effective and efficient methods of providing for safe operations in an industry which is international in scope, have government officials begun to consider alternative methods of regulating the industry. In addition, over the last decade industry has adopted an increased environmental consciousness and has recognized the need to work with government officials on new methods of reducing risk to human health, safety, and the environment.

Although there are requirements in specific laws or regulations for the Coast Guard to utilize cost/benefit analysis in promulgating specific regulations, there is no requirement for them to use any type of formalized risk assessment. Similarly, there is no current requirement for the IMO or the states to use such a methodology in determining whether or how to regulate. There are, however, a number of new initiatives which explore using risk assessment as a tool for more effectively regulating the shipping industry. Some of these initiatives are outlined below.

The International Maritime Organization has issued interim guidelines for the application of formal safety assessment to the IMO rule making process (Reference 11). The purpose of the guidelines is to facilitate trial applications of the formal safety assessment process. It is the intention of the IMO to keep the guidelines on an interim basis "as long as it is necessary to gain experience." It is proposed that FSA would be utilized to support the development of new regulations and in the review of existing ones. FSA is intended to promote the trend away from prescriptive regulations and towards regulations based on safety performance (Reference 18).

FSA is seen by the United Kingdom as comprising of five steps: the identification of hazards, the assessment of risks associated with those hazards, ways of managing the risks identified, cost-benefit assessment of the identified options, and decisions on which options to select. The United States supports the establishment of an FSA by the International Maritime Organization, and in a memorandum to the IMO Correspondence Group on FSA has presented a 6-step proposal to allow the maritime community to consider risk in an evolutionary rather than revolutionary manner (Reference 19).

The Coast Guard has developed a guide (Reference 9) which provides a structured format for gathering and analyzing information and the professional knowledge required to evaluate and manage risks in United States' ports and waterways and to support decisions affecting maritime safety in these waters (Reference 20). This guide is intended to assist the Captain of the Ports, under the Ports and Waterways Safety Act of 1972, and the U.S. Coast Guard Marine Safety Manual, to maintain an acceptable level of safety in the ports and waterways in its area of responsibility.

The Coast Guard established an initiative within the agency called the marine safety evaluation program (MSTEP). The purpose of this program, which has been terminated, was to improve the current process of assessing the safety of marine systems, subsystems, and components. While the MSTEP generated several important proof-of-concept studies on the use of risk assessment methods, it has been replaced with new initiatives placing more emphasis on people programs. In particular, the Coast Guard is developing their "prevention through people program" into a long-term program to refocus prevention efforts on human behavior (Reference 21).

3.3.2 Offshore Platform Regulations

The safety of offshore producing operations in the United States is regulated primarily by the coastal states to their limit of jurisdiction, and by the Minerals Management Service of the Department of the Interior in waters beyond state jurisdiction, which is designated the outer continental shelf (OCS). Other federal government agencies having specific regulatory responsibilities over offshore producing operations are as follows:

Federal Agency	Regulatory Responsibilities
U.S. Coast Guard	Life safety, including firefighting and evacuation from platforms, safety of mobile drilling units and mobile production units.
Army Corps of Engineers	Construction activity related to dredging, and platform and pipeline installation.
Environmental Protection Agency (EPA)	Air and water discharge and oil spills.
Department of Transportation (DOT)	Oil and gas pipelines which are not part of gathering systems regulated by the MMS.

While there may be exceptions, in general, state regulations are prescriptive, minimal, and focused on environmental protection and safety of well design. There are no requirements for safety case development or for the use of risk analysis.

Through the use of an interagency memoranda of understanding with the United States Coast Guard, the MMS has primary responsibility for establishing regulations and assuring compliance for design, construction, and operations in federal waters as it applies to the drilling and operation of wells, and the design, construction, and operation of fixed platforms, production facilities, and most pipelines. The current rules are of a command and control nature and do not specifically require the development of a safety case or the use of risk assessment.

The structural design, construction, installation, and integrity monitoring of fixed structures as prescribed in the Code of Federal Regulations (30 CFR 250) is based on American Petroleum Institute Recommended Practice 2A, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design." Inspection details and frequencies are mandated, as are rules for requalification due to inspection results.

Drilling and producing operations are required to meet certain prescribed safety standards detailed in 30 CFR 250, which are based for the most part on API Specifications and Recommended Practices. All production processes must be analyzed in accordance with API RP 14C, "Recommended Practice for Analysis, Design, Installation, and Testing of Basic Surface Safety Systems for Offshore Production Platforms," to determine that sufficient shutdown and other safety devices have been installed to detect and automatically respond (with specified minimum redundancies) to measurable process upsets (level, pressure, and temperature). Process equipment, piping, safety devices, and electrical components must be specified and manufactured in accordance with specified API, American Society of Mechanical Engineers (ASME), and NEC requirements. Minimum training requirements are also specified in 30 CFR 250.

Although not mandated by regulation, the MMS (with support from API, the Offshore Operators Committee, the National Ocean Industries Association, the Independent Producers of America Association, and the International Association of Drilling Contractors), is encouraging operators to implement a safety and environmental management program. This is based on API RP 75, "Recommended Practices for Development of a Safety and Environmental Management Program for Outer Continental Shelf Operations and Facilities."

4. RISK ASSESSMENT METHODS FOR MARINE SYSTEMS

One of the major events contributing to the consideration, use, and acceptability of risk assessment methodologies on marine systems, especially offshore systems, was the Piper Alpha accident of July 6, 1988. The safety case regulations in the United Kingdom, implemented as a result of the Piper Alpha accident, have resulted in safer offshore platform operations. The safety case approach has demonstrated the value of assessing mechanical, structural, procedural, and organizational features of a marine system as interrelated components that all affect risk. The safety case approach was effective in relating specific equipment failures, such as gas compressor leaks, to overall system performance.

Following the Piper Alpha accident, considerable work was done in the application of current risk assessment tools towards improving the design and operation of multipurpose platforms. Work was also undertaken to develop new tools to assist in real-time risk management. One example is the dynamic risk management systems (DRMS) architecture designed for the real-time risk management of critical engineering facilities (Reference 22). These systems are hybrid in that they combine the powers of probabilistic risk assessment and artificial intelligence. They are dynamic in that the risk assessment is performed for a given time window, accounting for the evolution of the physical system, its modes of operation, anticipated external loads, and the changes in the set of available options.

The offshore industry has started to explore the application of risk assessments to a greater extent than just safety case regimes. Offshore operators can now use a comparative risk assessment tool to assist in making decisions over the selection of a platform from the wide variety of alternative production systems including those based on fixed platforms, tension leg platforms (TLPs), compliant towers, floating production systems, and remote subsea systems. Eighteen sponsoring organizations have assisted in the development of this comparative risk assessment methodology, known as methodologies for comparison of alternative production systems (MCAPS). MCAPS is an engineering procedure (see Appendix A for a brief description) that can assist the process of making rational comparisons among design alternatives for offshore drilling and production systems. Currently, such comparisons are often made on the basis of initial cost estimates without explicit consideration of risks and related life cycle costs that can be several times the initial costs. MCAPS makes use of recent developments in structural system reliability and the risk sciences. The important effects of human and organization errors (HOE) in design, construction, and operations of marine systems are integrated into the MCAPS process in an implicit manner. If data are not available, risk analysis tools such as MCAPS provides insights on the behavior of the system by allowing expert elicitation from engineers and others on expected performance in a systematic and orderly way.

Just as the Piper Alpha accident stimulated greater interest in more detailed risk assessments of offshore facilities, so did the Exxon Valdez grounding in Prince William Sound do the same for oceangoing vessels. Government agencies have primarily been reactive in the implementation of regulations designed to prevent or minimize risks. With respect to the maritime industry, some of their regulations have resulted in conventions such as the safety of life at sea (SOLAS) rules or the requirements for double bottom hulls on oil tankers. Unfortunately, these regulations were developed as the result of an accident, which is hopefully prevented by implementation of the new requirements. The regulations did not arise from an analysis of ship systems, an analysis which was performed to identify problems and solutions before they occur. The reactive approach does not prevent or minimize the consequences of the accident to which the regulatory effort is responding, but it does offer the potential for preventing future incidents. Prevention of accidents that have not occurred can result from successful use of risk assessment tools. Fortunately, this reactive posture to risk management is changing.

The Office of Marine Safety in the state of Washington uses a mix of data from various sources, including Lloyds Register of Ships; Lloyds SEADATA; U.S. Coast Guard casualty and violations histories; agents, owners, operators, and various publications such as trade journals; and expert opinion, all to support the screening program implemented in 1991 to reduce the risk of marine oil pollution events in Washington state. A risk matrix was developed using available data and expert opinion, which establishes a vessel boarding priority. The highest priority is assigned to vessels, which, based on the Office of Marine Safety's semiquantitative risk assessment, are believed to present the greatest oil pollution risk. In California, the California Harbor Safety Committees developed methods to reduce navigational risk in California's major ports. The methods employed by the California Harbor Safety Committees are based on a combination of "checklists" and "what if" analyses.

As indicated earlier, the U.S. Coast Guard undertook an effort called the marine safety evaluation program to improve the current process of assessing the safety of marine systems, subsystems, and components that fall within its domain of regulatory control. Major drivers of MSTEP were to upgrade ship safety assessment practices and to provide a basis for better connecting UCSG regulations to safety assessment methods. An important consideration in the program was the role of contemporary risk assessment methods in the improvement process.

MSTEP involved attending courses on risk assessment methods, the development of discussion and position papers on the use of such methods, and some preliminary applications to real issues and systems. For example, among the applications were the evaluations of cargo electrical lighting systems on RO/RO ships and electric power generation options for a specific class of ships. The cargo lighting project was targeting the applicability of the current regulations in relation to a risk based approach. The power generation study, on the other hand, was more of a demonstration of how the risk thought process can aid decision making in the design process by comparing different alternatives and their effect on risk and reliability.

Both the USCG and the state of Washington are taking a progressive approach to risk management and are attempting to explicitly use risk assessment in the regulatory process. International safety bodies are also attempting to use risk assessment in their regulations. Care must be taken to closely examine the risk assessment basis of a proposed "risk based" regulation. The IMO has adopted a Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Wastes in Flasks On Board Ships (INF Code). Potential accidents involving these cargoes carry risks of great public interest. The code contains increased requirements for firefighting equipment, stability, etc., and is based upon various quantities of radioactive material being carried. However, even though the regulation would appear to be risk based, there is no underlying risk assessment to support the regulation. The risk mitigation measures required by the regulation cannot be demonstrated by risk assessment techniques to have any measurable impact. Because a vessel has a sprinkler system that may provide some water over a container of radioactive material in a fire, the vessel may be classed as a type of vessel superior to another vessel that may have many other features such as a better crew, a newer and more seaworthy ship, and a better shipboard firefighting system. The appearance of sophistication in the IMO code leads one to believe that the requirements are risk based when in fact they are not.

The most explicit evidence of the consideration of risk assessment methods in shipping operations is the Prince William Sound risk assessment project (Reference 10). This risk assessment was performed by a team from Rensselaer Polytechnic Institute, George Washington University, and a Norwegian classification society, Det Norske Veritas (DNV). A combination of shippers, local groups, and the U.S. Coast Guard sponsored the study. A review of the study was performed by the National Research Council (Reference 23).

The stated objectives of the study were to: 1) identify, evaluate, and rank the risks of oil transportation in Prince William Sound; 2) identify, evaluate, and rank proposed risk reduction measures; and 3) develop risk management tools. The principal measure of risk in the study was the likelihood of a major oil spill in the Prince William Sound. Environmental and public risk was not quantified. The scope of the study involved the following:

- Geographic area: Valdez marine terminal to 20 miles outside of Hinchinbrook.
- Type of incidents: All tanker related underway events that could result in spills of oil cargo.
- Vessel specific factors: Human error, mechanical failure, technical and operational aspects of the trans-Alaska pipeline system fleet, operating company management.
- Environment specific factors: Marine traffic, weather and ice conditions, location.
- Regulatory factors: Traffic management, escort requirements.

The PWSRA methodology involved the combination of fault tree and event tree techniques with the marine accident risk calculation system (MARCS) and a dynamic simulation model. MARCS and the fault/event tree techniques were developed by DNV while the simulation model was developed by a team from George Washington University.

The results of the PWSRA did include calculations of the frequency of accidents and the average oil outflow per year. For example, for inbound tankers the calculated accident frequency led to a potential average oil outflow of 30 tons/year. A similar estimate was made as a result of considering outbound accidents. Perhaps the most important results of the study had to do with risk reduction measures. At the summary level, the study concluded that the most effective measure for reducing accidents is revising traffic rules and the most effective measure for reducing oil outflow is improving human and organizational performance.

The principal conclusions of the PWSRA are:

- Current safeguards in the Prince William Sound oil transportation system have effectively and substantially reduced risk.
- The most effective risk reduction measure to date has been the current escort system, which effectively reduces potential oil outflows due to groundings.
- Accident scenarios with the greatest potential for additional risk reduction include groundings and collisions of various types and specific locations.
- A significant increase in the risk of collision and powered grounding in the Arm exists when ice is present in the traffic lanes during transits.

While containing many shortcomings, the PWSRA is an important step forward in the application of quantitative risk assessment to marine systems. The attempts made by the study team to involve stakeholders are to be applauded. As a pioneering effort, it is to be expected that shortcomings will exist. As for specific shortcomings in the study, the reader is referred to the review by the National Research Council (Reference 23). From a methods standpoint, the primary weakness is judged to be the somewhat awkward three-part methodology. The combination of the three methods lacks a logical coupling process. In particular, the study does not have an overarching risk assessment framework, such as depicted in Appendix B. Such a general framework would greatly facilitate its technical clarity.

4.1 MARINE MEASURES OF RISK

An important consideration in risk assessment is the choosing of a measure of risk. For example, the Prince William Sound risk assessment used "oil in the water" as the risk measure. As indicated earlier, *oil in the water* is a very limited measure of risk as it does not directly address environmental impacts or public health and safety. Obviously, the probability of the spill and its impact on flora and fauna would be a more complete measure of risk. A more comprehensive approach would be to use the triplet definition of risk (see Appendix B) in reference to several risk measures to get a much more complete picture of risk.

At the present time the marine industry measures "risk" with consequence levels or impact levels as follows:

Major Measures of Risk	Minor Measures of Risk
Loss of Vessel or Platform	Reparable Damage to Vessel or Platform
Loss of Life	Personnel Injury
Loss of Cargo	Delay of Schedule
Major Pollution	Minor Pollution

While the above measures of risk are the immediate and direct impacts, it should be noted that secondary impacts could be just as important. For example, the impacts of pollution can go beyond the immediate number of dead fish and birds. Loss of income as a result of depleted or contaminated fishing grounds can lead to job losses, meaning less revenues for local governments, potential bankruptcies of industries, etc.

4.2 MARINE DATA NEEDS

As marine systems become more unique, there is generally less data on a system's past performance. While historical data on the operation of the drilling equipment may be available, little data is available for new multipurpose offshore platforms, which combine exploration, drilling, production, and processing functions. For example, data is sparse on common cause failures and interdependencies between systems on offshore platforms. This is primarily because of the unique application of systems to platform operations.

This lack of sufficiently detailed knowledge of offshore systems and their expected performance characteristics, the lack of accurate probability data of initiating events, and the large uncertainties associated with determining consequences have been considered obstacles to the rigorous application of QRA to offshore marine systems (Reference 24). The Minerals Management Service maintains a database that has also been recognized as lacking in meaningful data required for performing rigorous QRAs (Reference 25).

Experience indicates that the best way to get a handle on the data issue as it relates to QRA is to simply do a few QRAs and use the results to guide the most efficient approach to data collection and processing. For example, in the nuclear power industry the best databases have evolved from the various risk assessments that have been performed. Most existing data collection and processing systems, including those in the marine field, have their roots in such areas as maintenance, hardware reliability, incidents, etc. Risk assessment data requirements are usually quite different. Much of the difference has to do with a greater need for human response data and data on events that are precursors to high consequence events. The differences are most easily exposed through the actual performance of risk assessments that expose parameter and modeling uncertainties. The uncertainties clearly point in the direction of data and information needs. The efficiencies of this approach have been demonstrated many times, and it is believed that QRA would be more accepted in the marine industry if the same approach were followed. It is expected that the quickened pace of risk assessment activity in the marine field is already demonstrating this and will eventually break down the remaining barriers to accepting QRA as a value added discipline for improving the decision making process associated with risk management.

This lack of data for the offshore industry is interesting since the industry has a long operating record and there is high value associated with the assets involved. The perceived low likelihood of occurrence of events important to a quantitative risk assessment may be one of the reasons for not collecting some event data. The scarcity of data is also a result of a lack of visible return on the data collection investment, or proprietary control over the information to maintain competitive advantages. So, while ship operators are seeking advantages through improved vessel safety, reliability, and life cycle cost effectiveness in the face of ever-increasing global competition, they are at the same time faced with a lack of available performance data, especially with respect to the newer marine systems and ships.

It is believed that much more data exists than is used. One important recommendation to be made in the Summary and Conclusions of this review is for the marine industry to establish stronger ties with other agencies active in the use of quantitative risk assessment methods. For example, the U.S. Nuclear Regulatory Commission has for years been assessing United States and foreign operational data and reliability information for historical trends and patterns. They have tapped numerous databases for information that can directly support the risk assessment of systems that in many cases have hardware and human response requirements similar to marine systems.

It is important to note that the absence of systems performance data is not a valid reason for failing to do a risk assessment of a complex system. On the contrary, it can even be argued that the less data there is on a system the more important it is to do a risk assessment, given the desire to know what the risks are. In the case of essentially an infinite amount of data, a risk assessment is unnecessary as the experience base indicates exactly what the risk is. That is, the *need* for a risk assessment is inversely proportional to the experience base. The reason a risk assessment in the absence of high quality data is valuable is because most of the effort is in modeling the logic of the system, something that does not require performance data and is critically important in understanding how the system works. Understanding from a risk perspective how the system actually works is, in itself, important in being able to envision *what can go wrong* with the system, perhaps the most important part of a risk assessment. Of course, the availability of performance data is a major advantage as it reduces the uncertainties in the risk results. It also allows for better replication and verification of the risk assessment.

5. CHANGES IN METHODS AND PRACTICES THAT WOULD ENHANCE THE RISK ASSESSMENT OF MARINE SYSTEMS

In order to realize the greatest benefits of applying risk assessment methods to a particular industry or field, it is necessary to tailor the methods to the special requirements and characteristics of that industry. As has already been discussed, marine systems, their operation, and their response capability to accidents are generally much more constrained than similar shore based systems. There is a long history, tradition, and philosophy of doing business that leads to the industry being very cautious about change, unless the value added is clearly understood. It is probably this extensive experience base that makes many mariners not feel the need for sophisticated analyses to improve safety and performance. It may also be the explanation of why the marine field lags several other similar industries in the depth and breadth of its risk assessment activity. Meanwhile, there are signs of change as signaled by the Prince William Sound risk assessment project, the safety case work, and new guidance from such sources as the IMO and the U.S. Coast Guard.

The question is: "What changes in methods and practices would enhance the risk assessment of marine systems?" By enhanced, is meant methods that would lead to improved safety through improved decision making. A thorough response to this question would require a major review of the work that has been performed in the marine field. This review has only skimmed the surface of the safety assessment practices and methods, but enough to identify some activities that could bring greater clarity and credibility to the understanding and quantification of the risks associated with marine operations. It is possible that the activities noted below are already underway and that real change is not necessary. The issue then is simply a matter of timing and implementation. In particular, the following proposed changes are discussed:

- Adoption of a general framework or theory of risk assessment.
- Performing risk assessments of highest return.
- Adoption of a phased approach to risk assessment projects.
- Appropriate use of marine data.
- Improved treatment of external events.
- Improved treatment of human reliability.

5.1 A GENERAL FRAMEWORK OF RISK ASSESSMENT

The marine industry is very much in transition in its use of risk assessment methods, particularly quantitative risk assessment methods. And while there is a trend towards greater use of more formal risk assessment methods to assess safety and other performance measures, there does not appear to be an obvious and emerging framework for risk based assessments that is universally accepted. To illustrate what is meant by a general framework, or general theory of risk assessment, Appendix B has been included. In particular, Appendix B presents a general theory of quantitative risk assessment that is currently in practice on many engineered and natural systems. It is general enough to embrace essentially any specific risk assessment, but specific enough to provide clarity on the definition of risk terms and the language of the risk discipline.

The idea of a general theory is to have a basic structure of an approach to risk assessment. It provides a measure of the scope and meaning of any system-specific risk assessment in terms of its relationship to the general theory. Iterations can be made between the specific risk assessments and the general theory to improve both.

Should the idea of a general theory of the scope of Appendix B not be appealing, then it may be constructive for some body such as the Coast Guard or the IMO to agree on a set of guiding principles for conducting formal risk assessments. Of course, the principles should accommodate both qualitative and quantitative risk assessments. The IMO's guidelines for formal safety assessment and the Coast Guard's guidelines for risk-based decision making represent reasonable takeoff points. What is missing in the latter two guidance documents are specifics in the risk assessment process.

5.2 RISK ASSESSMENTS OF HIGHEST RETURN

Essential to the acceptance of the risk assessment discipline in the marine field is a clear indication that its application adds value to the marine business. The value received from application of the risk assessment thought process, of course, is dependent on the goals and objectives of the assessment. That is why a clear objective or set of objectives is key to the success of performing any risk assessment, limited scope or full scope, qualitative or quantitative.

Risk assessments can have one or several objectives. Most often the objectives are associated with issues of safety, which is the emphasis of this paper. But the same principles (see Appendix B) can be applied to financial risks, production risks, environmental risks, regulatory risks, or whatever. It all depends on the objectives of the assessment and an appropriate selection of risk measures (scenario end states) to meet those objectives.

In some circles within the marine field there have developed stigmas about risk assessment, especially quantitative risk assessment, that have interfered with its acceptance. Such stigmas are that risk assessment is something only for statisticians; it is only something you do when there is a disaster such as Piper Alpha or Exxon Valdez; it is a result of a regulatory requirement, or it is merely a research project. That is, it has little to do with reality. Clearly, the need exists to not only identify applications where it is obvious that there is value added, but also to overcome some of the associated stigmas in order to see the opportunities that may exist. This is often referred to as a need for a cultural change. First, there must be the recognition that risk assessment is founded on the desire to become explicit about assessing *what can go wrong* with a system. This is an engineering question, not a statistical question. It is the building block for answering the other risk questions of *likelihood* and *consequence*. Statistics enter into the process only to the extent of reducing information uncertainties, but do not have much to do with the hard work of risk assessment, of structuring the *what can go wrong* scenarios. Second, there must be clarity on the results you wish to achieve and that those results do, indeed, represent real value added.

Having observed that risk assessments of highest return depend on applying the principles of good project planning, there are candidate areas of expected high return. One would be to use risk assessment to improve safety in those operations of marine systems where the safety record is considered poor or at high risk. An example might be high traffic density ports, harbors and waterways that involve simultaneous passenger ships and cargoes of hazardous materials. Some harbors have better safety records than others. Studying the ones with the worst safety records or the highest perceived risks would seem to be good candidates.

Another candidate area of high return would be in the design and building of new first-of-a-kind vessels and platforms. The performance of risk assessment concurrent with the design effort has the potential for very high payoff. This application also removes the stigma that risk assessments can only be done on existing or already operating systems where there is a large amount of data. On the contrary, a risk assessment of an evolving design is probably the highest payoff application that exists in terms of both safety and economics. This phase of risk assessment is extremely creative in that methods are necessary that apply to the case of limited data. The risk assessment becomes an inherent part of the design process and has the advantage of influencing design changes on paper rather than requiring expensive modifications of hardware and structures.

The above candidate areas are only based on a cursory review of the marine safety literature. Information exists to do a thorough review of global marine operations and safety assessments to develop a list of risk assessment projects of highest return. The results of such reviews would provide the best possible foundation for trial or "pilot applications" of risk based formal safety assessments.

5.3 PHASED APPROACH TO RISK ASSESSMENT

Experience in the quantitative risk assessment of complex systems, such as nuclear power plants, has verified the value of a phased approach. The idea is borrowed from the field of mathematics and the method of successive approximations. It involves doing a quick first-pass analysis to obtain, in this case, a zero or first order approximation of the risks associated with the system under investigation. While the uncertainties in the results of such analyses are usually great, more often than not there are very valuable lessons learned. For one thing, the scope and need for additional analyses become much more transparent. Perhaps one of the biggest advantages of a phased approach is the definition it provides for data requirements. Many risk assessment projects have failed because of the costly exercise of developing a generic data collection and processing system before the specific data requirements are really understood. An understanding of data requirements can only come from understanding the risk assessment to be performed. While it is not the purpose of this paper to offer specific methods of analysis, it is possible to observe some broad guidelines on the elements of a phased approach. As Appendix B discusses, much of a risk assessment may be viewed as a structured set of scenarios that lead to the end states or risk measures of interest and answers the basic question of *what can go wrong*. Besides the end states that form the termination points of the scenarios, there are the initiating events that trigger the scenarios. A first phase might use a small set of initiating events that tend to capture a much larger set if the results suggest that such decomposition of initiating events is necessary. A smaller set of initiating events means a much smaller set of scenarios. This process of building a risk model from the top down is a very efficient way of controlling the analysis. Of course, if the uncertainties are too great to achieve the desired goals of the analysis, then a second or third pass may be necessary to reach the desired level of detail and certainty in the results. The level of detail in the analysis may not only be driven by the desire to reduce the uncertainties, but also by the desire to expose the contributors to risk at an increasingly detailed level (hardware, human response, external events).

It should be noted that while the structuring of the risk model may be a top down process, the actual quantification will be from the bottom up, that is, from the level at which there exists information and knowledge up to the level of the scenario model where the results can be propagated to the risk measures.

It is observed that in one sense the marine field has adopted a phased approach, but not quite in the context of that just discussed. What has just been discussed is the application in *phases of a theory of quantitative risk assessment.* What the marine field is doing has more to do with *phasing in risk assessment methods* into the overall safety assessment process, which, of course is also the reasonable thing to do.

5.4 APPROPRIATE USE OF MARINE DATA

The data requirements for a risk assessment, especially a full scope risk assessment, generally extend well beyond the data requirements for traditional hardware reliability analysis. This is because a risk assessment is generally of a much broader scope than just hardware performance. Risk assessments usually consider in addition to hardware data, human response and the impact of such external phenomena as severe storms, fires, flooding, aircraft impacts, and earthquakes. The result is that most traditional data systems are severely lacking in the kind of information to support risk assessments. The founding of a data collection and processing system on the basis of risk assessment requirements would be an enormous enhancement to risk assessment practices in the marine field.

As indicated earlier, the absence of data is not an excuse for failing to take advantage of what can be learned from a risk assessment. There are systems, such as first of a kind, for which there are no accident data at the total system level. Suppose we are asked to perform a risk assessment of a new type of large deep draft vessel carrying hazardous materials. Further, suppose that it is desired to adopt as a measure of risk the likelihood of grounding the vessel in restricted waters. At first glance it appears that we have nothing to go on. A serious study of the vessel most likely would reveal that although it may be a first of a kind, it is made up of systems for which there is considerable experience. Also other deep draft vessels do exist and their experience, especially with respect to movement in restricted waters and hostile environments, may be very applicable. The point is that there is always something to go on. The key is the adoption of methods that properly characterize the uncertainties involved. It then becomes a matter of correctly propagating that uncertainty to the desired risk measure. A general theory points the way on how to do this.

In summary, there are two issues with respect to data and the enhancement of marine risk assessment methods. The first has to do with designing a data management system that has as its goal to support contemporary risk assessments. The second has to do with adopting an approach to risk assessment that accommodates conditions of little or no data. The key properties of such an approach are methods for quantifying the uncertainties involved and directly communicating those uncertainties in the risk measures and the contributors to the risk measures.

5.5 TREATMENT OF EXTERNAL EVENTS

By the very nature of the marine field, marine systems are routinely exposed to the extreme forces of nature and external factors. In this regard, the domain of "external events" (storms, earthquakes, collisions) is extremely important for marine systems. When combined with marine system characteristics of confined, isolated systems for which no quick emergency response assets are typically available, it becomes extremely critical that "external events" scenarios be addressed explicitly and quantitatively.

At present it is not evident that the risk assessments performed in the marine industry fully incorporate the threat of such external events. And while collisions/allisions are being addressed by the shipping industry, it is less evident that other external events are receiving a similar amount of attention. Most of the new offshore platform risk assessments do include tidal wave interaction, etc., during the design phase. Again, the scope seems to be limited and hurricanes, storms, collisions, etc., do not appear to be addressed with the same rigor.

It is critical that external events be included in the quantification of marine system risks. Examples of external event methods and models from the nuclear industry risk assessments would serve as a reasonable starting point of methods to consider.

5.6 TREATMENT OF HUMAN RESPONSE

As has already been noted, marine systems and especially offshore platforms and ships, are unusual in their dependence on human response. Not only do they involve round the clock work conditions, but ship and platform crews are most often isolated with minimum access to additional human resources. The management of the human resources is further complicated by crews of widely diverse nationalities and qualifications, and a nonstandard enforcement of safety rules and qualification requirements. The marine industry is sensitive to the role of human response in the safety of marine systems. In fact, the often heard conclusion is that 80% of the marine accidents are the result of human actions (Reference 26).

A closer look at the 80% conclusion suggests that it may be an oversimplification of the problem. For example, a Norwegian classification society, Det Norske Veritas, while believing that up to 95% of human errors associated with marine accidents are caused by lack of knowledge, skill, instruction, or motivation, does not see human error as the real cause of accidents. They believe the high rate of human errors is a symptom of failures in the management system (Reference 27). Furthermore, much can be done through design to reduce the occurrence frequency and impact of human errors. The point is that to just observe that most accidents result from human errors is a gross oversimplification of the opportunities for corrective actions. It is a matter of distinguishing between symptoms and underlying causes. Risk assessment has been a powerful tool for quantifying contributors to risk in such a way as to greatly reduce human errors through better management, procedures, and system design. In this respect the Coast Guard's prevention through people program would appear to be on the right track, but other considerations are also important to reducing human errors.

In spite of the softness of the conclusions about the impact of human errors, it is clear that it is an important player in the risk of marine accidents. The opportunities for enhancing the risk assessments of marine systems in the human response area are extremely great as there is little evidence of modeling human response in past marine risk assessments or accident analyses. This is observed at the same time that major advances are being made in other industries in the treatment of human response in their risk assessments. Industries most active in human response analysis as a part of risk assessment are nuclear power, aerospace, and defense. It appears that the strategy of the marine field is not so much one of incorporating new methods that address people and organizational impacts into the risk models, but rather one of generically addressing human behavior through the prevention through people program at a fundamental level. Certainly, both should be done.

5.7 ADDITIONAL MARINE RISK ASSESSMENT ISSUES

Despite our belief that a properly planned and implemented risk assessment program is necessary to perform the most meaningful risk management practices, there are some notes of caution. Just like navigation and collision protection systems, the availability of a risk assessment while an important aid in itself is not something that can be used with blind faith. For example, marine experts often observe that collision avoidance systems have contributed to a false sense of safety resulting in poor risk management decisions. In particular, the temptation is to use the collision avoidance systems to mitigate the risk of collision while allowing the ship to proceed at excessive speeds through restricted visibility (contrary to training and rules of the road).

The improper use of a risk assessment could also increase the risk, not decrease it as it is intended to do. For example, because a particular activity or piece of equipment is not cited by the risk assessment as an important risk contributor, it may not receive the operational and maintenance treatment attributed to it in the risk assessment. It may suffer from a tradeoff of resources with more important systems according to the risk assessment. The result could be that the system could, indeed, become an important contributor to risk. What this suggests is that just doing a risk assessment is not enough. It must be understood, its limitations and its bases. The risk assessment must be an important part of the crew training, emphasizing that while navigation systems, collision avoidance systems, and risk assessments are valuable tools for risk management, they all have their limitations. In the final analysis the crew must avoid accidents; systems and analyses are only aids for making good operating and accident management decisions, but should never be the sole basis for such decisions.

Finally, risk assessments should always be performed with the user in mind. The user is most often the operations and maintenance personnel on the platform or the ship. If not the risk assessment itself, a version of the risk assessment should be prepared that is understandable and transparent to the people in the best position to assure safety, the operations and maintenance personnel. For the case of being in the design and construction phase, then the user includes the designer and builder as well.

6. SUMMARY AND CONCLUSIONS

A brief examination was made of risk assessment methods in relation to the safety performance of marine systems. Risk assessment, while meaning different things to different people and different institutions, is rapidly becoming a major input into societal decision making. Decisions having to do with the acceptance of technological systems, food safety, legislation, social systems, and environmental impacts are increasingly turning to risk assessment for illumination and quantification of the issues involved. As with all new disciplines, there are serious language problems with the field in the definition of terms and concepts, but there are signs of maturation. The risk field seems to have settled down into three broad areas of activity: risk assessment, risk communication, and risk management. This review principally addresses risk assessment. In fact, the emphasis of the review is on the application of quantitative risk assessment. Appendix B is offered as an illustration of what is meant by quantitative risk assessment. The review does acknowledge the role of qualitative risk assessments, but with the bias that the biggest rewards come from moving in the direction of quantification of the risks.

The questions that have guided this review are the following:

- What is the general status of quantitative risk assessment?
- What are some of the unusual characteristics of the marine field?
- What risk assessments have been applied to marine systems?
- What lessons have been learned from the limited risk assessments of marine systems?
- What enhancements to risk assessment methods would facilitate their application to marine systems?

6.1 STATUS OF QUANTITATIVE RISK ASSESSMENT

The greatest advances in quantitative risk assessment are still being made in the nuclear industry, and it now appears to be firmly embedded into their safety culture. No other industry has advanced as far. Several industries, including marine, can point to specific quantitative risk assessment projects and make some claims about embracing the discipline. The Prince William Sound risk assessment project is an example in the marine industry, and the probabilistic risk assessment of the space shuttle is an example in the space field. There are numerous, somewhat isolated applications in such other fields as defense, chemical, transportation, etc. The bottom line is that QRA as an inherent and pervasive part of the safety culture does not yet exist except in the nuclear power and nuclear waste fields where quantitative risk assessment policies and regulations are in place.

In general, the marine field lags other major industries in the development, application, and use of risk assessment methods, although there are signs of change. The other industries, in addition to nuclear, include chemical, space, and defense. There are even differences among the marine systems groups. The offshore designers and operators show evidence of being more aggressive in adopting more formal risk assessment methods although lacking in quantitative methods. They appear to be ahead of the transportation field in terms of the scope of their analyses, i.e., in terms of the risk measures being considered. Examples are the analysis of actual facility damage, external events, cost benefits, and the use of formal decision analysis. The emphasis with ships continues to be primarily on releases (e.g., oil in the water), although their analyses in this limited context are as thorough, if not more so, than those performed for offshore systems.

Taking a broader view, risk assessment as opposed to quantitative risk assessment, results in a slightly improved picture, especially in the marine field. The formal safety assessment methodology advocates elements of a risk based approach, but is not specific in its implementation. Norway requires risk assessments in petroleum activities, but does not prescribe or provide guidance on specific methods. Australia requires a formal safety assessment of selected marine systems, but allows the flexibility of nonquantitative approaches. The United States currently has no requirement for the use of risk analysis on marine systems, but is in transition relative to safety assessment requirements. A key factor in the future direction of the United States marine industry in the use of the risk sciences is what the regulatory organizations decide to do, including the coastal states, the Marine Management Service, and the U.S. Coast Guard. The publication by the Coast Guard of a manual on Risk Based Decision-Making and G-M Business Plan Goals in 1997 (Reference 9) indicates their interest in the development of "risk management tools."

Recommendation

The marine industry should continue their programs of increased guidance on the use of risk assessment and the implementation of such activities as the prevention through people program. The context offered by the Coast Guard of "improving the decision-making process" is appropriate and on target. It is recommended that a deliberate effort be made to take advantage of the experience of industries with more mature risk assessment programs to assure the best possible future direction of the marine program. It is further recommended that the guidance coming from such organizations as the International Maritime Organization and the U.S Coast Guard include more specific reference to quantitative methods for selective applications.

6.2 MARINE SYSTEM CHARACTERISTICS

Marine systems have some characteristics that are shared with other industries. For example, the nuclear and marine industries both depend heavily on complex systems of large rotating equipment, electric power systems, control systems, heating and cooling systems, accident mitigating systems, and centralized control rooms. Chemical plants share some of the same systems. The nuclear and chemical risk assessment experience of analyzing these systems, their interaction with each other as well as humans, provides an important resource of both risk assessment methods and data.

There are characteristics of marine systems that do set them apart from most other engineered systems. Except for shore facilities, they are confined and isolated. They must rely on self-produced electricity, water, and propulsion (except for platforms). They are limited in human and material resources. And most importantly, they are limited in accident recovery and emergency response capability.

Considering that human factors and organizational matters have been identified as major contributors to risk in the marine field (see the Prince William Sound risk study, Reference 10), here too are some major challenges. Marine systems, and especially ships and offshore platforms, are unusual in their dependence on human response. Working conditions tend to be round the clock, and crews are most often isolated with minimum access to supplementary human resources, especially under abnormal or accident conditions. The management of human resources is further complicated by crews of widely diverse nationalities and qualifications and a nonstandard enforcement of safety rules and qualification requirements.

There too is the diversity of marine systems and the dynamics of their environment. The diversity includes ships of various sizes and classes with both hazardous and nonhazardous cargoes, onshore and offshore production facilities, drilling operations, refineries in some cases, pipelines, terminals, docks, tankers, barges, and all the interfacing systems. Ships are getting larger and carrying less crew. Oil exploration, drilling, and recovery operations are moving further offshore into deeper waters subject to more violent forces of nature. Floating production systems are being introduced into the mix of marine systems and will involve the combining of the analysis of stationary and dynamic systems. The dynamics of the environment of marine systems is evident by their routine exposure to the extreme forces of nature and external factors. Being subject to such threats as collisions and allisions is also an important consideration in the risk assessment of marine systems.

Other characteristics of the marine field that impact the use of risk assessment methods are industry attitudes and the regulatory environment. To the outsider, there is the impression that while safety and competitiveness are essential elements of their business, both the marine industry and their regulators believe they operate within an adequate safety environment. They believe their large experience base makes them less dependent on exotic analyses to find answers to questions concerning risk and other performance measures. In particular, many within the industry do not see the need for quantitative risk assessment. They do see the need for sophisticated analyses in such specialty areas as platform failure due to ocean forces and vessel structural integrity design.

With respect to the regulatory characteristics of the marine industry, there is considerable regulation of both shipping and offshore production operations. Shipping is heavily regulated. The principal regulators are the U.S. Coast Guard at the federal level with increasing oversight and involvement of the coastal states. The shipping industry also is regulated by the International Maritime Organization. Offshore operations in the United States are regulated primarily by the coastal states and the Minerals Management Service. While the regulatory activity in both offshore and transportation operations is extensive, there is very little activity underway to implement a risk based regulatory practice for marine systems.

Recommendation

Marine system characteristics require special consideration in performing system-specific risk assessments. Methods applicable to both movable and stationary systems must be appropriately combined to adequately represent their risk. The movable component can be likened to the types of problems found in chemical process (process flow), space systems, and defense systems risk. The stationary component can be likened to nuclear power plant and chemical plant risk. While there are differences in the systems, the marine systems do have much in common with power and chemical systems, especially with respect to hardware and human performance. Also, the extensive experience in the nuclear field of quantifying the impact of external events (severe storms, earthquakes, floods, fires, etc.) provides an information base for modeling hostile environments of offshore and marine transportation systems. It is recommended that exchange programs be initiated with these industries to make maximum gains in the quality and maturity of risk assessment applications to marine systems. If it has not been done, one contact that could benefit the marine field in both methods and data is the Reliability and Risk Assessment Branch of the U.S. Nuclear Regulatory Commission's Office for Analysis and Evaluation of Operational Data.

6.3 APPLICATION OF RISK ASSESSMENTS

With respect to the actual application of risk assessment tools to marine systems, the greatest amount of activity has been in the safety analysis of offshore platforms. The one exception in the shipping area is the Prince William Sound risk assessment. Other applications in the transportation field are noted in this review, but they are generally of much smaller scope. The safety case regulations in the United Kingdom have resulted in more systems engineering based analyses of platforms and platform operations. These analyses have demonstrated the value of assessing mechanical, structural, procedural, and organizational features of a marine system as interrelated components that affect risk. They no doubt have made the operation of offshore platforms safer. While risk is a part of the language in the safety cases and many of the analyses involve risk assessment practices, there still lacks a quantitative risk assessment structure guiding the overall process. There appears to be the belief that what is done is enough. The problem is that what has been done is primarily reactive to accidents and accident investigations and not an outcome of a systematic framework for quantifying the risks to prevent future accidents.

Even in the absence of any commitment to the formal use of quantitative risk assessment, there are indications of increased use of risk assessment methods. One of those indications is a methodology known as methodologies for comparison of alternative production systems (see Appendix A for a brief description). MCAPS is an engineering procedure to help make decisions among design alternatives for offshore drilling and production systems. The procedure makes use of recent developments in structural system reliability and the risk sciences. The experience with MCAPS is too limited to determine the direction it may actually take.

In the shipping area there are also isolated examples of regulators and analysts in the United States taking a risk perspective. For example, the Office of Marine Safety in the state of Washington has developed a risk matrix they apply to vessels to reduce the risk of oil pollution events in the state. The risk matrix is based on existing data and expert opinion. The U.S. Coast Guard through such efforts as the marine safety evaluation program examined the application of risk based methods to develop better marine safety criteria with a goal to reduce regulatory burden while making the regulations more safety relevant and therefore more effective. Meanwhile, on the international level there are efforts to actually incorporate risk methods in the regulations. Some examples already exist such as the International Maritime Organization's code for the transport of selected nuclear materials. Again, while these regulations appear to be risk based, there is no underlying risk assessment to support them. Also, an examination of the codes reveals considerable vagueness when it comes to the specifics of the risk methods.

At the regulatory level the United States appears to be lagging, rather than leading, in the adoption of tough safety requirements. In contrast to the extensive requirements of the safety cases in Europe, the Minerals Management Service, a United States regulator, only asks for voluntary compliance with safety and environmental programs. Such government supported safety programs as facility assessment, maintenance, and enhancement were terminated and other programs such as the safety and environmental management program are only voluntary (both programs are highlighted in Appendix A). The bottom line appears to be that the Europeans are moving towards quantitative risk assessment practices faster than the United States, especially in the offshore area. The United States is managing to maintain a leadership position in the specific area of structural reliability in both offshore and vessel design.

The single exception on the shipping side to what appears to be a lack of interest in seriously adopting a risk perspective in safety design and operations is the Prince William Sound risk assessment. While lacking in scope and technical clarity, the PWSRA is a major step forward in demonstrating the value of a systematic risk assessment of marine operations.

Recommendation

The Prince William Sound risk assessment, sections of some of the safety case studies, and a variety of operational risk assessments convey the general notion that risk assessment has found its way into the marine field. It has and it hasn't. In a relative sense, much progress has been made over the last ten years in the marine field in recognizing that the discipline of risk assessment can greatly enhance the decision-making process concerning safety. On the other hand, considering the size of the industry, risk assessment has yet to make much of a difference in the overall risk management practices of the industry. In particular, the application of risk assessment to marine systems would greatly benefit from a clear plan of a major component (if consideration of the total system is impractical) of the industry, such as transportation, on the overall direction it is taking to embrace the risk sciences in their decision-making process. It is recommended that there be guidance provided and priority pilot programs implemented on the application of risk assessment to selected marine systems. The guidance and selection of marine systems should provide continuity in terms of clear building blocks to an integrated systems approach to formal risk management.

6.4 LESSONS LEARNED FROM THE RISK ASSESSMENT OF MARINE SYSTEMS

Considering that risk assessments have been applied to marine systems in only a very limited way, there is not a large body of experience in which to examine the resulting benefits. Applications such as the Prince William Sound risk assessment and the formal safety assessments that have been applied have contributed to the confidence in the value of more disciplined and systematic safety studies. Few would argue with the improved safety environment and consciousness of safety that has come from the safety case studies for offshore platforms. And while they contain only elements of risk assessment, it is a beginning that is paying off with what appears to be improved safety practices and fewer accidents.

The Prince William Sound risk assessment, while limited in scope and to a single operation, did demonstrate the value of a systematic and deliberate process for exposing accident threats, vulnerabilities, and risk reduction measures. It highlighted the important and real connection between hardware performance and traffic rules, procedures, crew qualifications, human response, and organizational impacts (although much more could be done, especially in the last three areas). The study pinpointed specific risk reduction measures having the greatest return such as the escort system that effectively reduces potential oil outflows due to groundings. Another example was the quantification of the risk of oil spills due to collisions and powered groundings when ice is present in the traffic lanes during transits.

The proof-of-concept risk studies associated with such programs as the marine safety evaluation program of the U.S Coast Guard demonstrated the safety performance of such systems as electrical cargo lighting aboard a RO/RO ship and electric power generation and, in particular, various alternative designs of diesel electric power generation. The results of the lighting study provided insights on possible reductions in the regulatory requirements for such lighting. The power generation study demonstrated how risk assessment methods could aid the design process by exposing the safety and reliability performance of alternative designs. While these studies have very narrow applications, they do indicate a desire on the part of the U. S. Coast Guard to advance their methods of safety assessment and to consider risk based methods in the process. They also contribute to the types of insights and lessons learned from the application of the risk sciences. The studies noted earlier (References 12-16) have also provided valuable lessons on the benefits of systematic risk assessment. Finally, there is considerable excitement about the expected benefits from the prevention through people program.

Of a different vane, but important in terms of lessons learned, is the interest of the marine field in so called qualitative methods over quantitative methods. Such interest should be encouraged, but it should be guided with the intent of a natural evolution towards quantitative methods for those applications, such as design analysis, where qualitative approaches are simply inadequate. The review of risk assessment methods has also revealed the high interest of the marine field in risk measures that are not just for catastrophic events. In particular, there is the sense that there would be greater interest in risk assessment methods if they were targeted on the more likely events (fires, propulsion failures, power failures, etc.) as opposed to the catastrophic events (major spills, major loss of life, etc.). Of course, both interests can be satisfied with a well conceived risk management program.

Recommendation

Sufficient risk assessment experience now exists on marine systems to have some direct evidence of lessons learned from real world applications. It is recommended that the methods, scope, and results of these studies be the basis for an industry-wide review of lessons learned. The results should be the supporting evidence to the next phase of guidance documents, the consideration of changes in regulations, and the development of a plan for the future use of the risk sciences in marine safety decision making. It is also recommended that the guidance provided recognizes the industry's interest in the compatibility of both qualitative and quantitative methods as well as a wider range of risk measures to accommodate the consideration of noncatastrophic events.

6.5 ENHANCEMENTS TO FACILITATE THE APPLICATION OF RISK ASSESSMENT METHODS TO MARINE SYSTEMS

A review of the various risk studies and safety cases that have been performed on marine systems suggests one overarching way to enhance the application of quantitative risk assessment to marine systems. That would be for the marine industry to adopt a general theory or framework of quantitative risk assessment. The National Research Council in their review of the Prince William Sound risk assessment cited the lack of a general framework of risk assessment as a deficiency of that study. Appendix B has been included as an example of a general theory of quantitative risk assessment—a theory that is being practiced in several industries and is general enough to apply to marine systems as well. The seeds of this theory appear in the publications from the U.S. Coast Guard's marine safety evaluation program, but there is very little evidence of any kind of follow-up or general commitment.

It is true that the formal safety assessment methodology approaches the concept of a general theory or at least a general approach. The problem is that it lacks specifics, especially with respect to its reference to probabilistic or quantitative methods. The FSAs that have been performed also lack a sense of structure to what they really want to do in the probabilistic or quantitative arena. One of the major benefits of the marine industry having a general theory or a set of guiding principles would be to eliminate some of the myths on what is meant by "quantitative." Too often quantitative is taken to be something that can only derive from a very large database. What is really meant by quantitative in the risk sense is a full expression of confidence in the parameter(s) representing the measure of risk. Even though there may be low confidence (a broad uncertainty band) the parameter may be *quantified* in the risk sense as the curve expresses a quantification of the knowledge about the parameter. Such expressions of knowledge in the form of a risk curve are referred to as "telling the truth" about the risk.

An area of great opportunity for enhancing marine system risk assessments has to do with risk measures. The risk measure *oil in the water*, while an important precursor to risk, does not lead to the results of greatest interest. It is necessary to know what *oil in the water* means in terms of the risk to people, the environment, plants, and animals. It is in the interest of the marine industry to have such answers since for many spills the real risk may be inconsequential. As it is, the real risks are left to the imaginations, some of which could influence extremely irresponsible decision making for lack of the whole truth. Above, the matter of risk measures is discussed in terms of the desirability of assessing the risk of noncatastrophic events. The principles are the same, only the risk measure is different. Clearly, such options should be emphasized in any risk management plan.

The development of a risk assessment strategy for marine applications would probably enhance the general acceptance of such methods. Two examples of a strategy are the risk assessment of systems providing the highest return on investment and the phasing of specific risk assessments to achieve near term results that add confidence in the value of the analysis and provide direction for continued study, if necessary.

There are a number of specific analytical representations that could enhance the risk assessment of marine systems. These include the treatment of uncertainty; the consideration of human response, the analysis of common cause and external events; and, as alluded to above, the quantification of health effects. A cross cutting consideration that would improve the credibility of marine system risk assessments is greater accountability of the dynamics of marine systems. Examples of dynamic impacts are weather, cargoes, maintenance, performance requirements, procedures, regulations, and crews.

Recommendation

There are believed to be a number of areas where enhancements could be made to the current practices of risk assessment in the marine field. They include methodology, the use of more encompassing risk measures, the adoption of an integrated risk management strategy, and specific analytical techniques. It is recommended that a plan for risk management be developed for a major component of the marine field. The plan should address the above issues through the integration of the various elements of risk management and especially address the issue of the evolution of activities, including qualitative methods, to an increasingly quantitative approach to risk assessment and risk management. In particular, the plan should indicate the progression from basic guiding principles of risk assessment to qualitative methods, to plans for a general approach, and eventually to quantitative approaches for selected applications. The plan need not be prescriptive, but needs to provide a sense of direction to a particular goal of risk management, while clarifying the role of quantitative methods.

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APPENDIX A

EVALUATION OF METHODS

The approach taken to review risk assessment methods was to prepare evaluation summaries of a select number of the more visible methods. The hope was to end up with source material that puts the different methods and programs into some level of context based on experience and acceptance. The factors used in the evaluation summaries included the descriptor of the method or program; the triggering event for its existence; the form of the results, its scope, technical features, sponsorship and developer, where it is applied; and its history and experience, current status, and measures of risk or performance.

Provided on the following pages are evaluation summaries of those methods and programs considered as most important for application to marine systems.

PROBABILISTIC RISK ASSESSMENT (PRA)*

1. **Method Identifier**

PRA, PSA, QRA—Probabilistic Risk Assessment, Probabilistic Safety Assessment, Quantitative Risk Assessment. All are in use and taken to mean the same thing. The differences are in their origin, PRA comes from the U.S. nuclear power industry, PSA is the name adopted by the international nuclear power community, QRA is the preferred descriptor of such industries as chemical, aerospace and the marine field.

2. **Triggering Event**

Inquiry from the U.S. Congress for a more quantitative assessment of the risks of nuclear power. The result was the seminal study known by such names as *The Rasmussen Report, The Reactor Safety Study,* and *WASH-1400.* The study, which was sponsored by the U.S. Nuclear Regulatory Commission, was completed in October of 1975. Its full title is, *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants.*

A triggering event for the application of the principles of the Reactor Safety Study was the Zion and Indian Point Nuclear Power Plant probabilistic risk assessments performed by industry. This study extended many of the concepts of the Reactor Safety Study, especially in regard to the treatment of uncertainty and the quantification of the effectiveness of accident mitigation systems. These studies were performed by the three firms of Pickard, Lowe and Garrick; Inc., Westinghouse Electric Corporation; and Fauske and Associates, Inc., under the sponsorships of Commonwealth Edison Company, Consolidated Edison Company of New York, Inc., and the New York Power Authority.

3. **Form of the Results**

The PRAs submitted to the U.S. Nuclear Regulatory Commission as a part of their Individual Plant Examination program were limited in scope and usually only required a point estimate of the core damage frequency. Later submittals considered other risk measures as well as information about the uncertainties in the risk measures. The earlier full scope industry PRAs presented a more complete set of risk measures in the form of risk curves of different consequences. The industry full scope risk assessments usually involved 5 or 6 risk measures (5 or 6 different consequences) presented in the form of probability density functions and complementary cumulative distribution functions, depending on the specific risk measure. As the PRAs became a part of the regulatory process, their scopes were reduced as were the form of the results.

4. **Scope**

The early risk assessments, (1976-1985) performed by industry were extensive in scope and included a considerable amount of development work, particularly with regard to methods for quantifying uncertainty and risk contributors, methods for atmospheric dispersion, and the analysis of the effectiveness of specific accident mitigation systems, such as containment systems. As the regulators began to use PRA and request PRA arguments in their licensee submittals, the scopes were simplified over the industry PRAs with respect to the number of risk measures to be calculated and the extent of the uncertainty analysis.

5. **Features of Methodology**

The underlying characteristic of the PRA methodology is the triplet definition of risk, or more precisely, risk assessment. Risk assessment is defined as the answer to three questions, *What can go wrong?*, *How likely is it?*, and *What are the consequences?* Generally the first question is answered by a structured set of scenarios that can lead to the consequences, or risk measures, to be calculated. The second question is a matter of organizing the evidence to support the probabilities of occurrence of the individual scenarios that

* Since the overwhelming amount of PRA experience resides with the nuclear industry, this evaluation is essentially based on nuclear applications.

are aggregated into the consequences of interest. The consequence question is usually defined in advance of the analysis in the form of preferred measures of risk.

6. **Sponsor/Proposer**

A mixed bag. Congress initiated it. The U.S. Nuclear Regulatory Commission kicked it off with the Reactor Safety Study and industry really developed many of the detailed methods to the point of practical applications. Industry also took the initiative to perform the first full scope applications on several nuclear power plants. The U.S. NRC later required risk assessments by their licensees of all the nuclear power plants in the U.S.

7. **Developer**

Same as item 6.

8. **Application**

Nuclear power plants. Although there have been spot applications in a variety of industries, including chemical, aerospace, and defense; by far the leader has been nuclear power with the nuclear waste field rapidly gaining ground through their performance assessment work. The space program is becoming increasingly aggressive in the use of PRA, but they have not committed to any broad-based program. There are examples of PRA use in the chemical industry, but they are mostly in relation to spot applications or chemical operations involving nuclear materials.

9. **History**

For the most part the history of PRA is simple. Triggered by Congress, the U.S Nuclear Regulatory Commission, and the nuclear power industry, it represents a major shift in the way we think about safety, especially with respect to the technological risk of complex engineered systems handling or involving large quantities of hazardous materials. While PRA has not yet caught on with many industries, it is very definitely in the safety culture of the nuclear power industry worldwide. It is also gaining in its acceptance as indicated by the U.S. Nuclear Regulatory's movement towards risk-based regulation.

10. **Status**

The status of PRA in the nuclear power industry is that it is now an inherent part of the nuclear safety culture. The U.S. NRC is committed to the practicing of risk informed performance based regulation. PRA has also become a major discipline in the performance assessment of nuclear waste repositories. Beyond the nuclear industry, the picture is fuzzy. Many industries, including the marine field, have examples of probabilistic risk assessments, but have not yet made the investment or commitment of the nuclear industry. It is not yet clear if they will.

11. **Risk/Performance Measures**

The risk measures employed in the nuclear industry were several in the early industry sponsored PRAs. They included the probability (of frequency) of core damage, releases, injuries, fatalities, thyroid cancers, radiation dose, and in some cases, property damage. As the PRAs became a part of licensee submittals the risk measure of choice was core damage frequency. More recently, large early release frequencies have been added. In the performance assessment of nuclear waste repositories, the risk measures include release frequencies to the biosphere and dose to members of a critical group.

PROCESS HAZARD ANALYSIS (PHA)

1. **Method Identifier**
Process Hazard Analysis is the name for a group of hazard evaluation techniques that include hazard and operability (HAZOP) studies, what if analyses, failure mode and effect analysis (FMEA), preliminary hazard analyses (PrHA), human reliability analyses (HRA), etc.

2. **Triggering Event**
The chemical industry's desire to develop a set of methods for the chemical process operations to enable them in the performance of safety and hazard assessments. Although a number of chemical industry related accidents such as Piper Alpha and Seveso had occurred in the past, the Bhopal incident could be singled out as the triggering event for the maturing of the process hazard analysis techniques.

3. **Form of the Results**
The process hazards assessments culminate in the identification of various hazards and safety issues. Mitigating measures are also identified. The assessment results usually take the form of an exhaustive set of potential accident scenarios with qualitative assessments of their likelihood and consequence estimates.

4. **Scope**
The scope of process hazard assessment can cover all modes of operations in the life cycle of the process facility. This could range from design, construction, startup, normal operations, maintenance, decommissioning, etc.

5. **Features of the Methodology**
The key words that could be used to describe the process hazards analysis would include the following:
- qualitative techniques capable of identifying and ranking hazardous scenarios in terms of risk
- top down approach in identification of risk and safety issues
- cost effective
- pragmatic
- wide acceptance

6. **Sponsor/Proposer**
No one sponsor can be identified or singled out. The AICHE, Center for Chemical Process Safety, and regulators such as fire departments, OSHA, EPA, etc., have taken an active role in promoting the PHA methodologies in the recent years.

7. **Developer**
No single developer. Major chemical companies like ICI and DOW were instrumental in making first attempts at developing the PHA methodologies.

8. **Application**
Although developed for the chemical process industries, the PHA methods could be universally applied to all type of industries.

9. **History**
Methods such as FMEA began in aerospace after World War II. Chemical industry in PHA began in the early 1980s in response to reducing the severity and likelihood of severe accidents such as Flixborough.

10. **Status**
Currently the method of choice of the chemical process industry in USA. These methods are endorsed and recommended by EPA, OSHA, and other regulatory bodies.

11. **Risk/Performance Measures**

Select PHA methodologies allow for the identification of risk ranks for individual accident scenarios. These risk ranks are the combined measures of the scenario likelihoods and their potential consequences. This risk ranking technique enables the process of prioritization, risk reduction, and the measurement of risk-management through recommending and ranking risk reduction measures.

RISK MANAGEMENT PROGRAM (RMP)

1. **Method Identifier**
Risk Management Program

2. **Triggering Event**
Bhopal 1987, Phillips Petroleum, Pasadena, 1989, and other major chemical and petroleum facility accidents. Clean Air Act of 1990, Section 112r, Risk of Accidental Releases of Hazardous Material.

3. **Form of the Results**
Results are a set of documents describing the risk management program established for a stationary source (storage or process facility) containing acutely hazardous materials (regulated substances) in more than threshold planning quantities (TPQ). The program is prepared by the source owner/operator and documented in a risk management plan which EPA wishes to make available to the public in an electronic format. The EPA or state and local governmental bodies or local emergency planning committees are the administrators of the programs. The RMP is a public information document containing summary data and descriptions of the source facility, programs, procedures, training, and equipment used to manage the risk of accidental release. It also contains summary information on the extent of offsite impacts from accidental releases for "worst case" and alternative case (more likely) scenarios. The RMP summarizes information from technical documents. The technical documents are reviewed by the local RMP administrator and/or the EPA but retained at the source. Triennial reviews/upgrades of the documents are required if no changes have been made prior to the 3-year anniversary.

4. **Scope**
Documents the organization, procedures, testing, inspection, equipment, training, emergency response plans, and safety assessments provided to assess and manage the risk of a process unit containing TPQ amounts of an AHM. Also describes the prevention program to prevent releases and the hazard assessment used to characterize the impact of accidental releases.

5. **Features of Methodology**
Requires a process hazard analysis (PHA) and an offsite consequence analysis by the source owner. No assessment of accident frequencies required, but a 5-year accident history must be provided. The PHA and OCA are used to identify risk management improvements and provide technical information for use by the source owner, the administrative agency, the local emergency planning committee (LEPC), and others in planning emergency responses for accidental releases of AHMs.

6. **Sponsor/Proposer**
U.S. Congress/U.S. EPA

7. **Developer**
U.S. EPA, Chemical Emergency Preparedness Office, Kraig Matthiesen

8. **Application**
All stationary sources in the U.S. having TPQ amounts of any of 140 AHMs. TPQ amounts specified by 40 CFR 68.

9. **History**
Legislated in 1990 as Section 112r of CAA. Regulation requiring implementation established as 40 CFR 68 on June 20, 1996. Full implementation by all covered sources required within 3 years. Incorporates process safety management (PSM) program elements established by OSHA in 29 CFR 1910.119.

10. Status

See History and Sponsor.

11. Risk/Performance Measures

Process hazard analyses are required by the prevention program section of the regulation. PHAs performed in response to process safety management program developed for OSHA will be accepted. Recommendations for reduction of risk must be identified and tracked for remedial actions. OCA is provided to characterize the extent of area impacted by "worst case" scenarios and more likely "alternative" accidental releases identified in PHA. The only consideration of accident frequency occurs in the PHAs which may assign likelihood and consequence severity categories to accident scenarios. The likelihood of OCA scenarios is not estimated. The RMP is not a true QRA.

RISK MANAGEMENT AND PREVENTION PROGRAM (RMPP)

1. **Method Identifier**
   Risk Management and Prevention Program

2. **Triggering Event**
   Bhopal 1987, Phillips Petroleum, Pasadena, 1989, and other major chemical and petroleum facility accidents.

3. **Form of the Results**
   The results are a set of documents describing the RMPP established for a particular process containing acutely hazardous materials in more than threshold planning quantities (TPQ). The documents are a public information document retained by the administering agency having jurisdiction over the process unit and a series of technical documents assessing the risk associated with the process units. The technical documents are reviewed by the administrative agency but retained at the process unit. Triennial reviews/upgrades of the documents are required if no changes have been made prior to the 3-year anniversary.

4. **Scope**
   Documents the organization, procedures, testing, inspection, equipment, training, emergency response plans, and safety assessments provided to assess and manage the risk of a facility containing TPQ amounts of an acutely hazardous materials (AHM). Defines over 350 substances as AHM.

5. **Features of Methodology**
   Requires a process hazard assessment (HAZOP, What-If, FMEA, etc.), a hazard analysis, an external events analysis, and an offsite consequences analysis (OCA). These analyses are used to identify risk management improvements and provide technical information for use by the process owner, the administrative agency, the local emergency planning committee (LEPC), and others in planning emergency responses for accidental releases of AHMs.

6. **Sponsor/Proposer**
   State of California Legislature in its Health and Safety Code.

7. **Developer**
   State of California, Office of Emergency Services

8. **Application**
   All process facilities in State of California having TPQ amounts of any of over 300 AHMs. TPQ amounts specified by legislation.

9. **History**
   Legislated in 1989. Full implementation by all covered facilities required within 3 years. Most facilities have been implemented as of 1996. Some administrative agencies have not required implementation even as late as 1996 because of lack of funding for administration or other reasons. As of 1998 renamed as the California Accidental Release Prevention (CalARP) program and revised to include all requirements of USEPA RMP regulation.

10. **Status**
    See Sponsor and History.

11. Risk/Performance Measures

Process hazard analyses are required to assign frequency and severity indexes to events resulting in releases of AHMs. High frequency/high severity events require recommendations for reduction of risk and tracking of remedial actions. OCA is provided to characterize the extent of the area impacted by "more likely" accidental releases identified in PHA and external events analysis. RMPP preparers have typically estimated frequencies of OCA scenarios.

FORMAL SAFETY ASSESSMENT (FSA)

1. **Method Identifier**
Formal Safety Assessment

2. **Triggering Event**
The Piper Alpha Disaster. The concept of FSA was introduced by the UK in its paper MSC 62/24/3.

3. **Form of the Results**
Probabilistic, although the exact form is not yet known.

4. **Scope**
FSA is seen by the UK as comprising of a) the identification of hazards, b) the assessment of risks associated with those hazards, c) ways of managing the risks identified, d) cost benefit assessment of the options identified above, e) decisions on which options to select.

5. **Features of the Methodology**
Rooted in probabilistic risk assessment methods and similar to the risk assessment for Prince William Sound.

6. **Sponsor/Proposer**
The UK has been the principal proposer of the method. The UK considers that FSA can be applied by the International Maritime Organization to ensure a strategic oversight of safety and pollution prevention.

7. **Developer**
The UK's research on FSA was carried out by AEA Technology.

8. **Application**
The Maritime Safety Committee (65th session) of the IMO recommends the introduction of FSA for the management of safety in the international shipping industry.

9. **History**
The method was principally driven by the Piper Alpha disaster of July 6, 1988, and the publication of the public inquiry in the disaster on October 19, 1990.

10. **Status**
In various stages of implementation.

11. **Risk/Performance Measures**
To be determined.

SAFETY AND ENVIRONMENTAL MANAGEMENT PROGRAM (SEMP)

1. **Method Identifier**
   SEMP - Safety and Environmental Management Program

2. **Triggering Event**
   Industry recognition of need for voluntary safety and environmental management program for outer continental shelf (OCS) production facilities.

3. **Form of the Results**
   Reports for checklist-type hazard analyses, procedures, practices and programs. Hazard analysis is checklist of compliance items noting missing or deficient items, resulting potential hazards, consequences of failure of administrative and engineering safeguards and effectiveness of safeguards, and recommendations.

4. **Scope**
   Review of procedures, practices, design information, training, mechanical integrity programs or practices, emergency response plans/controls, audits and accident investigation requirements and hazard analysis conforming to one of the methods
   in API RP 14J.

5. **Features of Methodology**
   Organized very much like API RP 750, a recommended practices guide for process safety management programs in process facilities. Also includes many elements similar to PSM programs required by OSHA in 29 CFR 1910.119. Hazard analysis uses a "safety flow chart" for offshore production facilities to define design and protective features that should be present and "safety analysis checklists" to verify adequacy of design and protective features in actual facility using the safety analysis flowchart. Focus is on performance based evaluation where performance measures are quality of performance of attributes listed on checklists.

6. **Sponsor/Proposer**
   American Petroleum Institute, Minerals Management Service (MMS), and Department of Energy (DOE).

7. **Developer**
   American Petroleum Institute Exploration and Production Department

8. **Application**
   Offshore production facilities on the OCS.

9. **History**
   Developed by API in 1992-1994 time frame. MMS requested voluntary industry application in June 1994. DOE contracted case study application on 5 or more Taylor Energy Company facilities in 1994.

10. **Status**
    See History. 105 of 111 companies participated in survey of SEMP applications in 1995. Industry still evaluating applicability. MMS considering regulatory implementation if industry does not voluntarily implement.

11. Risk/Performance Measures

Extent to which safety analysis checklists are satisfied and all required procedures, practices, and programs are implemented. Self-audits used to determine status of implementation. All measures are qualitative; i.e., index type based on deficiencies identified when using checklists and auditing procedures, practices, and programs.

METHODOLOGIES FOR COMPARISON OF ALTERNATIVE PRODUCTION SYSTEMS (MCAPS)

1. **Method Identifier**
   Methodologies for Comparison of Alternative Productions Systems

2. **Triggering Event**
   Industry seeking a better basis for decision making regarding offshore production in deeper and more hostile environments.

3. **Form of the Results**
   A mix of probabilistic and single valued measures. Generally, safety measures are treated probabilistically and cost measures are expected in single valued numbers.

4. **Scope**
   MCAPS is designed to allow comparisons of alternative drilling and production systems. It involves a) defining the alternative systems to be evaluated, b) determining reliability and economic characteristics of each system, c) assessing the ability of each to meet production goals, based on identification of the primary risk contributors, d) choosing the "best" system, and e) proceeding with life cycles implementation.

5. **Features of the Methodology**
   The objective of MCAPs is qualitative and quantitative. It involves a) analysis of systems and interacting components, b) randomness of safety related and other events, c) multiple phases of the life cycle of the system including design, construction, commissioning, drilling, production, and decommissioning, d) a multiple vector valued representation of possible outcomes including monetary, injury, and environmental impact measures, e) a scaler-valued preference measure (such as expected present worth), and f) explicit representation of the uncertainty in the estimates of the frequencies and outcomes.

6. **Sponsor/Proposer**
   Amoco formally offered the MCAPS project for joint industry participation. Eighteen companies eventually joined the project.

7. **Developer**
   The organization to conduct the project was comprised of a four-part team: 1) Amoco administered the project, provided technical guidance, assistance, and technical reviews. 2) C. Allin Cornell had responsibility to develop a methodology for comparisons of alternative systems. 3) PMB Engineering (San Francisco) was responsible for the introduction of U.S. risk assessment technology for evaluation of alternative systems, for the "coarse quantitative" full scope risk assessment of the tension leg platform structural and foundation system configurations, and quantitative illustrative comparisons involving the two and four tendons per column TLP configurations. 4) SikteC A/S (Trondheim, Norway) was responsible for the introduction of Norwegian risk assessment technology, etc.

8. **Application**
   The initial application is to perform qualitative comparisons of three tension leg platform (TLP) configurations, complete with drilling and production systems. The base case configuration was a TLP with four tendons per column and well completions at the surface. The two variations of the base case were: a) two tendons per column instead of four and b) subsea well completions instead of surface well completions. These configurations were determined *a priori* to be of considerable interest within the industry. There were other applications planned.

9. **History**

MCAPS was initiated by a meeting for project participants' representatives at Chevron's offices in San Ramon, California, on April 25-26, 1988. This was followed by three meetings of the MCAPS project team. The final report was published in December 1990.

10. **Status**

To be determined.

11. **Risk/Performance Measures**

Performance measures included expected numbers of severe injuries, damage repair costs, production impacts, hydrocarbon releases, spill costs, etc.

FACILITY ASSESSMENT, MAINTENANCE, AND ENHANCEMENT (FAME)

1. **Method Identifier**
Facility Assessment, Maintenance, and Enhancement. While FAME is a safety program, not a true method, it is included for its historical significance.

2. **Triggering Event**
The marine industry wanted to develop a screening method to provide operators with a practical approach to performing a qualitative assessment of an existing offshore facility.

3. **Form of the Results**
The form of the results is a database that contains all 383 fire and explosion accidents that occurred in the 9-year period from 1981 through 1989 during production operations on platforms in federal waters in the Gulf of Mexico. The fire and explosions database was merged with two platform population databases containing information on all 4044 current and removed platforms in the Gulf of Mexico.

4. **Scope**
The merged databases permit a detailed analysis of a number of the risk factors on the basis of the population data.

5. **Features of the Methodology**
The objective of FAME is qualitative. It involves searches of the database to perform fire and explosion statistical analysis based on the cause of the accident.

6. **Sponsor/Proposer**
The Minerals Management Service performed the study based on a recommendation of the Marine Board.

7. **Developer**
The organization that conducted the study was the BELMAR Engineering and Management Services Company. The original study consisted of four tasks, of which only Task 1 (establish a risk factor list) and part of Task 2 (prepare data base) were funded.

8. **Application**
The initial application examined a) the incident rate for platforms in federal waters in the Gulf of Mexico from 1981 through 1990; b) fire and explosion causes; and c) the age platform age factor as it contributed to fire and explosions.

9. **History**
FAME was initiated by the Minerals Management Service in response to a Marine Board report "Alternatives for Inspecting Outer Continental Shelf Operations." The report was published in August 1992.

10. **Status**
Not supported by industry.

11. Risk/Performance Measures

Performance measures included the incident rate of fires and explosions. The most significant finding was that compressors were responsible for approximately 65% of the fires on the platforms being studied. Some work was completed on equipment aging, but it was inconclusive.

FIRE AND LIFE SAFETY INDEXING METHOD (FLAIM)

1. **Method Identifier**
   Fire and Life Safety Indexing Method

2. **Triggering Event**
   The National Research Council's report in 1990 recommending that Minerals Management Service develop a "comprehensive system for collecting event and exposure data, calculating frequency and severity rates, analyzing trends, and performing several other functions necessary to produce usable data." The NRC report was written after Fire and Blast Research Project's Interim Guidance Notes noted that rigorous QRA methods used for Piper Alpha were either impractical or impossible for a variety of reasons. FLAIM may be considered the methodology outgrowth of the facility assessment, maintenance and enhancement (FAME) study sponsored by the Minerals Management Service in 1992.

3. **Form of the Results**
   Numerical risk indexes for various platform topside systems and an overall risk index for topside facilities. Indexes are assessed independently for fire safety and life safety.

4. **Scope**
   Eight separate risk assessment modules are used to calculate individual risk indexes which are combined to calculate an overall topside risk index. The modules are general factors assessment (GEFA), life safety assessment for accommodations (LISA-A) and for platform (LISA-P), loss of containment assessment (LOCA), vulnerability to escalation assessment (VESA), layout and configuration assessment (LACA), operations (human factors) assessment (OHFA), risk reduction assessment (RIRA), and safety management assessment (SAMSA). Each module is composed of a series of questions regarding the systems, procedures, training, or organization being evaluated. The questions are answered by a consensus of opinion by teams of experts and reflect design as well as past performance or experience. The worksheets are calibrated at the beginning of the assessment much like in a HAZOP study. All information is recorded by a software package designed for each module. The software prompts the assessment process for each module using the calibration rules established for the worksheets at the start of the assessment. The software package can be obtained through UMI Dissertation Services at (800) 521-0600, Ext. 3879.

5. **Features of Methodology**
   Indexes are developed in accordance with algorithms that may be customized for specific applications of each module. Indexes are developed in accordance with yes/no and good/bad answers to a series of questions, qualitative letter grades, and numerical values, whichever has been selected for the indexing algorithm. Letter grades are A to F using the same 4.0 grading system found in academics. Numerical values are units such as barrels per day. Each grading factor is assigned a weighting factor similar to the "units" assigned to a course, the greater the importance the greater the weighting factor. The overall index is equivalent to the grade point average in an academic system.

6. **Sponsor/Proposer**
   Minerals Management Service Committee on Alternatives for Inspection (CAI).

7. **Developer**
   William E. Gale is developer. Robert G. Bea of the University of California, Berkeley, is responsible for software development. William H. Moore and Robert B. Williamson are participating consultants.

8. **Application**
   Offshore platforms only.

9. **History**

Outgrowth of the FAME study in 1992. Note that FAME is neither a method or technique. Rather it is a study suggesting/recommending approaches for assessment of offshore platform risk. It was documented in a paper presented at Sandia National Laboratories in July 1994. No data on applications as of 1996, but the number of applications are believed to be small. A trial application project sponsored by Paragon Engineering Services was proposed for completion in 1997 using second generation software and methodology called FLAIM II.

10. **Status**

Supported by the Minerals Management Service as a means of assessing the risk for offshore platforms.

11. **Risk/Performance Measures**

System safety indexes and improvement measures identified by consideration of primary detractors to safety index.

APPENDIX B

THE GENERAL THEORY OF QUANTITATIVE RISK ASSESSMENT[1]

by
Stan Kaplan
B. John Garrick

B.1 INTRODUCTION

As the readers of this report know well, risk is always with us, and always has been. Human beings, therefore, continuously do and have always done risk assessments. Until recently, these assessments have been primarily "qualitative"; i.e., informal, intuitive, implicit, and nonnumerical. Over the last two or three decades, however, as mankind reaches for the stars, and attempts to harness ever more powerful energies, and as concern for the planetary home has grown, so the risk assessment process has grown into a discipline that is "quantitative"; i.e., formal, rigorous, explicit, numerical, and increasingly useful in many widespread applications. So much so, that today we see the U.S. Congress moving to make QRA an official, required part of the governmental regulatory process.

In the last one and a half decades, quantitative risk assessment (QRA) itself has evolved into a form and style that emphasizes the quantification of uncertainty, which we call "telling the truth," and emphasizes the necessity of making these quantifications "evidence based," as opposed to "personality based," "politics based," or "opinion based." Thus, in this latest form of QRA, when we deal with experts as sources of information, we do not ask them for their opinions, we ask for their evidence.[2] This makes the whole QRA process more objective and more useful in building understanding and consensus on the decisions that need to be made.

As a result of these evolutionary developments, it is now possible, from the many existing applications of QRA, to abstract a rather small set of simple, but powerful and elegant ideas, which together constitute a "General Theory" of QRA; general in the sense that it must apply to any quantitative risk assessment, whatever the type of risk, in whatever field or industry or activity it arises.

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[1] This appendix is a slight variation of material that has been published by the authors in various other publications including a summary report of a NATO Advanced Research Workshop on "A Risk-Based Approach to the Evaluation of Disarmament Strategies and Technologies." The authors, Drs. Stan Kaplan and B. John Garrick, have modified the text some to make it more appropriate for a discussion of marine applications of quantitative risk assessment.

[2] Kaplan, S., "'Expert Information' Versus 'Expert Opinions,'" Another Approach to the Problem of Eliciting/Combining/Using Expert Knowledge in PRA," *Reliability Engineering and System Safety*, 35, pp. 61-72, 1992.

It must therefore apply also to marine systems, and it must show us how to structure QRAs of various aspects of shipping and offshore operations. We shall discuss these potential applications shortly, after first sketching out some of the key ideas within this general theory.

B.2 THE QUANTITATIVE DEFINITION OF RISK

The first and most important step in developing a theory and methodology of risk assessment is to define "risk" in a way that supports quantification. Regrettably, this step has been one of much controversy and confusion within the risk assessment community. In our experience, we have found that what always works, and what always gets a risk assessment off on the right foot, is to define risk, R, as a "complete set of triplets":[3]

$$R = \{ < s_i, \iota_i, x_i : > \}_c$$

where

s_I	=	the "ith risk scenario"; i.e., an answer to the question, What can go wrong?
ι_I	=	the "likelihood" of the ith scenario happening.
x_i	=	the set of consequences resulting from the ith scenario.

The curly brackets, { }, denote "set of" and the subscript c denotes "complete." Thus defined we see, as in Figure B-1, that risk is the answer to the three questions:

- What can go wrong (with this operation/action, s_o, that we are planning)?
- What is the likelihood of that occurring?
- If it does happen, what are the ultimate consequences?

The remainder of the theory deals with techniques for identifying the s_i, with the use of the language of probability curves to express our knowledge of ι_i and x_i, and with the use of the logic of Bayes' theorem to ensure that these curves express, are based on, and indeed are dictated by, the total body of evidence available.

B.3 THE DAMAGE INDEX (RISK MEASURE)

As shown in Figure B-2, x_i is called the "damage index," or the "damage vector" to remind us that it can be a multicomponent quantity. The amount of damage can be a function of time after occurrence of s_i. Since at the time of doing the risk assessment there will always be some

[3] Kaplan, S., and B. J. Garrick, "On the Quantitative Definition of Risk," *Risk Analysis*, Vol. 1, No. 1, March 1981.

uncertainty about the magnitude of damage, that uncertainty should be expressed in the form of probability curves as shown.

B.4 QUANTIFYING LIKELIHOOD

Thus far we have deliberately used the term "likelihood" because it is vague and undefined in everyday usage. For our quantitative purposes, however, we must now define it in a more technical way. In Figure B-3, we show three different formats for capturing quantitatively the intuitive and qualitative idea of "likelihood." The first of these, suitable for a repetitive operation, is the idea of "frequency." Thus we ask, "in what fraction of these operations will the scenario s_i occur?" Similarly for a continuing, steady state operation we would ask, "how many times per hour or per year will s_i occur?"

When we are dealing with a nonrepetitive, "single shot" operation, such as a voyage to Mars for example, we capture the idea of likelihood with the idea of "probability" or "confidence." In this case we ask, "how confident may we be that s_i will occur"? Note that we are using the word "probability" here in the sense of Laplace and Bayes, not in the statisticians' sense. For the latter, we use the word "frequency."

Note also that the word "confidence," as we use it here, is not subjective, and does not refer to personality traits as in a confident versus a hesitant person. We use it here in the sense of "evidence based"; i.e., "what degree of confidence does the evidence permit us to have or, better, does it dictate that we have"?

The third format, which we call the "probability of frequency" format, applies where a frequency exists but we do not know exactly the numerical value of that frequency. We then express what we do know, based on the evidence, in the form of a probability curve against possible values of that frequency.

This third format is usually, but not always, the preferred format. Note that it includes the other two formats as special cases.

It is important to note also that when we say "exists" above, we include the idea of "exists conceptually." For example, we can conceive of a thought experiment in which we launch many trips to Mars. In this experiment, there would be a frequency with which s_i would happen. We can then express with a probability curve what the evidence tells us about what the numerical value of this frequency would be if we were actually to carry out this experiment.

B.5 IDENTIFYING AND STRUCTURING THE SET OF SCENARIOS— OBTAINING AND MAINTAINING COMPLETENESS

The set of scenarios is obviously the most important part of a risk assessment and constitutes the most important part of what is known as the "risk model." The process of identifying and structuring this set, however, is only part science and a large part art, requiring skill and judgment on the part of the modeler. Thus, we cannot give a cookbook type recipe for this process. However, we can call attention to some of the key principles involved, see Figure B-4.

We will briefly discuss a few of these and in the course of that convey the idea of how completeness can be maintained in the set of risk scenarios.

The first principle is that one should start a QRA by making the "as-planned" scenario s_0 totally clear and explicit. In other words, get clear on what we are assessing.

The second principle is recognizing that any risk scenario, s_i, that we define is actually a whole category of scenarios; it can be divided into subscenarios indefinitely. Similarly any set of s_i can be aggregated into a superscenario. Hence, how one cuts up the pie is part of the modeler art, and determines how understandable, useful, and costly is the study.

The third principle is illustrated by Figure B-5. If we represent the as-planned scenario, s_0, by a trajectory, as shown, then any risk scenario, s_i, must depart from s_0. Any departing scenario must have a point of departure, at which some initiating failure or initiating event occurs, as shown. This initiating event must occur at some time during s_0, and at some point or part of the system. Thus, if we divide the mission time into a finite number of phases, and divide the system into a finite number of parts or subsystems (including the humans involved), then we obtain a gridwork with a finite number of space/time boxes as shown in Figure B-6. If we now define initiating event (IE) i,j as "something goes wrong with subsystem i during mission phase j," then we obtain a complete and finite set of initiating events, IE_{ij}.

Correspondingly, if we define $s_{i,j}$ as the set of scenarios beginning with IE_{ij}, then the set $\{s_{i,j}\}$ is a complete set of risk scenarios.

If we wish to subdivide these scenarios further, then we may note the Principle of Emanation, in Figure B-4, which states that from each IE a whole "tree full" of scenarios emerges depending on what happens next. This leads to the concept of "scenario trees," see Figure B-7, of which the well known "event trees" are a special type.

Each path in the scenario tree now represents a specific scenario emerging from the IE. By giving some care to this matter, the tree can be drawn in such a way that the set of paths in the tree constitutes a complete set of scenarios for that IE.

Thus, we have a complete set of IEs, and for each IE a complete set of scenarios.

Furthermore, combining the ideas of Figures B-5 and B-7, we obtain Figure B-8, which makes the point that different scenarios even emanating from different IEs, can have the same end state. This suggests that we may draw on "incoming" scenario tree to given end state, as shown in Figure B-9. Incoming trees are also known as "fault trees." In a similar way we can draw "mixed" trees, as in Figure B-10, which have incoming and outgoing sections about what we could call "intermediate" or "mid" states (MSs).

Each scenario terminates in what we call an "end state" (ES). Among end states those of most interest are what we call "harmful end states" (HESs).

Thus, we have shown how a complete and finite set of scenarios may be obtained. If more detail is desired, the important paths in the trees may be subdivided further.

B. 6 QUANTIFYING THE SCENARIOS ACCORDING TO THE EVIDENCE —THE USE OF BAYES' THEOREM

Having identified the s_i, we now must calculate the likelihood of each. Let us illustrate this using the probability of frequency format, and the sample event tree of Figure B-11. At the bottom of the figure, an equation is given for the frequency of path s as the product of the frequency of the initiating event I, and the "split fractions," $f(A|I)$ etc., at each branch point along the path. In this way, the scenario frequencies can be calculated from more elemental parameters. The question is, "where do we get the values of the elemental parameters"?

The answer to this question is, and must always be, the same. We get them *from the evidence,* using Bayes' theorem, which is the fundamental mathematical principle governing the evaluation of evidence.

Figure B-12 illustrates this process. The set of evidence items relevant to each parameter is shown listed under that parameter. These items are processed through Bayes' theorem to produce probability curves quantifying our state of knowledge about the numerical value of each parameter. These curves are then processed through the frequency equation to obtain a curve for the frequency of the scenario. That is the basic idea. The same thing is done for the damage index of each scenario. And this is what we mean by an "evidence-based" risk assessment.

The point is that the evidence speaks, not the personality!

B.7 RISK COMMUNICATION—GRAPHICAL DISPLAY

In the previous chapters, we have talked about risk assessment, i.e., how to define and actually calculate the risk involved in any given operation, process, or facility. When the quantification of risk is complete, the next issues to be dealt with are risk communication and risk management. Included under these headings are the communication of the risk assessment results, the understanding of why they are the way they are, the understanding of what the major contributors are, and an exploration of what changes could be made to the underlying system or operation in order to improve the risk situation.

In all this it helps to develop pictorial ways of displaying the risk results. Figure B-13 shows an example of this. This figure is a one page summary of a study that fills several feet of shelf space.

In the case of a nuclear plant, the first thing we want to know is, "what is the likelihood of a core melt?" The answer to this is given, in the upper left graph, in probability of frequency format. The graph shows a probability curve against the frequency of core melt, measured in occurrences per plant year. The curve tells us that the evidence indicates a frequency in the neighborhood of once in 10,000 plant years, and that we can have high confidence that the frequency is no bigger than once in 1,000 years, and no smaller than once in 100,000 years.

The second question we ask in the case of a nuclear plant is, "what is the likelihood that radiation will be released to the outside of the containment structure?" The answer to this is given in the center figure on the top line. The figure shows the probability of frequency curves for a set of "release categories," designated 8A, 2RW, etc. These categories define the amount and isotopic content of the release, its timing, physical form, etc. Note that the sum of the individual release category curves must add up to the core melt curve.

The third question to be asked in the case of a nuclear plant (or of any facility housing weapons or dangerous substances) is, "what is the effect of these releases on the surrounding population and environment?" The remaining figures in Figure B-13 answer this question. These figures are also probability of frequency curves, but in what is called "complementary cumulative" form. The figure in the upper right, for example, answers the question, "how frequently do we have an incident that results in 10 fatalities or more, 100 or more, 1,000 or more, etc?" The frequency is given on the vertical scale, and the probability is expressed by the band of curves.

B.8 RISK MANAGEMENT, DECISION MAKING, THE ROLE OF QRA

Once the risks are identified, quantified, and communicated, the next step is to make the proper decisions for risk reduction, control, mitigation, etc. This opens up the whole subject of decision theory, the balancing of costs, benefits, risks, etc.

We shall limit ourselves here to presenting a single figure, Figure B-14, which shows the anatomy of a typical decision problem, and the role of QRA and Bayes' theorem in the solution of that problem.

The figure is pretty self-explanatory. The decision problem is to choose between the available options A, B, etc. Each option brings with it costs, benefits, and risks. At the point of decision, we have uncertainty about these costs, benefits, and risks, and these uncertainties are reflected in probability curves as shown.

Each decision option is thus characterized by a set of three probability curves. Our degree of preference for each such set is expressed by what is called a "utility function," and the optimal decision is to choose that option having the maximum utility.

The role of QRA in the decision-making process is to provide the three probability curves for each option, as shown.

The role of Bayes' theorem is to make these curves reflect and express the total body of relevant evidence available, as we have described above. This makes the decision analysis open, overt, explicit, and objective. This can go a long way towards eliminating the miscommunication, misunderstanding, arguments, litigations, and conflicts that typically occur in these situations.

B.9 DECISION IMPLEMENTATION

Part of risk management, as we have said above, is to make the correct decisions. Another part is to get those decisions implemented properly. Proper implementation requires the understanding, agreement, and desire on the part of the implementing people. This brings us back to the subject of risk communication. They must understand why the decision is the way it is and why it is important to them to carry it out.

QRA can help bring about this understanding not only because of the quantification (replacing fuzzy and emotion laden words with numbers) and not only because of the integrity of analysis (acknowledging uncertainty and tying the numbers to the evidence in a disciplined way), but also because the QRA provides a precise, uniform conceptual, and linguistic framework with which to think and communicate about the issues of risk and decision. It helps make the intangibles tangible.

In this connection, we cannot help noting that the world has been arguing about the subjects of risk and decision, and particularly about the meaning of the word "probability" for hundreds of years, at least. The linguistic situation in these subjects is totally chaotic and has often been likened to the tower of Babel.

Dealing with this situation, over the last two decades, has led us to formulate two communication theorems, which we offer, with tongue only partially in cheek, in Figure B-15.

B.10 APPLICATION TO MARINE SYSTEMS

The general theory of risk assessment and its relationship to risk communication and risk management as discussed above has evolved over the past two decades. It has been tested and modified as a result of a variety of applications on engineered and other types of systems. It is also sufficiently general to embrace the methods and techniques of Appendix A and thus accommodate marine system applications. Each application may be different and require special treatment of the details, but the steps of defining risk, choosing risk measures (i.e., parameters for measuring risk), structuring scenarios, gathering data (evidence), quantifying scenarios, and assembling the results apply to all system problems. Systems may be hardware, software, people, engineered, natural or combinations.

In order for the theory to be considered a general theory it must accommodate system-specific features and constraints. For example, features of marine systems that are extremely important to adequately address their risk include confined spaces, limited resources, multiple states of operation, different mission phases, international crews, and extreme exposure to natural and manmade external threats. These features of a risk assessment of marine systems must be addressed in all phases of the analysis. The scenarios indicating "what can go wrong" in a ship, for example, must be structured for the different shipping activities and phases involved. They include dockside operations, entering and exiting a harbor, and sailing the open seas.

One of the most important elements stressed in the general theory is the treatment of evidence. Whether the analysis be qualitative or quantitative the basis of the results should be extremely clear and traceable. The principal ingredients are the data utilized and the methods of processing the data into basic input to the risk model. In this regard consider one of the most recent and contemporary risk assessment applications of marine systems, the Prince William Sound risk assessment (Reference 10). An interesting question is "does it fit within the general theory presented above"? The answer is yes, it does as far as it goes. It involves many of the elements of the above general theory. It has elements of being scenario based, involves different initiators, utilizes several different techniques including fault tree analysis, adopts different measures for risk (accident frequencies of different severity and the probability of different levels of oil outflow), and considers uncertainty analysis to be an integral part of the risk assessment.

One of the few areas where the Prince William Sound risk assessment falls short of the spirit of the general theory is the failure to explicitly expose the evidence for the analysis including the critical step of assigning input probabilities to the basic risk model. While the argument is offered that the information is confidential, it should be possible to structure the data in such a form that issues of confidentiality are not compromised. Furthermore, the exact method of processing the data and assigning probabilities should be visible as stressed in the general theory. This certainly can be done without disclosing confidential information, and it is the foundation for establishing credibility in the analysis.

When considering the use of a theory such as this *General Theory*, it is important to examine its strengths and weaknesses. The principles and concepts presented have been tested in numerous applications and have evolved accordingly. They will continue to evolve, but generally they have stood the test of application well, primarily because of the their very basic level of structure and definition. Perhaps, the biggest obstacle (maybe weakness) to the use of such a general theory is doing that first application to such a depth and breadth that its benefits are truly exposed. A principal strength of QRA according to the general theory proposed is that it integrates complex systems in terms of exposing what is really important to the chosen measure of risk. Furthermore, it quantifies the role of uncertainty in the risk measure(s).

Clearly, the general theory applies to marine systems. Its use as a general framework would contribute much to the standardizing of marine system risk assessments while providing a consistency check for the completeness of the analysis. Perhaps the most important advantage of adopting a general framework for doing risk assessments of marine systems is the opportunity it would provide for exchanging information with other industries using the same general theory.

B.11 A CONCLUDING THOUGHT

Quantitative risk assessment is becoming an increasing part of the regulatory process. Regulatory agencies are increasing their dependence on risk assessment, conducting QRAs themselves, and requiring that applicants conduct QRA as part of the licensing process. This has been going on for some time in nuclear energy, and is now spreading into agriculture, chemicals, transportation, weapons management, etc.

Part of this regulatory movement is the idea of a "living QRA. That is, a QRA is not simply done once at the start of a project, and then put on the shelf and forgotten. Rather, it is used as a monitoring and management tool. It is continually updated as the project or operation proceeds, and as new evidence and experience develops. In fact, the Prince William Sound risk assessment had as one of its "primary objectives," to "develop a risk management plan and risk management tools that can be used to support a risk management program."

Experience in other industries, the trend towards formal safety assessments of offshore and related oil production and shipping operations using risk analysis principles, and the Prince William Sound risk assessment, as a specific example, all point to a movement towards more quantitative risk assessment practices in the marine field. A possible direction in marine risk management would be for an international agency such as the International Maritime Organization to have QRAs performed on the various marine operations. It would do all this openly, and make all its evidence available, so that everyone could see what is going on. This would improve trust and communication and help us all see that our self-interest lies in openness and cooperation.

A general framework within which all the QRAs could be evaluated would contribute much to expediting this current trend.

What can happen?
How likely is that?
What are the consequences?

"An" Answer $< s_i, \ell_i, x_i >$

Set of Answers $\{ < s_i, \ell_i, x_i > \}$

Complete Set $\{ < s_i, \ell_i, x_i > \}_C$

$$R = \{ < s_i, \ell_i, x_i > \}_C$$

Include s_0 = "As-Planned Scenario"

Figure B-1. Quantitative Definition of Risk

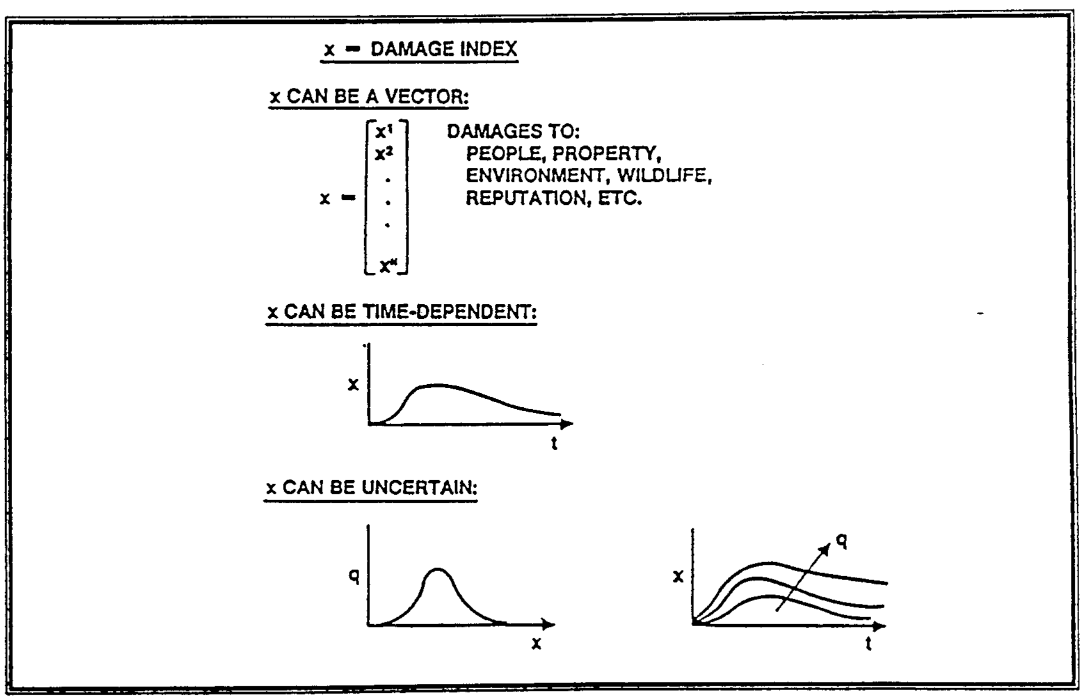

Figure B-2. Expressing the Idea of Damage

1. Frequency (Occurrences per Action or per Unit Time)

   $\ell_i \rightarrow \varphi_i \quad ; \quad R \rightarrow \{ < s_i, \varphi_i, x_i > \}_C$

2. Probability (Level of Confidence)

   $\ell_i \rightarrow p_i \quad ; \quad R \rightarrow \{ < s_i, p_i, x_i > \}_C$

3. Probability of Frequency

   $\ell_i \rightarrow p_i(\varphi_i) \quad ; \quad R \rightarrow \{ < s_i, p_i, (\varphi_i), x_i > \}_C$

Figure B-3. Expressing the Idea of Likelihood —Three Different Formats

- Principle of Categories
- Initiation Principle
- Structuring by Initiating Failure
- Completeness Principle
- Analysis Principle (Zoom Lens Idea)
- Emanation Principle
- Pinch Point Principles
- Scenario Organization Logic — Tools for Display
- "Other" Category

Figure B-4. Principles of Scenario Structuring

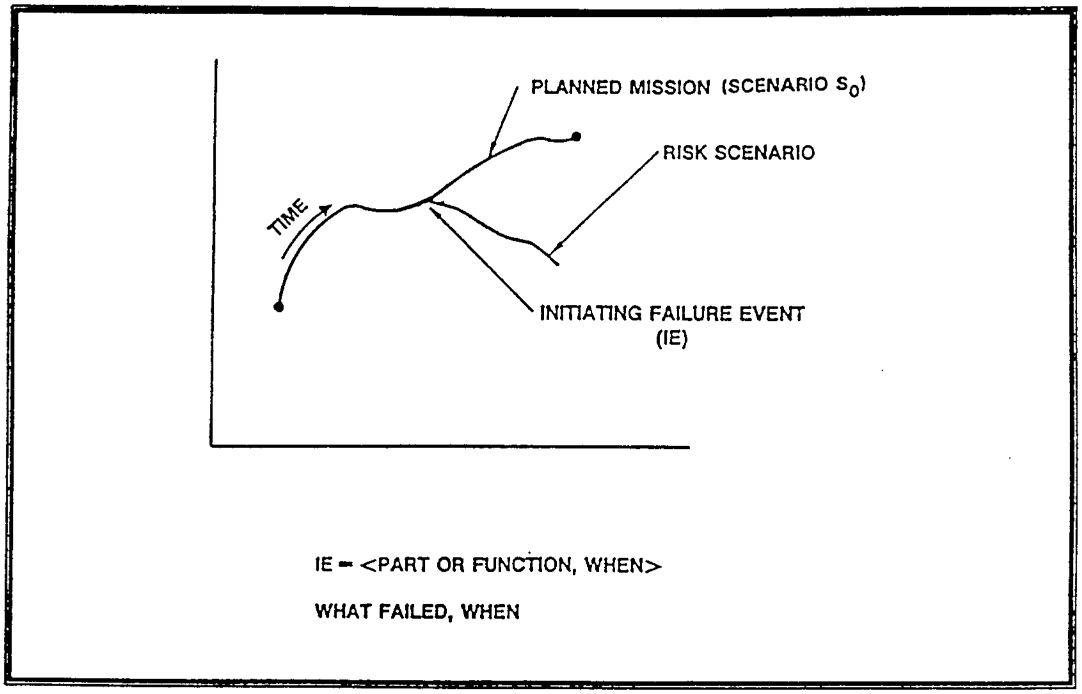

Figure B-5. Mission Trajectory in Phase Space

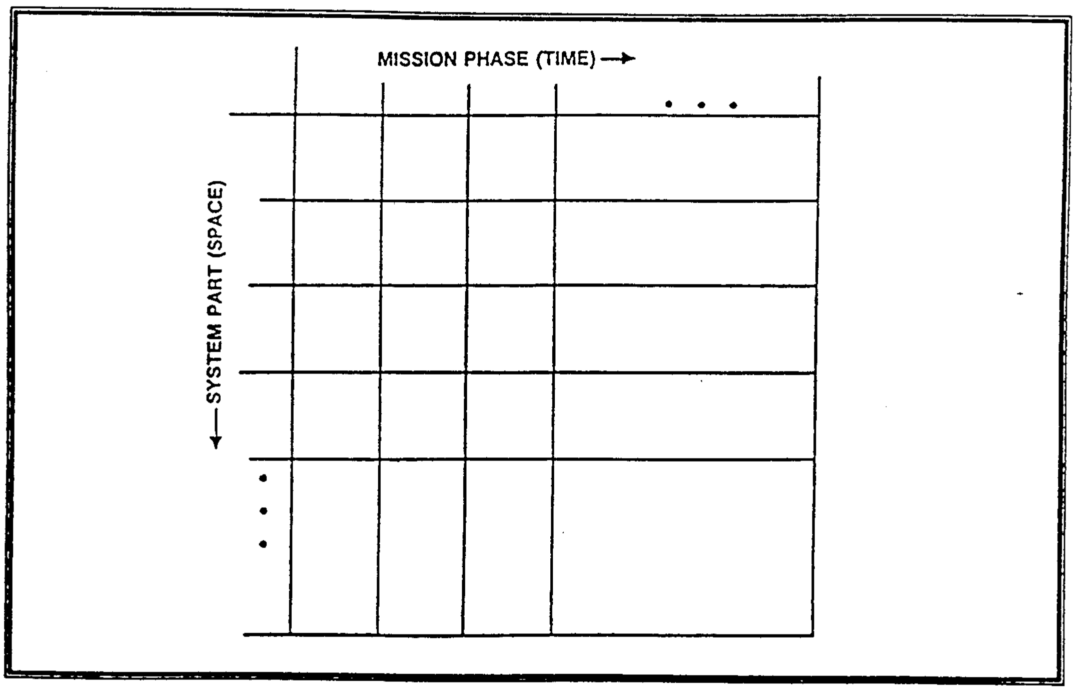

Figure B-6. Two-Dimensional Coordinate Axes in the Space of Initiating Failures

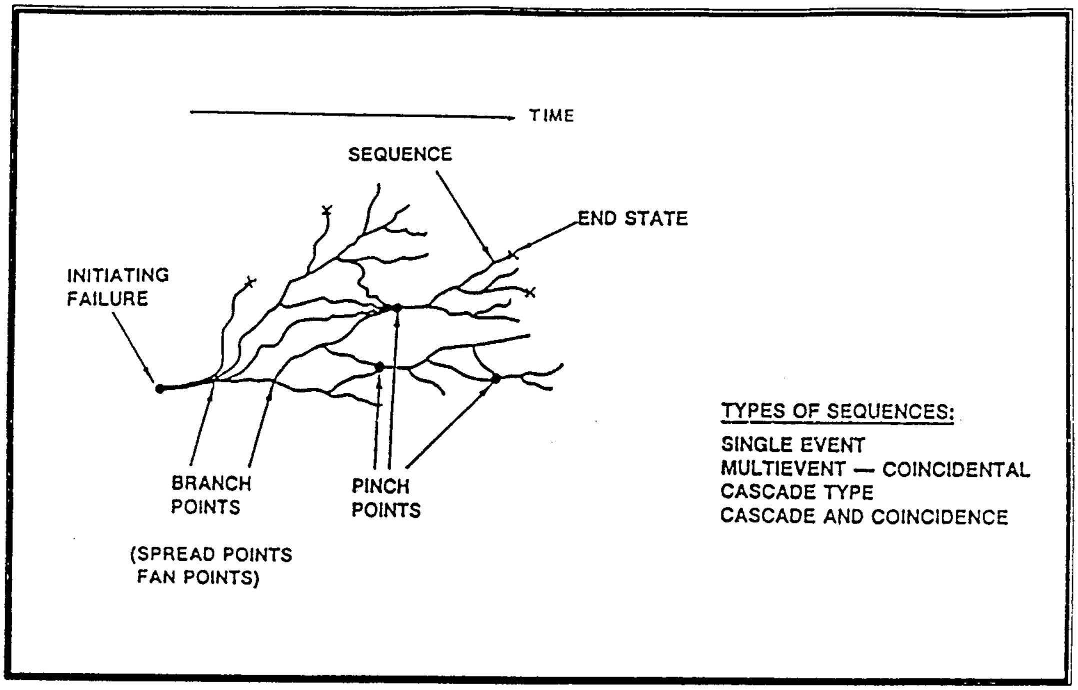

Figure B-7. Emanation of Scenarios from Initiating Failures

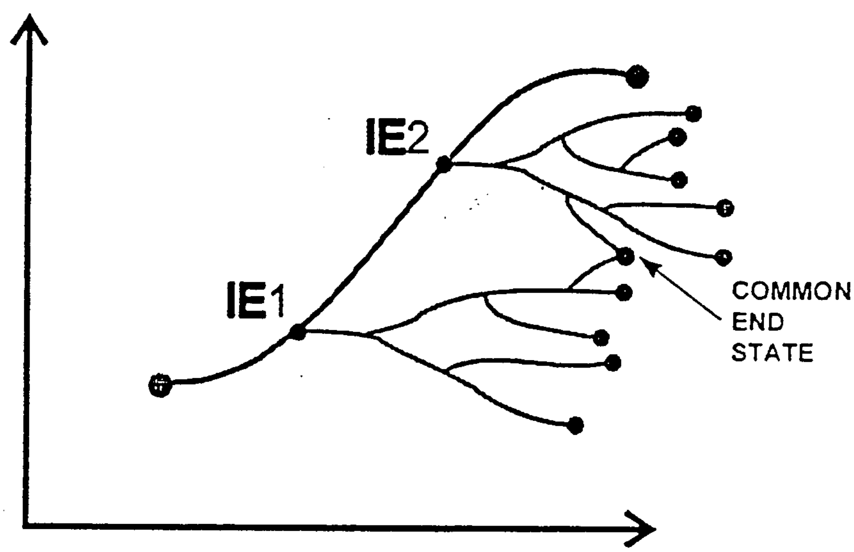

Figure B-8. Scenarios with Common End State

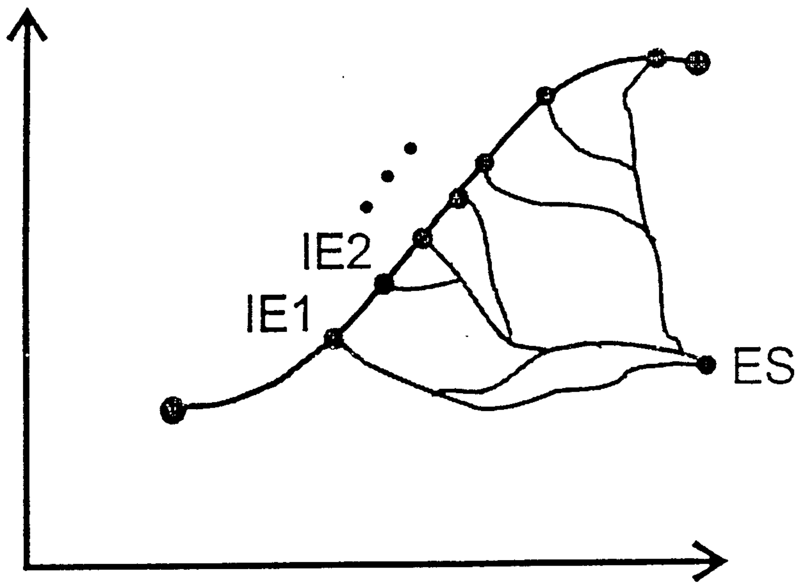

Figure B-9. Incoming Tree

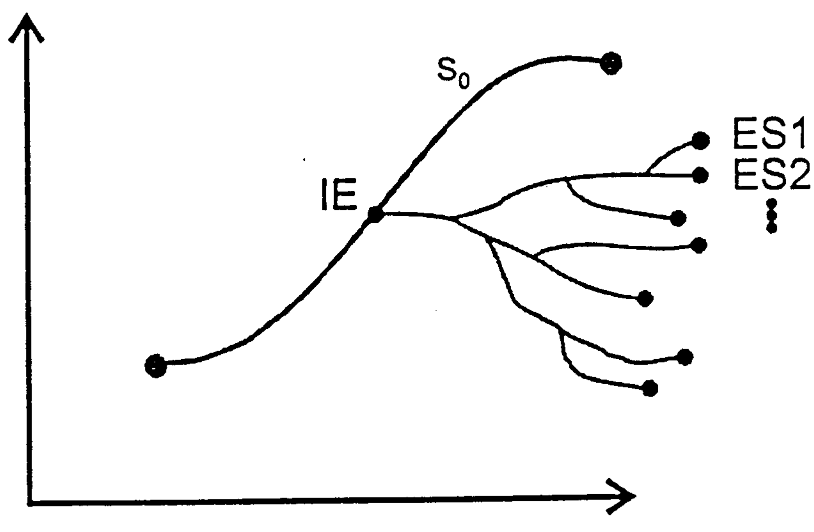

Figure B-10. Mixed Scenario Tree

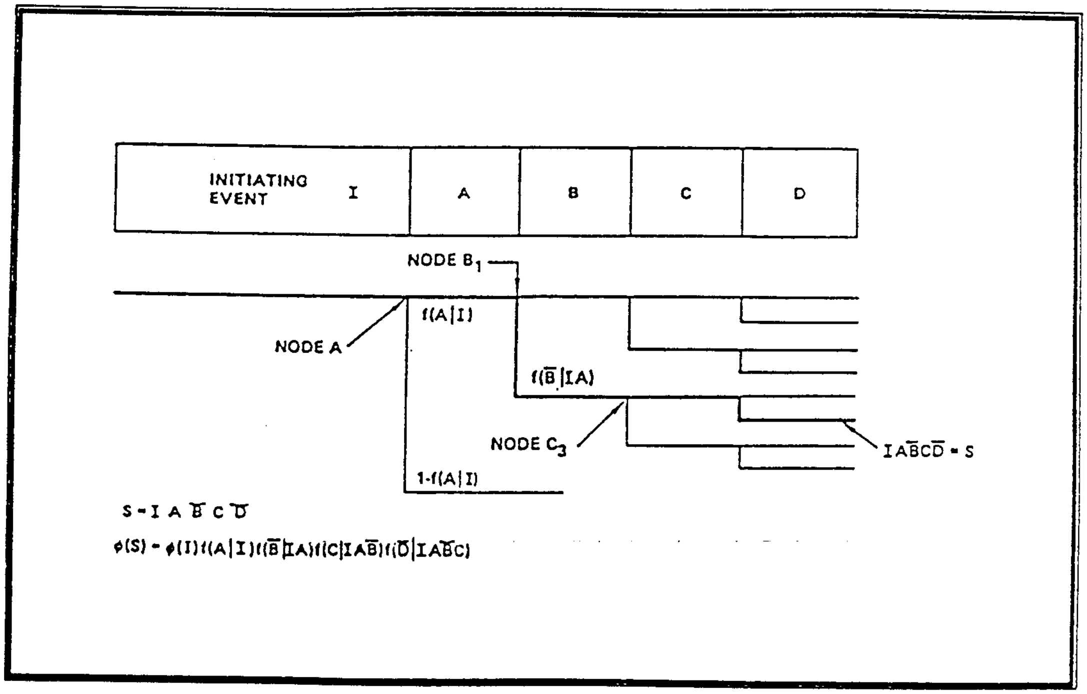

Figure B-11. Quantifying Scenarios

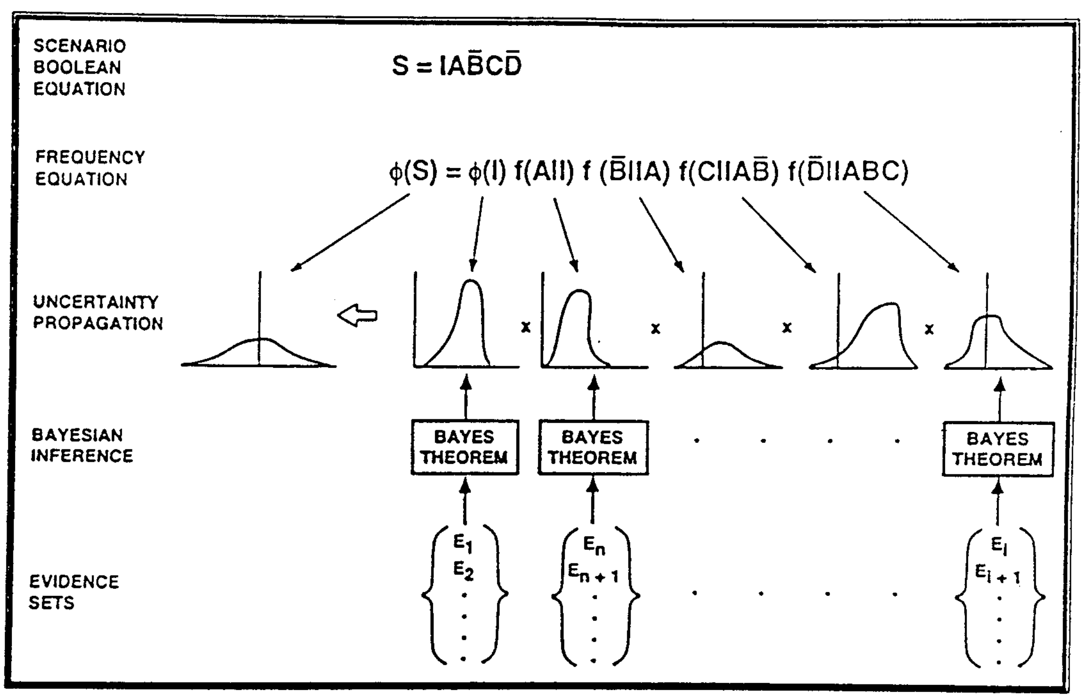

Figure B-12. "Evidence-Based" Quantification Scenarios —Uncertainty Propagation

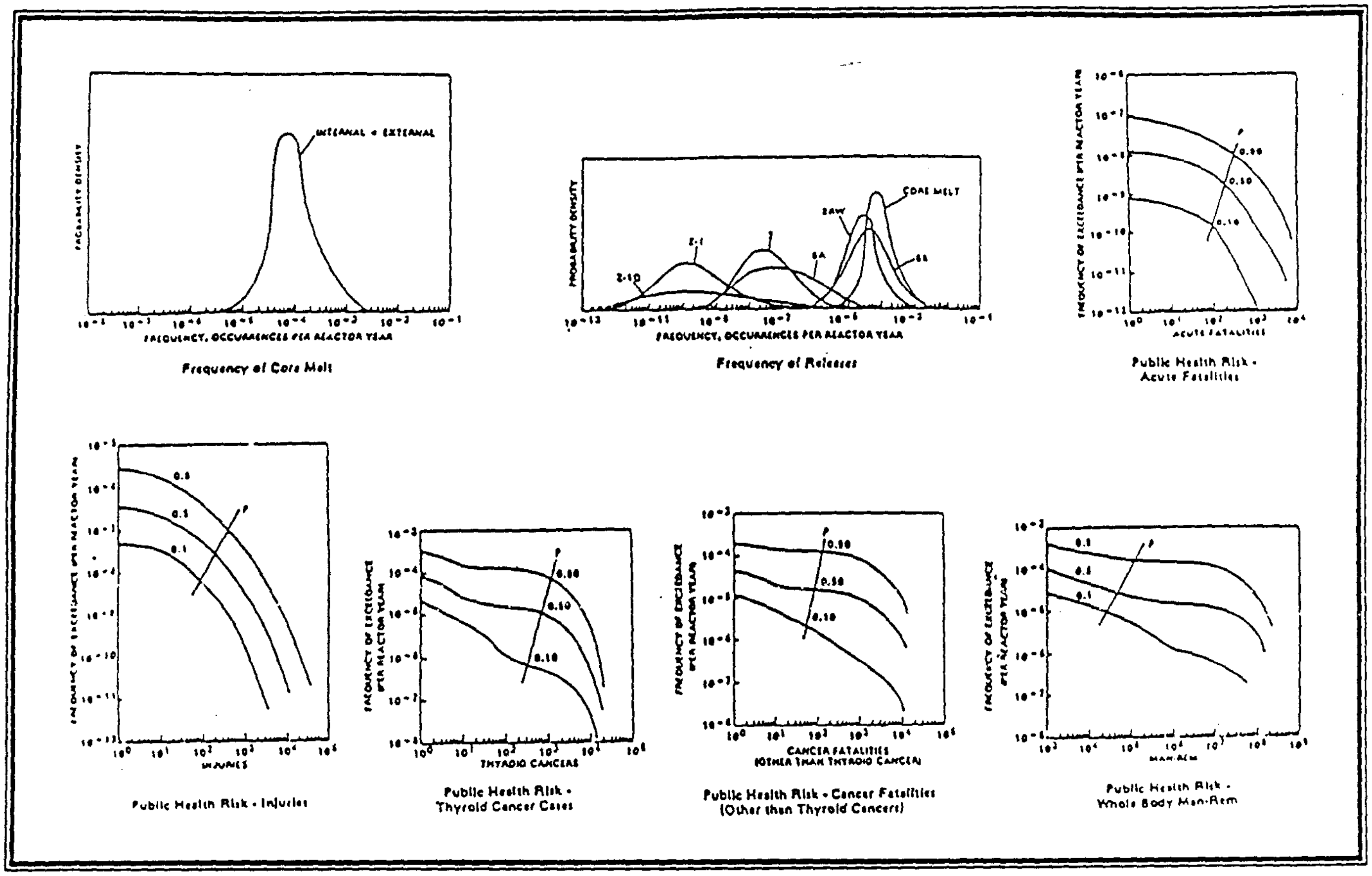

Figure B-13. One-Page Expression for a Nuclear Power Plant

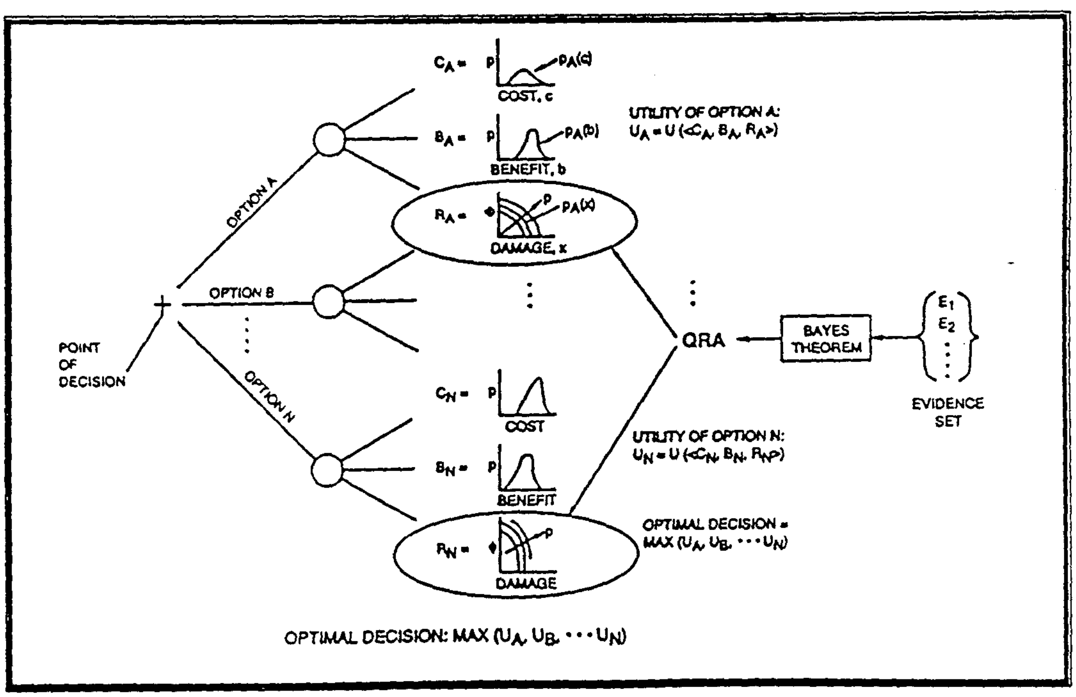

Figure B-14. Anatomy of an "Evidence-Based" Decision —Role of Bayes' Theorem

Kaplan's Communication Theorems

Theorem 1: 50% of the problems in the world result from people using the same words with different meanings.

Theorem 2: The other 50% comes from people using different words with the same meaning.

Figure B-15. Kaplan's Communication Theorem