RISK ASSESSMENT

OFFSHORE OIL AND GAS OPERATIONS

The combination of hostile environments, uncertain technological methods, and large-scale operations increases the likelihood of accidents and the potential severity of the consequences for workers, the environment, and investors

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Oil and gas production offshore has become an increasingly important component of total world petroleum production. At present, over 26 percent of the world's oil is produced from offshore wells, up from approximately 20 percent in 1979. And notwithstanding currently stabilized demand and price for oil, more than 3700 exploration and development wells are expected to be completed offshore in 1984—about a 6 percent increase over 1983.

Varied and complex technologies and human activities are involved in the exploration, development, and production of oil and gas offshore. Failure to provide for the safety of these operations can result in a wide range of undesirable consequences to people, the environment, property, and to continued production. Major accidents have already occurred—most notably the collapse of the Alexander Kielland and the sinking of the Ocean Ranger and the Glomar Java Sea, as well as several helicopter crashes, and the Ekofisk and Ixtoc-I blowouts—with large loss of life.

In earlier phases of the offshore industry, development of the necessary technology and methods was for the most part an evolutionary process that grew out of techniques for drilling on land. However, offshore installations are among the largest structures constructed by man. They must be fabricated in drydock or sheltered water, towed over open sea, and installed at a precise location. In addition, new and unproven technological methods have been required as exploration and production have moved into more hostile regions where weather is more severe and less predictable, waves are higher, water depths are greater, temperatures are lower, onshore facilities are less accessible, and formation pressures are less predictable. Installations in these more hostile regions are generally much larger and more costly than those used in regions such as the Gulf of Mexico. Thus, the combination of hostile environments, uncertain technological methods, and large-scale operations increases the likelihood of accidents and the potential severity of the consequences for workers, the environment, and investors.

Risk, which combines the probability of occurrence of an event and its consequences, can be used to compare large potential hazards (e.g., to pipeline risers) and high-probability events (e.g., pump or compressor leakage). Thus, risk analysis techniques provide a framework for a better understanding of risks, for improving designs, and evaluating the effectiveness of proposed improvements. Increasingly, formal risk analysis is being used in planning, designing, managing, and regulating offshore activities worldwide.

Details of formal risk analyses on specific installations, operations, or systems are not generally available in the open literature, most studies having been done by industry for internal use or for submission to a govern-

mental agency. Currently, only Norway has formally introduced risk analysis into its regulatory framework. The usefulness of these techniques is sufficiently illustrated, however, by the generic examples and summaries of studies that have been published. Available examples include a summary of the application of risk assessment techniques to an offshore development project at the conceptual stage of design [1], an analysis of ship/platform collision risk in the U.K. sector of the North Sea [2], a risk assessment of offshore pipelines and risers [3], and a risk assessment of emergency evacuation from offshore installations [4].

Use of risk analysis for the management of offshore safety and environmental risks has also been documented to a limited extent. A five-year, multiproject study of offshore safety in Norway considered both the assessment and the management of offshore risks. Recently, an international workshop conducted by the National Bureau of Standards reviewed the applications of risk analysis and reliability engineering techniques to offshore oil and gas development. In this meeting, four working groups specifically examined standards, codes, and practices; concept evaluation, and structural design; design, operation, and maintenance of facilities; and logistics and support. Finally, a study is presently being completed which is concerned with the use of risk analysis in the management and regulation of offshore activities by the Minerals Management Service of the U.S. Department of the Interior [5].

FORMULATION OF RISK ANALYSIS

The main elements of a risk analysis for an offshore installation are shown in the flow diagram in Figure 1. They include:

- identification of potential hazards
- analysis of hazards
- analysis of consequences
- evaluation of risk

This same general approach is useful for evaluating both specific design options and the total risk of an entire installation.

Before a risk analysis can be performed, the purpose of the analysis must be clearly defined and the system to be analyzed must be specified. Since a risk analysis is always per-

Table 1
Recommended Sequence of Analyses for Offshore Development Project [7,8]

Phase	Analysis Description
Feasibility study	Rough risk estimate of field development concept
Concept study	Rough risk estimate of installation concept Preliminary process and layout safety study Concept safety analysis (required by Norwegian authorities)
Preengineering	Hazard analysis of process and auxiliary systems Overall risk analysis
Detailed engineering	Detailed hazard analysis of process and auxiliary systems Availability analysis of safety systems Updated overall risk analysis Risk analysis of platform construction work

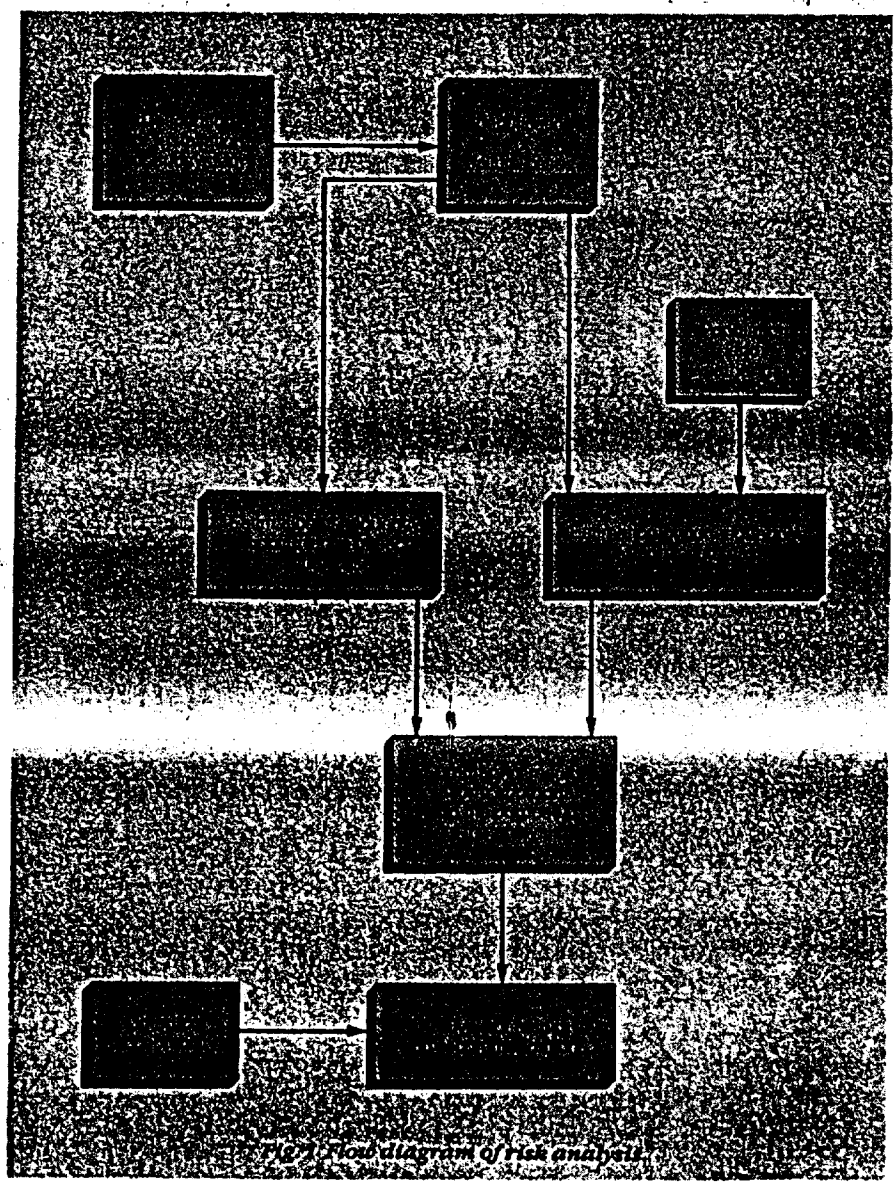

Fig. 1 Flow diagram of risk analysis

Table II
Checklist of Hazards on a Fixed Offshore Installation [9]

Platform Area	Hazard	Potential Causes
Wellhead and manifold	Blowout	Leakage Valve failure Wellhead operation Falling object
	Fire/explosions	Blowout Rupture Leakage Falling object
Process	Oil/gas leakage	Pipe or vessel rupture Valve, flange, instrument leakage Falling object Riser rupture
	Fire/explosion	Oil/gas leakage
Utility	Fire in inflammable liquids	Leakage from pipes, valves, etc. Spill
	Turbine fragments	Crack Overspeed
	Crane accident	Overload Fatigue
	Flare boom accident	Structural failure Falling object Fire
Living quarters	Helicopter crash	Power failure Navigation failure
	Fire	Failure of drain systems Kitchen Smoking
	Evacuation accident	Rough weather Technical/operational failure Extreme accidental load
Deck frame	Structural failure	Material/design failure Welding failure Fire/explosion Falling object Extreme load from splashing wave
Platform support structure	Earthquake	
	Wave load	
	Collision with ship, barge, mobile platform, loading buoy	Technical/operational failure Extreme weather conditions
	Foundation failure	Installation failure Landslide
	Diving accident	Technical/operational failure
Complete platform	Working accidents	

formed so that some kind of decision can be made, the object of the analysis determines the technique and level of detail which is most appropriate. Different organizations involved in the offshore activity may have different purposes for risk analysis, namely to:

- Assist designers and operators in selecting among design alternatives.
- Demonstrate the required safety level of a facility to governmental authorities to obtain approval to proceed with the next stage of the project, such as construction or drilling.
- Aid operators in making nonmandated decisions concerning allocation of resources and introduction of measures to reduce risk.
- Provide a basis upon which governmental authorities and certifying agencies can formulate codes, standards, practices, and regulations.
- Aid public interest and labor organizations in determining the risks to their constituencies.
- Provide the basis upon which governmental authorities and operators can establish research and development priorities.
- Aid operators and governmental and certifying agencies in investigating the causes and effects of accidents.

Often designers and operators directly implement the recommendations of their own analyses, while governmental authorities usually manage risks on the basis of an independently prepared evaluation.

In addition, different types of analysis are appropriate at various stages of an offshore project. Recent reports describing the use of risk analysis and a model for safety management in Norway suggest as many as ten safety studies for the planning and design phases of an offshore development project. Only by carrying out each analysis at the correct stage of the project, is it possible to make the particular changes that the analysis might indicate. The suggested sequence of analyses is shown in Table 1.

To simplify the analysis, the installation activity is usually described by a set of subsystems, such as

- task or activity area: drilling floor, living quarters, pipeline, etc.
- physical barriers: firewalls between areas.
- operation: drilling, helicopter landing, etc.
- system: fire fighting, personnel transportation, etc.

• typical hazard: ship collision, earthquake, etc.

IDENTIFICATION OF HAZARDS

The first step in the actual risk analysis of an offshore operation is the identification of potential hazards. This step must be complete enough so that the fewest possible failures are missing in the later, more detailed analysis steps. The approach for identifying hazards can be informal or, in more complicated cases, rigorous and systematic. Usually a combination of techniques is used to most effectively identify the range of hazards.

Constructing checklists is the most straightforward procedure for hazard identification. The particular activity can be categorized by subsystems for which all the potential hazards are itemized. For example, the hazards on a fixed offshore installation, categorized according to functional area of the platform are listed in Table 2. Other areas of potential hazards or concern include: basic processes, mechanical specifications, deviations from normal operation, containment integrity, personnel protection, and documentation.

Another method for identifying hazards is to conduct a qualitative engineering review of the system based on experience with other identical or sufficiently similar systems. For example, an engineering review of pipeline risers was based on pipeline transmission of oil and gas, the utilities connected to pipelines, and pipeline safety systems. This review showed the major areas of concern to be collision and corrosion of the riser in the splash zone [3].

The practice recommended in RP 14C, published by the American Petroleum Institute, combines checklists and a qualitative engineering review and is based on the knowledge and experience of the oil and gas industry. Proven practices are systematized to provide a basic surface safety system for offshore production platforms. In this widely used approach, undesirable events that can affect various production subsystems are identified, and checklists are used to ensure compliance with general safety principles and specific design guidelines.

The most detailed methods for identifying hazards are failure modes and effects analysis (FMEA) and hazard and operability studies (HAZOP).

Table III
Qualitative Ranking of Hazards for Pipeline Risers [3]

Likelihood	Initiating Cause
Most probable	External corrosion
	Ship accident (collision)
Expected occurrence	Operator errors
	Equipment malfunctions
	Unnoticed damage during installations
	Internal corrosion
Least probable	Sea and environment conditions exceeding design criteria
	Marine life attack
	Abrasions and chafing
	Severe storms
	Debris discharge
	Fire and explosion
	Fishing activities
	Design deficiencies
	Material deficiencies
	Poor quality control
	Erosion

Table IV
Failure Cause Experience for Risers in the Gulf of Mexico [3]

Cause	No. of failures	Percent of total
Mechanical/operational	[illegible]	[illegible]
External corrosion	14	48
Internal corrosion	[illegible]	[illegible]
External forces (natural)	9	31
External forces (manmade)	[illegible]	[illegible]
Total	29	100
Unknown	10	

Table V
Major Platform Hazards for a Typical, Large North Sea Platform Incorporating Development, Production, and Living Facilities [3]

Initiating Cause	Probability of Occurrence per Platform Year
Blowout	3×10^{-4}
Escalation of topsides fire/explosion	5×10^{-4}
Riser leakage	4×10^{-4}
Topsides fire/explosion leading to major structural damage	1×10^{-4}
Collision, earthquakes, helicopter crashes	0.2×10^{-4}
Total platform	13×10^{-4}

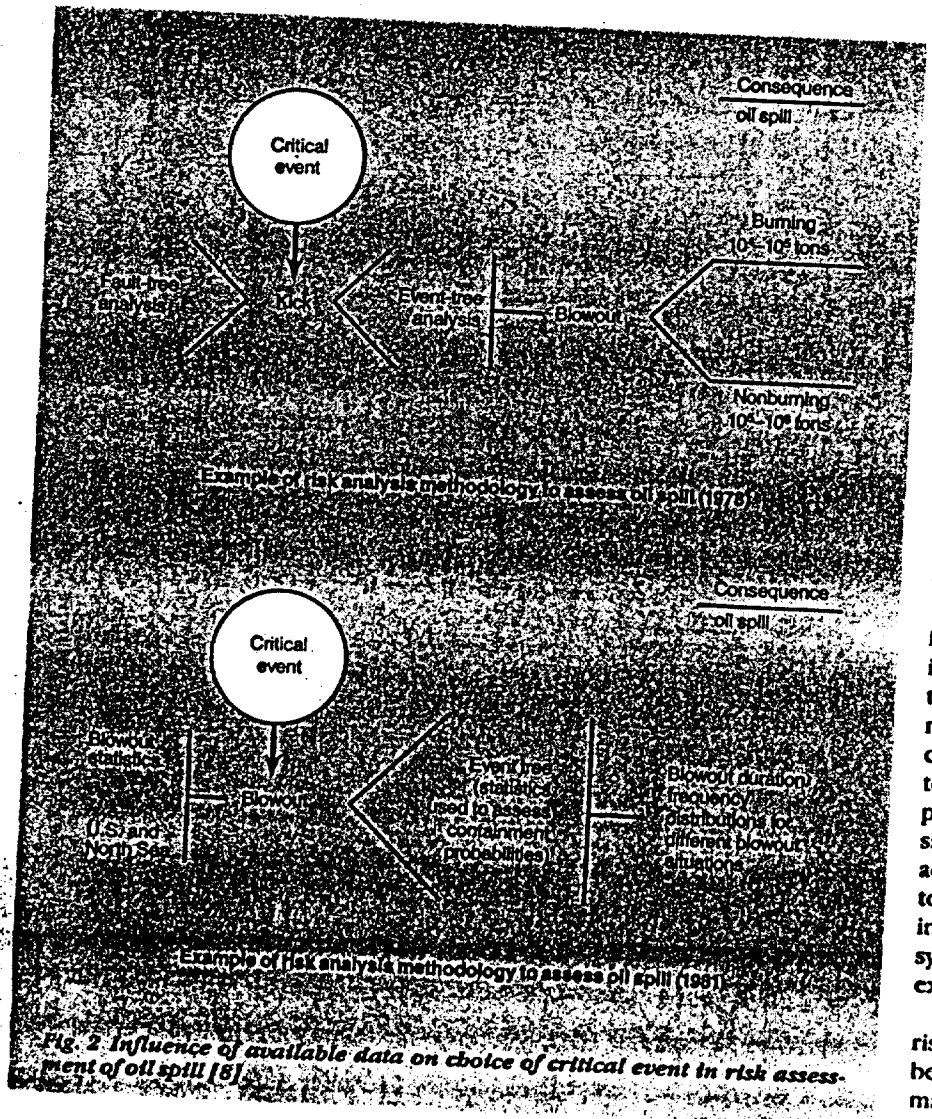

Fig. 2 Influence of available data on choice of critical event in risk assessment of oil spill [8]

With these techniques it is possible to identify and evaluate ways in which a system could fail. In an FMEA, a specified reporting format provides a framework for an engineering analysis in which the possible failure modes are listed and the consequences of each are considered.

HAZOP is a formal technique for identifying process hazards in which a group of experts, each one knowledgeable in a particular aspect of the system function, reviews all aspects of the operation. Deviations from normal operating conditions (i.e. flowrates and directions, pressures, or temperatures) are identified so that the response of the system to possible failures can be examined. For example, leaks, control failures, and valve failures, their causes, and the response of the system to these failures were investigated in a HAZOP of pipeline risers [3]. The major concerns identified were the inability to limit the quantity of gas or oil released if the leak is located upstream of the first isolation valve, and the lack of installed fire-fighting equipment to contain a fire resulting from a pipeline leak.

Using a combination of methods for identifying hazards during a study of the safety of a conceptual design of a fixed installation in the North Sea, 200 accidental events were defined [1]. The events, which included fires, explosions, and structural damage from external impact and extreme environmental conditions, varied in severity. However, all were considered to be sufficient to cause significant damage to the platform.

ANALYSIS OF HAZARDS

After the hazards have been identified, the next step in the risk analysis is to identify the possible causes of these accidental events and determine their expected frequency of occurrence. In this way, various hazards to an offshore installation can be compared for relative importance. The basis for estimating the probability of an accidental event can come from historical accident data or from operating experience for sufficiently similar systems. When these are not available, expert judgement can be used.

Depending on the purpose of the risk analysis, the hazard analysis can be done at varying levels of detail. In many cases qualitative analysis provides a sufficient basis for determin-

ing where to focus efforts in risk reduction. For example, the causes of possible hazards to pipeline risers are ranked qualitatively according to their likelihood of occurrence in Table 3 [3].

In quantitative risk analysis, the frequency (or probability) of critical events is calculated from statistical data, or when there are insufficient data, from detailed causal analysis. If sufficient data are available from accident statistics or experience on a similar system, the rate can be estimated for each failure cause identified in the qualitative hazard analysis. Thus, for example, although the study of pipeline risers was concerned with their use in the North Sea, since no local data were available, failure causes in the Gulf of Mexico were analyzed to give the percentage of failures for each cause, as shown in Table 4 [3]. Care and judgment must be exercised, however, since accident statistics and descriptions can be misleading if there are differences in the standards, design, operation, or environmental conditions of the installations being compared.

The risk of a particular hazard can be put in perspective relative to other hazards by comparing their likelihood of occurrence. Table 5 shows the major hazards and their frequency of occurrence for a typical large fixed platform such as might be found away from shipping lanes in the North Sea, incorporating well development, production, and living facilities. These data indicate that fire and explosion, blowout, and riser leakage are the major hazards to these offshore installations [3].

When no detailed statistical data are available for critical events, detailed causal analysis such as the fault-tree method is used. The top events in the fault-tree analysis are the failure modes previously identified. For example, in a major safety study of a platform in the North Sea, failure modes analyzed with this technique included: overpressure of separator vessel leading to rupture; release of flammable liquid through flare system; failure of firewater deluge system when demanded; failure of emergency power generators; and failure of free-fall lifeboat launching system when demanded [6].

Data for the component failure events that lead to the top event are usually easier to find or estimate than data for the top failure event. Generally, if data for offshore operations are not available, experience from other industries or activities (i.e. onshore operations or chemical plants) is used. Under a project called OREDA —Offshore Reliability Data, seven European oil companies are currently combining their experience with the object of publishing a handbook containing generic reliability data for offshore safety, drilling, and production systems.

ANALYSIS OF CONSEQUENCES

While the purpose of the hazard analysis is to identify and quantify the failures which could possibly lead to a critical event, the consequence analysis estimates how potential hazards may affect each element in the system. Separation of the analysis of the hazards from the analysis of the consequences depends on the choice of critical event. Most commonly, failures leading to the critical event are analyzed using fault trees while the pathways leading from the critical event to the undesired consequences are analyzed using event trees. Cause/consequence analysis is a combination of the two analysis techniques.

Often the choice of the critical event is based on the availability of appropriate data. For example, component failure data associated with leaks and ruptures may be available while direct statistics for fire and explosion are not. In this case it is convenient to begin the analysis of fires and explosions with critical events such as leaks and ruptures.

Figure 2 shows how the choice of the critical event is influenced by the available data. When the environmental risk associated with blowouts was first analyzed in 1977/78, appropriate blowout statistics were not available, and *kick*—an imbalance between formation pressure and well pressure—was chosen as the critical event. In 1981 when the analysis was updated, more statistical data for blowouts had become available, so that blowout could be chosen as the critical event. Accordingly, more detailed consequences such as blowout durations could be determined.

In the early stages of a project when the object of a risk analysis is to specify the design loads by determining the probability of different loads on a component, the most general critical event is selected so that as many load combinations as possible can be obtained. Later, after the active and passive protection systems have been specified, the object might be to verify their effectiveness against accidental loads. Then, a more specific critical event allows the probability of loads that exceed the design loads to be determined.

In the offshore industry, consequence analysis requires engineering modelling of thermal and mechanical loading resulting from fires, explosions, collisions, impact from falling objects, wind, waves, and earthquakes. For example, a rigorous consequence analysis could require sophisticated models of nonlinear dynamic structural response, dispersion of dense gas/aerosol clouds, two-phase discharge behavior of hydrocarbons, initial mixing of high-pressure releases, and combustion of hydrocarbons in realistic circumstances of confinement and high turbulence. However, except in critical cases, cruder analyses based on static linear analysis and simple energy concepts are often sufficient for risk analysis purposes.

Results of a consequence analysis can be very specific. For example, an analysis of pipeline risers considered the effects on the structure of flame from ignition of a riser leak [3]. The calculations indicated that the consequences would depend on the type of platform structure: exposed members of a steel jacket structure could lose their strength within 15 to 30 minutes under direct flame, while a concrete structure would be resistant for up to a few hours.

EVALUATION OF RISK

The final step of the risk analysis is to compare the results, summarized from the hazard and consequence analyses, with criteria of acceptability determined by the initial objectives. Depending on the purpose of the analysis, the acceptability criteria are most often established by industry, government, or a standard-setting or certifying agency. Thus, the conclusions of a risk analysis usually take the form of a ranking of risk for various design and operation alternatives and recommended options, a go/no-go evaluation, or a recommended framework for management and regulation to reduce risks from offshore activities. As a guide for making recommendations, critical events that contribute

most to the risk can be identified to indicate whether it is the frequency of occurrence or the consequences or both that cause the events to be significant.

The findings of the hazard and consequence analyses are usually presented as a set of particular event-tree results. These can take the form of either a qualitative ranking or an estimated frequency of occurrence including the number of fatalities or amount of work time lost, the amount of oil spilled, the degree of damage to a specific area of the platform, or the amount of loss of platform capital value. However, more detailed risk presentations can provide the complete probability distribution over the range of consequences. Additional levels of detail can be achieved by determining the distribution of risk as a function of location on the installation or of worker activity.

IMPLEMENTATION AND RISK MANAGEMENT

The results of a risk analysis can be used to make specific engineering recommendations. For example, analysis of pipeline risers identified three ways to minimize potential damage: corrosion protection, protection from falling objects, and protection from ship operations [3]. Engineering solutions were identified for each measure, although further evaluation, analysis, or research and development might be required before the recommendations could be implemented. Thus, control of external corrosion could be provided by various protective coatings and/or cathodic protection, while covers and fenders could provide protection from falling objects and collisions. In addition, the possibilities of alternative riser locations could be examined during the design phase. Thus, internal locations within the structure would limit damage to the risers, although difficulty of maintenance or replacement would be increased. However, attaching the riser externally to a platform leg would increase the possible hazards and their likelihood of occurrence.

In Norway, risk analysis was used within the regulatory framework. A concept safety analysis of the platform design (see Table 1) must be submitted as part of the general field development plan required by the governmental authorities for fixed installations. Acceptance criteria specified by the authorities are based in part on a group of accidental events which must have a total expected frequency less than a stated target level. Although the method of analysis is not specified, the criteria lead naturally to a risk analysis approach. About a dozen of these studies have been completed for a wide variey of installations, and there is general agreement that the concept safety analysis requirement has a strong influence on consideration of safety of the installation at a formative stage of the project.

Definition of acceptance criteria for offshore oil and gas operations raises issues which find little agreement among governments, industry, and the public. Data show, however, that the offshore industry has an accident rate which is not very different from other heavy industries, such as mining, maritime transportation, and heavy construction.

There are a number of limitations to the application of risk analysis to offshore oil and gas operations that should be mentioned:

- Reliability data for safety, drilling, and production systems used in the offshore environment are not readily available. Publication of the OREDA Handbook should help to alleviate this problem in the near future.
- There is a shortage of risk analysts who understand offshore technology and the interaction between operations personnel and the technology.
- Formal risk analysis tends to focus attention on the catastrophic events, while ignoring the routine events which in aggregate may also cause significant damage and loss. Thus, risk analysis should not be a substitute for other, more traditional approaches to safety management.
- Since considerable judgment is involved in risk analysis, an implicit bias for or against offshore activities could be introduced into the results.
- Risk analysis may be subject to the fallacy of "misplaced concreteness," where the consequences that can be quantified take on an exaggerated importance relative to those that remain more qualitative.
- Analyses using logic diagrams are subject to error resulting from uncertainty of data, omission of branches, neglect of interdependencies of failure modes, difficulty in incorporating human error, and incompleteness.

Notwithstanding these limitations, experience has shown that risk analysis can provide a rational framework for safety decisions in planning, design, construction, operation, management, and regulation of offshore oil and gas activities. Although risk analysis has been applied mostly to safety management in North Sea operations, the present trend is to increase the use of these methods in offshore activities worldwide. ME

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