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Methodology for Comparison of Alternative Production Systems (MCAPS)

A Report to the Joint Industry Project Participants

by

The MCAPS Project Team

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Consultants

and

J. F. Geyer, G. J. Shoup and B. Stahl

Amoco Production Company

December 1990

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[1] Ocean Engineering Services; formerly with PMB Engineering, Inc.
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1.0 Introduction

Offshore production is moving into deeper and more hostile environments. Operators faced with development of leases in these environments have a variety of alternative production systems from which to choose. Examples of such systems include fixed platforms, tension leg platforms (TLPs), compliant towers (guyed, piled, flexible, and buoyant), floating production systems, remote subsea systems, as well as pipelines or tankers for transportation of produced hydrocarbons.

These systems involve varying degrees of technical innovation and technological risk. Life cycle costs, including initial costs and operating costs over the life of the project, should be carefully considered to define systems that will minimize cost and maximize return on investment in the development of deepwater reserves. The life cycle includes all stages of the project, including design, construction, operation, and decommissioning.

To address decision-making issues in the selection of alternative systems, Amoco formally offered the MCAPS project for joint industry participation. Eighteen companies eventually joined the project, which 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 first meeting was held directly following the San Ramon meeting; the second was held at Amoco's Tulsa Research Center during the week of July 11, 1988. A mid-term progress report was issued and reviewed with participants in San Francisco in October 1988. In March 1989, a summary of project results and various appendices to the project reports were transmitted to the participants. A review of these documents was held in Tulsa with the participants on April 4, 1989, at which time the MCAPS project team met for the third time.

This is the final report for the MCAPS project. It pulls together the various appendices prepared by the consultants and draws conclusions concerning the applicability and the future direction of this technology.

1.1 Objectives

The MCAPS methodology is intended to be an engineering procedure that will assist the process of making rational comparisons among design alternatives for offshore production systems. Currently, such comparisons are often made primarily on the basis of initial cost estimates without explicit consideration of risks and related life cycle costs, which can be several times the initial costs. Use was made of recent developments in structural system reliability and full scope risk assessment. The latter includes consideration of all identifiable hazards to the operation, including those involving the riser system, equipment, and the environment.

Specific objectives were:

1. To develop, document, and assess a methodology for comparison of alternative production systems.

2. To perform qualitative comparisons of three (3) 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: (1) two tendons per column instead of four and (2) subsea well completions instead of surface well completions. These configurations were determined *a priori* to be of considerable interest within the industry.

3. To review the basis for quantitative comparisons, perform illustrative quantitative comparison involving the two variations of the TLP base case configurations, and assess the usefulness and limitations of quantitative comparisons.

As the project progressed, some changes in the objectives were made. One of the major decisions made was to add a "coarse quantitative" analysis approach to the qualitative analysis work originally planned. The qualitative work was necessary but it was not documented in detail. The MCAPS team felt that emphasizing the quantitative aspects would result in a better work product and avoid ambiguities, for example, in combining measures of event probability with measures of consequence. This decision was also motivated by Peter Marshall's presentation in San Ramon entitled, "Comparative Reliability Analysis of Production Systems (CRAPS)," which produced quantitative comparisons.

1.2 MCAPS Project Organization

The organization to conduct the project was comprised of a four part team (see project organization chart, Figure 1.1):

1. Amoco administered the project, provided technical guidance, assistance and technical reviews, ensuring that the relevant views of all participants were fully considered.

2. C. Allin Cornell, Inc. (CAC; Portola Valley, California) had responsibility to develop a methodology for comparison of alternative systems. CAC worked with PMB and SikteC in applying the methodology to the TLP system configurations, ensuring that the interactive aspects between the mechanical and structural subsystems of each TLP configuration were fully considered. CAC, with assistance from Amoco and the technical advisory committee, was responsible for critically reviewing project results and assessing the benefits and limitations of the methodology.

3. PMB Engineering, Inc. (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 TLP structural and foundation system configurations, and for 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 for evaluation of alternative systems, for the "coarse quantitative" full scope risk assessment of topsides and operational systems for the TLP configurations, and for the quantitative illustrative comparisons involving the surface vs. subsea well completion systems.

An important benefit of organizing an international team to conduct this project was the merging of technologies residing in the U.S. and in Europe. Members of the MCAPS project team were R. G. Bea, Ocean Engineering Services, formerly with PMB Engineering, Inc.; C. A. Cornell, CAC, Inc.; J. E. Vinnem, SikteC A/S; and J. F. Geyer, G. J. Shoup, and B. Stahl, Amoco Production Company. H. J. Grundt of Statoil joined the MCAPS team, at no expense to the MCAPS project, as an adjunct member in the latter part of 1988 to contribute Appendix H on production availability analysis. In early 1989, P. H. Wirsching of the University of Arizona joined the MCAPS project team, as an adjunct member at Amoco's expense, to perform the tendon system fatigue reliability and maintainability analysis (Appendix G).

1.3 Approach

The three basic steps in the approach were:

1. review, select, and extend (as necessary) methodologies for comparing technical projects such as novel deepwater production systems;
2. conduct an application on selected systems (various TLP configurations);
3. evaluate the process and the results with respect to the viability and benefits of their future application in industry practice.

As would be done in an actual application, the second step was conducted in two phases - a qualitative (screening) phase and a quantitative, more detailed assessment of elements deemed important to the comparison. The qualitative (screening) phase was done without detailed documentation. Instead of spending efforts on detailed documentation of the qualitative phase, it was decided to add a "coarse quantitative" phase.

Detailed quantitative analyses were performed to illustrate how to complete such a study; selected "event trees" were used as examples of more detailed characterization of the differences between two alternative tendon systems, a two-tendon and a four-tendon system, and three alternative well system configurations, a surface tree concept, a split tree concept, and a subsea BOP concept.

1.4 MCAPS Philosophy

The MCAPS methodology is intended to be a structured and logical basis for comparison of alternative production systems. The analyses are intended to improve the consistency and quality of evaluations of alternatives within the constraints of knowledge, time, and manpower available at the time the alternatives must be evaluated. The analyses can be used for managerial, engineering, construction, and operational evaluations of the alternatives. Of particular concern are new and innovative systems for which there is limited experience.

The MCAPS comparisons have three basic objectives:

1. Assist in the choice of the "best" alternative system.

2. Assist in maximizing reliability of the chosen system at the lowest possible cost.

3. Define those key aspects of design, construction, and operation that must be closely monitored throughout the life cycle of the system to enable realization of the economic and reliability goals.

There is no magic in MCAPS technology. It is a disciplined process for examining the interaction of complex components and subsystems and the effect of uncertainties on the predicted behavior of a system. It is a process that is intended to disclose the presence of "critical flaws and hazards" and allow engineering and operations safeguards to be put into place to remove and defend against such critical flaws and hazards.

The power of MCAPS technology is centered in the human resources that are used to exercise this technology. Applicable experience with comparable systems is a primary requirement. In many instances, personnel with "perverse imaginations" are needed to identify critical hazards and combinations of events that can result in critical flaws. Because the systems of major concern are new and innovative, there is generally little definitive objective data to guide the characterizations of uncertainties (qualitative or quantitative). Here again, experience and proven judgement by those guiding and performing the analyses are critical to assuring meaningful results.

Although the MCAPS methodology uses formal probability analysis to facilitate communication among diverse disciplines and to ensure internal consistency in the analysis of multiple components, interactive subsystems, uncertainties and risks, it should be emphasized that the MCAPS methodology is not "a numbers game". The primary objective is not to produce quantitative estimates of risks. The primary objectives are to make good choices, maximize safety and economy, and then follow through during the life cycle of the system to insure that the safety and economic goals are realized.

MCAPS is a framework for thought, deliberation and communication. It is a framework intended to allow definition of the best system and safety management alternatives.

1.5 Organization of Report

The MCAPS project is comprised of the main body report, i.e., the text you are reading now, and Appendices A through F, published in separate volumes as indicated in the Table of Contents. The appendices document various aspects of the MCAPS process and its application. An Executive Summary is provided in Section 2 of this report. The Methodology is illustrated in Section 3 by application to an example tension leg platform, the MCAPS TLP. The comparative MCAPS cases along with results are discussed in Section 4. A number of observations, perspectives and evaluations of the MCAPS process are given in Section 5, and governmental requirements concerning risk assessment are discussed in Section 6. Finally, a number of conclusions are drawn in Section 7 and general recommendations are made in Section 8.

2.0 Executive Summary

The MCAPS project illustrates a full scope, life cycle risk assessment of an offshore production system involving an example tension leg platform. The emphasis of the project is on comparative assessment of alternative tension leg platform configurations. The term 'full scope' implies consideration of all components and subsystems of the production system. The term 'life cycle' implies that the evaluation encompass all phases of development and operation, from engineering design through decommissioning.

Methodologies for comparative risk analyses are presented and illustrated. Event trees were chosen in the MCAPS project as the basic vehicle for analysis and display of results, although other methods were used for detailed analysis and are not precluded for use in the future. A model for random cash flow was devised which incorporates the usual cash inflows and outflows in a project, but in addition, incorporates random outflows due to accidental events. Random accidental events including their consequences in various categories were modelled, leading to estimates of risk costs and fatal accident rates. Such risk-weighted, or mathematically "expected", costs may well be dominated by low probability, high consequence events. If so, this in itself is important management information.

Four cases were analyzed and compared involving three production riser alternatives and two tendon system alternatives for the MCAPS TLP. The three riser alternatives were: 1) a surface tree concept, 2) a split tree concept, and 3) a subsea BOP concept. The two tendon system alternatives were: 1) a 4-tendon per leg system and 2) a 2-tendon per leg system. The base case was considered to be the surface tree concept with the 4-tendon per leg tether system.

Comparative analyses showed that the subsea BOP riser alternative presented the highest risk. However, the MCAPS process identified possible design improvements to be investigated which could make this alternative the most attractive. Comparison of the 2- and 4-tendon systems indicated that when initial costs are ignored (the design philosophy employed required more steel and hence led to a greater initial cost for the 2-tendon system than the 4-tendon system), the 2-tendon system appears to be a viable alternative to the 4-tendon system from a risk standpoint.

The MCAPS process and how it should ideally work in practice is described. Shortcomings with regard to the process as it was applied in the MCAPS project are discussed.

General observations are made concerning risk assessment in the MCAPS process. A perspective on quantitative risk analysis results is provided including discussion of present worth values, risk costs, fatal accident rates, and notional vs. actuarial risks. The applicability and limitations of risk assessment are discussed as well as related existing and pending regulatory requirements.

The general conclusion from the MCAPS project experience is that risk assessment is not a simple process. It is an intensive interdisciplinary process requiring good teamwork and extensive familiarity with the system being analyzed. The judgmental elements of risk assessment can be considerable. Professional consensus or agreement on characterization of uncertainty is often lacking. Many of the issues confronted in the MCAPS project are still being researched, but it is concluded that this should not be a barrier to future development and application of this technology.

The MCAPS technology is available now for application, but developments of improved software, data bases for component load and strength uncertainties as well as failure rates, and guidelines for consistent applications of risk assessment are sorely needed. The benefits of risk assessment include an improved understanding, qualitatively and quantitatively, of risk mechanisms, identification and mitigation of hazards, improved cost-effectiveness of designs, and improved safety. Risk assessment can be applied to existing conventional systems and to new, novel systems for frontier environments, but it is most beneficial when it is applied to large and technologically complex systems (megasystems) and projects that are novel in their design, construction, installation or operation. The cost of applying risk assessment to an offshore development project typically falls in the range of 0.2% to 0.5% of the field development cost (excluding drilling costs), the amount depending on the size of the project and its degree of novelty. It is argued that the cost/benefit ratio of applying the MCAPS methodology is often less than 1 over 10.

While difficulties exist in performing risk assessment, the results are defensible provided there is a willingness to utilize quantitative results qualitatively, to help make judgements about the best design options or operations alternatives. Quantification of risks in an absolute, actuarial sense is extremely difficult because data is often lacking or insufficient, and therefore such risk estimates must be regarded as uncertain. The most important benefit of an analysis such as MCAPS is the process that is involved in carrying out the analysis, the teamwork that is facilitated, and the communication that is established among the various team members and management involved in the project. The specific risk numbers generated may be less important and should serve only as a guide to focus attention on those aspects of the project which generate the most risk and to indicate where cost-effective risk reduction measures can be taken.

3.0 Full Scope, Life Cycle Risk Analysis of the MCAPS TLP

3.1 The MCAPS Methodology

There are many methods in the literature and in practice that are potentially applicable to comparative analysis of offshore production systems. It was agreed in the MCAPS project that the method should be capable of considering quantitatively at least the following factors:

- Structured analysis of technical systems of interacting components
- Randomness/relative frequencies of safety related (and other) events
- The multiple phases of the life cycle of a production system
- A multiple (vector-valued) representation of possible outcomes, e.g., dollars, lives, environmental impact, etc.
- A scalar-valued preference measure (such as expected present worth)
- Explicit representation of the uncertainty in the estimates of the frequencies and outcomes.

These factors are best considered by a method that treats randomness and uncertainty by probability theory, and that includes multiple-valued outcomes as well as a single expected cost measure. There are several practical schemes by which the probabilistic models of accidents, external events, and the subsequent component and system response can be constructed and evaluated. Based on experience with similar problems in the offshore and other areas, event trees were chosen in this project to be the preferred model of operation and display of results. Other techniques are not precluded for use in the future, and were even used for detailed analyses within this project, e.g., structural and foundation reliability analyses using continuous random variables (Appendix F), the use of programs such as MIRIAM (Appendix H) for availability analyses, and fault tree analyses (Appendix E), etc.

A detailed presentation of the MCAPS methodology, including key concepts, alternative methodologies, and methodological issues, is provided in Appendix A. The remainder of Section 3 of this report presents the MCAPS methodology by illustrating its application to an example tension leg platform, the MCAPS TLP.

3.2 Description of the MCAPS TLP

Figure 3.1 shows an elevation view of the MCAPS TLP located in 2500 ft of water at a hypothetical location in the Gulf of Mexico. The deck section consists of a main deck and weather deck. The deck is supported by four vertical columns. These columns are interconnected by the submerged horizontal pontoons at the base of the hull. The hull and deck structure features bulkhead supports, plate girder stiffeners, and integrated deck fabrication. The hull and deck would be fabricated together using established ship building techniques.

Appendix B provides a more detailed description of the MCAPS TLP, including the structural and mechanical systems. The structural system includes the tendon mooring system and the integrated well/tendon template which has slots for 24 wells, 16 tendons, and 32 piles. Environmental design criteria are provided along with response analyses. Installation and operational considerations are also discussed.

The alternative tendon systems, i.e., the 2- and 4-tendon per column configuration, sizes, and selection criteria are also presented in Appendix B. These are the structural subsystem alternatives being compared in the MCAPS study.

Appendix B provides a detailed description of the mechanical systems including the topsides production equipment and the riser configurations. Three alternative production riser systems are described, i.e., the surface tree concept, the split tree concept, and the subsea BOP concept, which provide the basis for the MCAPS mechanical systems comparisons.

Appendix B also includes the major production characteristics that provide input to the production availability analysis described in Appendix H. Production rates are estimated for the MCAPS economic analysis. The best estimate production rates are indicated in Figure 3.2. The peak production rate is 43 thousand barrels of oil per day (BOPD) and 65 million standard cubic feet per day (SCFD) of gas. These production rates provided the basis for calculating the risk costs associated with deferred production.

3.3 Full Scope, Life Cycle Risk Analysis

The term "full scope" implies that the evaluations encompass both structural and non-structural aspects of alternative production systems. Structural aspects include all elements and components that provide a marine support base for the production system. Non-structural aspects include all equipment, facilities, supplies and personnel that are necessary to conduct drilling and production operations.

The term "life cycle" implies that the evaluations of alternative production systems encompass all phases in the production system development and operations. The 19 yr life cycle of the MCAPS TLP system was divided into five principal phases, as shown in Figure 3.2, and include:

Engineering (1 year)
Construction (3 years)
Predrilling (in same time period as construction)
Drilling and Production (15 years)
Decommissioning (at end of drilling/production period)

As a decision analysis problem, the full scope, life cycle analysis of a production system is characterized by (a) a simple choice among only a few alternatives, but (b) many event trees representing each alternative. The choice is either between two (or a small number of) alternative systems or between acceptance and rejection of a single system (implicitly, it is compared to unspecified alternative investments, i.e., is the expected present worth positive?). The many event trees are those associated with the many different structural and topsides initiating events (collisions, fires, etc.).

In addition, the parameters (probabilities and outcomes) may vary with time (e.g., as the operations on the platform change, as the number of wells grow, as fatigue occurs); this time change also effectively increases the number of different trees. Further, these many potentially serious initiators require that analysis resources be intelligently managed, especially if the industry or the investigators have had little prior experience with the particular production system under consideration, e.g., a novel system. Effective resource allocation demands that the analysis be done in increasingly focused stages.

3.3.1 Random Cash Flow

The economic analysis is structured around a familiar cash flow diagram. Figure 3.3 displays the successive periods of the production system's life cycle. Such a diagram displays the cash inflows, CI_i and outflows, CO_i, that are then appropriately discounted to obtain the present worth (PW).

For MCAPS, the diagram is generalized. First, the CO_i and CI_i may be random variables. Second, random events and their vector of random dollar loss outcomes, $\underline{E}_i$, are introduced in each year. An element E_{ij} corresponds to the dollar loss in year i from accident type j. Although CO_i, CI_i, and $\underline{E}_i$ can, with this methodology, be treated as random variables, it will be sufficient for all the illustrations in the project to include only their <u>expected</u> values, i.e., their mathematical mean values, because "risk indifference" is assumed in this project. If the possible losses were large compared to the owner's assets, this assumption would have to be modified. (See Appendix A, Section A.2.7).

A similar diagram, equation, and analysis can be constructed for each of the other attributes or consequence categories (e.g., lives lost, spill volume, etc.), although these will not contain terms corresponding to CO_i and CI_i, only accident-related terms similar to $\underline{E}_i$. To discriminate, let us call these (nondollar) random event consequences, $\underline{A}_i$, $\underline{B}_i$, and $\underline{C}_i$, vectors corresponding to lives, A_{ij}, spill volume B_{ij}, and years of deferred production C_{ij}, in year i due to accident type j. Applying the (expected) present worth equation once for each attribute, we obtain, for example, four such present values, one for each of the four attribute types, namely $\underline{A}_i$, $\underline{B}_i$, $\underline{C}_i$ and $\underline{E}_i$. These results are called risk costs to distinguish from the "anticipated" cash flows associated with CO_i and CI_i.

3.3.2 Modeling Random Events and their Risk Costs

Among the random events, only those events that are chosen to be modeled by event trees are retained. In this project's illustrations, these are primarily relatively rare events with potential safety or large economic implications. Costs such as routine maintenance and loss of system availability (e.g., anticipated or average downtime rates) can be included within the CO_i terms. Appendix H discusses the use of modern probabilistic availability analysis; its output was included in CO_i.

In the MCAPS analyses, attention was focused on the random costs or risk costs associated with damage to the structure and facilities, deferred production, and oil spills. Loss of life due to accidental events was also considered but this was kept as a separate category.

The analyses were done by dividing the assumed life cycle of the MCAPS TLP project into 19 years. For each year of the project life cycle, event trees were constructed to model the random events that could have significant negative consequences. The event tree is comprised of three major components (see illustrations in Section 3.3.5):

1. An initiating event and its frequency of occurrence
2. Nodes, branches, and branch probabilities
3. Terminal events and their consequences

Risk costs for a particular initiating event and year of the project were determined by summing the products of the terminal event probabilities times their attendant consequences. For each kind of initiating event, the annual risk costs were then discounted and summed over all years of the project. The net discount rate was assumed to be 10% per year. The total risk cost was finally obtained by summing over all initiating events and consequence categories.

The revenue stream is required to evaluate the risk cost associated with deferred production. It was determined by monetizing the production rates in Figure 3.2, with produced oil at $15 per barrel and gas at $2.35 per thousand standard cubic feet. Spilled oil was monetized at $30 per barrel.

Economic evaluations of the production system assumed that the time at which the TLP would not be replaced in the event of a major loss of serviceability would be at the end of eighth year of Phase 4 (indicated as T* in Figure 3.2). Time delays in production resulting from damage to the MCAPS TLP and required repair time to bring production back on stream were incorporated by a straightforward time shift of the production stream. The risk cost associated with deferred production was then calculated to be the difference between the present value of the revenue stream with and without the deferral period. When major damage occurred at times greater than T*, the remaining revenue stream was deferred forever (in effect, lost).

3.3.3 Major Initiating Events

In the analyses of the MCAPS TLP system, 40 initiating events (Table 3.1) were identified as being potential primary contributors to major consequences. The focus of these analyses was on those initiating events that could cause differences in the performances (risks) associated with the alternative systems.

The major initiating events were identified for each of the five life cycle phases and for structural and non-structural aspects. These identifications were based on previous experiences with similar types of production systems, and on the collective judgement of the study team.

Having identified the initiating events in Table 3.1, an informal qualitative screening study was performed to reduce the number of initiating events to a more manageable number for illustration of the process. As described in Appendices C and D, initiating events which the MCAPS study team felt were either of low consequence or low probability were eliminated to produce the reduced list of initiating events shown in Table 3.2. This is the list that was used to produce the coarse quantitative risk evaluation of the MCAPS TLP.

3.3.4 Consequence Evaluations

The event trees corresponding to each of the initiating events also required consequences at the terminal events of trees. An assessment was developed of the consequences that could result from the initiating events and subsequent paths (Table 3.3). The consequences were described in four categories:

1. Severe injuries (number).
2. Damage repair costs (1988 U.S. dollars).
3. Deferred production (months/years).
4. Hydrocarbons released (equivalent barrels of oils).

The consequence evaluations were based on previous experiences with similar types of production systems, analyses of this and comparable TLP systems, and on the collective judgement of the study team.

Ranges of the consequences were estimated (representing approximately ± 1 standard deviation) with the best estimate taken as the mid-point of the range.

3.3.5 Event Tree Analysis

Two event trees from the short list of initiating events (Table 3.2) will be illustrated. The first is the subsea blowout event tree in the drilling and production phase (Figure 3.4). This is one of the mechanical system event trees described in Appendix C. The second is the storm overload event tree, Figure 3.5, one of the structural system event trees from Appendix D. These are both examples of the simpler, coarse quantitative level of the total analysis process.

All event trees used in the MCAPS project have the same basic format illustrated by the subsea blowout event tree in Figure 3.4; it is comprised of:

- An initiating event and its frequency of occurrence
- Numbered nodes representing the critical questions specified to the right
- Branches (answers) from each node and their conditional probabilities (given all preceding branches)
- Terminal event numbers followed by their calculated conditional probabilities (given the initiating event)
- Consequence vector for each terminal event (expected values only)
- Verbal description of each terminal event

The initiating event frequency shown in Figure 3.4 is a representative value for illustration. The values used in the risk cost assessment are dependent on the particular drilling/production activities in that year. For the subsea blowout event in the drilling/production phase shown in Figure 3.4, the annual values used were:

Year 1- 4:	0
Year 5:	0.002
Year 6- 8:	0.01
Year 9-19:	0.004

The event trees are actually drawn upside-down. The "trunk" of the tree is the initiating event at the top. The "leaves" of the tree are the terminal events at the bottom. Following the branches downward from the initiating event leads to the successive nodal levels with their questions. For example, if the well is controlled in a short time and ignition and global hull failure occur, the branches lead to terminal event 1. Terminal event 1 has a probability of 0.012 conditional on the occurrence of the initiating event. This value is obtained by multiplying the associated set of branch probabilities, i.e., 0.2x0.3x0.2 = 0.012. To obtain the frequency of terminal event 1 occurring, the conditional probability is multiplied by the initiating frequency. If the representative frequency of 0.008 is used, the terminal event frequency is 0.000096 per year.

The four consequence categories, i.e., lives lost, damage cost as a percentage of platform value, deferred production cost in terms of the number of years of deferred production, and the expected spill in thousands of tons are shown in Figure 3.4 below the conditional probabilities. The expected values of these four consequence categories are shown in Table 3.3 for the illustrative subsea blowout event tree, Figure 3.4. It is clear from this table and figure that in such low probability, high consequence scenarios, the risk costs (or expected values of the costs) are very different from the costs given an accident.

The results in Table 3.4 are indicative of what is involved for one year of one event tree. The expected values of the economic consequences are all monetized, summed over all categories, discounted, and summed over all years of the project life and all initiating events to obtain the total risk cost. Lives lost were kept as a separate category and were not discounted, although arguments can be made for discounting even this category (See Appendix A). Although the computations are very simple and easily automated, it is apparent that the amount of bookkeeping involved can become enormous. The number of terminal events to be tracked in a risk analysis can easily run into the thousands. This fact reinforces the need for and benefit of a systematic, disciplined analysis method; it also implies that the results should be scrutinized to identify dominant contributions to risk.

The initiating frequencies and branch probabilities shown in Figure 3.4 are based on previous studies, except for the branch probabilities of global hull failure which are based on subjective engineering estimates. Appendices C and E discuss the availability of data for initiating frequencies and branch probabilities. It appears that for novel systems such as the MCAPS TLP, specific data is frequently not available and reliance must be placed on subjective engineering estimates. But making subjective estimates on the component level as is done in risk analysis is preferable to making such estimates on a global basis without the framework of risk analysis, because some information is usually available at the component level and because many of the components may be similar (if not identical) to those in existing systems.

The example storm overload event tree (structural damage in extreme condition) from the short list of initiating events (Table 3.2) is shown in Figure 3.5. This tree is very simple in this coarse analysis. Its basic format (binary events) is identical to the mechanical system tree in Figure 3.4, although in detail it appears somewhat different since it was constructed by a different consultant (Appendix D). For example, the YES-NO branches at each node go in the opposite direction from that shown in the mechanical system trees. As indicated in Appendix A, the binary event tree format was chosen for the MCAPS project. For structural events the primary variables (loads and capacities) tend to be continuous rather than discrete and thus the binary event tree is not the natural choice. It was used in the MCAPS project to facilitate communication within the project, to permit use of the same software, and for the sake of consistency in presentation of results.

3.4 MCAPS Coarse Risk Analysis - Case I

The results of the mechanical systems coarse analysis from Appendix C are summarized in Table 3.5 and plotted in Figure 3.6. Results shown are the expected risk costs in four categories: lives lost, direct damage costs, deferred production costs, and costs associated with oil spills. The total expected risk cost is the sum of the three risk cost categories.

The contributions to the total risk cost for the coarse mechanical system event trees are clearly seen in Figure 3.6. The main contributors are the following events:

SBP - Subsea blowout in the drilling/production phase
EM - Significant equipment malfunction, e.g., risers
BOB - Blowout at BOP level

These three events comprise 78% of the total risk cost in the coarse mechanical systems analysis.

The structural event trees from the coarse analysis of Appendix D are listed in Table 3.6, along with the expected risk costs, which are given in terms of direct damage costs, costs due to deferred production, and costs resulting from spills of hydrocarbons. In the case of the structural trees, the fourth consequence category, namely, lives lost, is not listed as these values are all zero. This is considered to be valid because of evacuation policies and procedures. The TLP will be evacuated in advance of approaching severe hurricanes. It is also designed to maintain a safe haven for personnel for a sufficient period of time to allow evacuation in the case of other initiating structural events.

The total structural risk cost (about $33 million) is comparable to the total mechanical system risk cost (about $39 million). Direct costs account for 56% of the total structural risk cost, while deferred production costs account for 42%. Both the structural and mechanical expected risk costs are dominated by low probability, high consequence accidents, an important characteristic of the project that should be communicated to the decision makers. This point will be emphasized in Section 5.3.2.

The storm overload event is the primary contributor to the risk cost. This event accounts for 58% of the total structural system risk costs.

Collisions account for 11% of the structural total. Fatigue failures make no significant contributions to the total.

For subsequent cases studied, many of the coarse mechanical trees were held constant since the detailed analyses of the alternative systems only encompassed a small subset of the mechanical systems. The list of "CM - constant mechanical" events is shown in Table 3.7.

The CM event trees include all events listed in Table 3.5, except EM-significant equipment malfunction and BOB-blowout at BOP level. The latter two events are labeled E&B (see Table 3.8). In the coarse analysis, E&B is comprised of two trees, but in the detailed comparative analyses in Section 4 these events are expanded in number.

Similarly, Table 3.6 shows results for all of the structural trees except the storm overload tree. This set of trees, from the coarse analysis, is termed "CS-constant structural" as they will stay the same or constant in the subsequent cases analyzed.

The results of the coarse analysis, Case I, in terms of the coarse event tree breakdown described, are summarized in Table 3.8. The structural related consequences account for 46% of the total risk cost of $72 million.

The $72 million risk cost (over the life of the project) can be compared, for example, to the estimated total investment of $421 million for the platform, its drilling and production facilities, and predrilling operations. It represents roughly 17% of the total investment. It should be recognized, however, that the total cost of a severe accident, should it happen, will likely exceed $1 billion; the $72 million risk cost is a weighted average or expected value. The justification for the use of expected values in decision making is discussed in Appendix A.

The coarse risk analysis is intended to illustrate how a complete risk analysis might be conducted. As discussed in Appendix C, many of the event trees are coarse and the short list of initiating events was the result of judgment at the qualitative level. The coarse analysis points out the areas requiring more detailed attention. Illustrations of more detailed analyses for comparative evaluations are reported in Section 4.0.

3.5 Expected Risk Cost Uncertainty - Case I

A detailed discussion of uncertainty analysis is presented in Appendix A. New terminology is introduced to distinguish clearly between two basic types of uncertainty. The term "aleatory" is used to describe natural or inherent randomness whereas the term "epistemic" is used to describe uncertainty about the fixed but unknown values of parameters and about the true, underlying deterministic or probabilistic models of components or systems. The important distinction between these two types of uncertainty is that the epistemic uncertainty is information sensitive and can therefore be reduced with acquisition of more information, whereas the aleatory uncertainty is not reducible with more information. The case is made in Appendix A for clearly distinguishing between these two types of uncertainties in the analysis and presentation of risk.

The aleatory uncertainty in accident costs is evident; the losses here may (with small probability) be as large as $1 billion, yet the expected (mean) risk cost is measured in tens of millions. But what is the epistemic uncertainty in this expected risk cost estimate?

An analysis to evaluate the epistemic uncertainty of the expected present risk cost for the coarse analysis, Case I, is illustrated in Appendix A. A number of simplifying assumptions were necessary to illustrate the analysis within the resources available. The illustrative result indicates that the expected risk cost of $72 million exhibits a coefficient of variation of 53% (a standard deviation of $38 million), which means that the expected value of the risk cost has a probability of 68% of lying approximately between $34 and $110 million representing a broad range (large epistemic uncertainty). It is also shown that 99% of the coefficient of variation of 53% is due to the wave overload tree. This suggests that more detailed modeling of the wave overload tree, involving more information, is needed to reduce uncertainty in the coarse risk analysis.

4.0 Comparative MCAPS Cases

This section of the report discusses the comparative cases analyzed in the MCAPS project. Here, the coarse analysis served to provide a measure of the total risk of the system. It showed where the big risk contributors are and hence where detailed analyses needed to focus (whether one is looking at one or several systems.) In order to perform the comparative analyses, the event trees for the comparative subsystems considered had to be expanded in number and/or treated in more detail. The mechanical system comparative results were taken from Appendix E whereas the detailed structural analyses were taken from Appendix F for structural overload and Appendix G for fatigue. Appendix G confirmed the analysis done in Appendix D that fatigue induced tendon system failures are negligible.

Four cases are compared. Three TLP riser design alternatives are considered as shown in Figures 4.1-4.3. In addition, a 2-tendon per leg TLP system was compared to a 4-tendon per leg TLP system.

The coarse analysis in Section 3.4 is labeled Case I. In this section the four cases analyzed and compared are Cases II-V as follows:

Case II - Surface tree and four tendons, Base Case, Riser Alternative 1
Case III - Split tree and four tendons, Riser Alternative 2
Case IV - Subsea BOP and four tendons, Riser Alternative 3
Case V - Surface tree and two tendons

Alternatives 2 and 3 each provide an added line of assurance against blowout should the riser fail above the riser connector. Alternative 3 allows for easier and more reliable major workover than Alternative 2. With Alternative 2 the entire riser and subsea tree must be pulled to the surface and replaced with a workover riser and surface BOP for major workover. This procedure may pose significant risk to adjacent wells if frequent workovers are expected.

Results for each of these cases are summarized in Table 4.1 and will be described next.

4.1 Surface Tree and Four Tendons (Case II - Riser Alternative 1)

This case was obtained by replacing the equipment malfunction and blowout at BOP level (E&B) trees from the coarse analysis (Section 3) with the set of trees from Appendix E enumerated in Table 4.2 for Alternative 1, the surface tree riser concept, and by substituting the coarse overload (OL) tree from Appendix D with the detailed analysis of the overload tree from Appendix F. This case is considered to be the base case in the MCAPS project.

The results show that the E&B set of event trees cause an increase in the total risk cost from \$17 million to \$45 million, whereas the risk cost from the overload tree for four tendons is reduced from \$19 million to \$3.2 million. The reason for the big difference in the E&B set of event trees is that the coarse analysis was too coarse and not sufficiently representative of all of the scenarios that may take place. With respect to the overload tree for the four-tendon system, the coarse analysis was too conservative in assuming that there is an infinite force increase when the wave crests reach the lower deck.

The expected number of lives lost increases from 2.8 to 6.4, again because of the more detailed modeling of the mechanical trees involved. The total risk cost for Case II is $84 million compared to a present worth investment of $421 million in platform, drilling and production facilities, and predrilling operations.

In Case II, the nonstructural events result in an expected risk cost of $67 million. The structural events result in a risk cost of $17 million, or about 20% of the total risk cost. This percentage seems to be reasonable based on general experience with large offshore drilling and production platforms.

In comparing Cases I and II, it should be noted that the coarse analysis underestimated the risk for equipment malfunction and blowouts at the BOP level and overestimated the risk for the overload tree. The reason for the discrepancy is that the coarse analysis lacked sufficient detail to accurately characterize the result.

4.2 Split Tree and Four Tendons (Case III - Riser Alternative 2)

These results are for the split-tree riser concept. The only difference between Cases II and III is the set of E&B event trees, which are enumerated in Table 4.3. The results for Cases II and III, shown in Table 4.1, are essentially the same.

4.3 Subsea BOP and Four Tendons (Case IV - Riser Alternative 3)

These results are for the subsea BOP riser concept, the E&B set of event trees enumerated in Table 4.4 being the only ones that are different. Here the results show an increase in expected lives lost to 5.5 and a total risk cost increase to $59 million. Detailed results for this case show a significant reduction in the probability of blowout at the BOP level, but a more than compensating increase in the wellhead connector failure probability.

4.4 Surface Tree Riser Concept and Two Tendons - Case V

The only difference between Case V and Case II is the number of tendons, which in Case V is reduced from four to two.

There is a relatively small difference between a 4-tendon per column and 2-tendon per column alternative. In the case of the storm overload event, the 4-tendon option has an expected risk cost of $3.2 million (Table 4.1) compared with the 2-tendon option expected risk cost of $2.1 million. The total expected risk costs remains virtually unchanged from that of Case II.

4.5 Comparison of Riser System Alternatives

Figure 4.4 presents a comparison of the riser system alternatives with respect to overall economic consequences and fatalities. The figure shows that the split-tree concept (Alternative 2) has the lowest fatality risk estimate, whereas the surface tree concept (Alternative 1) and the split-tree concept have about equal economic risk values. The subsea BOP concept (Alternative 3) is the worst alternative of the three with respect to fatality risk as well as economic risk.

Figure 4.5 shows the three risk cost categories for the three alternatives. The differences between Alternatives 1 and 2 are rather marginal with respect to economic risk. Alternative 2 is better for the direct damage costs as well as costs related to oil spills, while Alternative 1 is better from a deferred production point of view. Alternative 3 exhibits the highest risk for all three cost categories. The differences between Alternatives 1 and 2 are insignificant in relation to the applicable uncertainties.

Figure 4.6 presents a comparison between the direct damage cost contributions to the three alternatives for each of the initiating events. The two highest contributors are the "constant values" (from the coarse evaluation) and the secondary blowout on platform level. Both of these two categories are in fact sums with contributions from several events. It is worth noting that the highest contributors to the secondary blowout risk are the risers and the riser and wellhead connectors. The figure shows that the damage cost for a riser connector failure as well as riser failure is considerably higher for Alternative 1 compared with Alternative 2 (and to some extent also Alternative 3), to be offset against risk costs related to wellhead connector failure, which certainly is the dominating failure event for Alternative 3.

The following detailed conclusions can be drawn from Figure 4.6:

- The risk attributable to riser failure is reduced for Alternatives 2 and 3. The subsea tree and subsea BOP provide an added line of assurance against blowout should the riser fail.
- Workover risk is identical for Alternatives 1 and 2 since Alternative 1 is similar to Alternative 2 in the workover mode.
- The risk is reduced for Alternative 3 because during workover there is both a subsea and surface BOP.
- The risk attributable to riser connector failure is reduced for Alternatives 2 and 3. The subsea tree and BOP provide added lines of assurance against blowout should the riser connector fail.
- The risk presented by tensioner failure is small for all three cases.
- Wellhead connector failure risk, subsea tree failure risk, and subsea BOP failure risk appear in Alternatives 2 and 3 only. This is reasonable because these items are the additional mechanical components included in the design of Alternatives 2 and 3. These items generate considerable risk.
- The wellhead connector failure risk for Alternative 3 is high. This high risk is caused by a potential blowout through the packer, up the well-bore annulus, through the nonsealing tubing hanger, and into the sea. This possible sequence of events would be mitigated by the sealing tubing hanger in Alternative 2 and the annulus surface controlled subsea safety valve (SCSSV) in Alternative 1.

The most important MCAPS results from the mechanical system comparative analysis was the identification of design improvements for Alternative 3. The addition of a sealing tubing hanger and/or annulus SCSSV will lower the risk significantly for Alternative 3. Redesign and a recycle through the analysis would be in order at this point. It is worthwhile to note that this improvement would likely not have been identified without quantification of the risks involved.

It should be noted that very little data exists, especially for the subsea components involved. Nevertheless, the relative values which are important for the comparison should be good indicators since many of the same components are involved in all three systems.

4.6 Comparison of Tendon System Alternatives

The difference between the 2-tendon and 4-tendon systems shows up in the storm overload trees shown in Figures 4.7 & 4.8 taken from Appendix F. The controlling question of whether tendon system initiates failure leads to a YES probability of 0.12 for the 4-tendon system (Figure 4.7) and 0.06 for the 2-tendon system (Figure 4.8). The failure paths affected by the tendon system nodal point are drawn with bold lines.

If we sum up the conditional probabilities at the terminal events labelled Global Damage (GD) and multiply the sum by the initiating frequency of 0.6, we obtain 0.00045 for the 4-tendon system and 0.0003 for the 2-tendon system. These are annual probabilities which are not far off from the often quoted 0.0001 criterion (Reference 1). A small adjustment in the design, increasing the deck clearance, for example, could be made to achieve this target.

The binary tree format used for the overload tree creates some complications for structural reliability analysis, as discussed in Appendix A, and is not a natural choice. For example, the dependency between the three failure modes, i.e., hull, tendon, and foundation systems, should be treated more rigorously. These three failure modes are likely to be highly correlated because of the common extreme load. Considering 100% correlation, the above annual failure probability of 0.00045 would be reduced to 0.00032 and the value of 0.0003 would be reduced to 0.00016. It is clear that the assumptions that go into the analysis can make a difference in the final analysis. One should not perform the analysis just to generate the numbers, but to gain insight into the behavior of the system while being aware of the various limitations and uncertainties involved.

One might expect the difference between these two systems to be larger because of the difference is safety factor (2.8 for the 2-tendon system vs 2.1 for the 4-tendon system). However, once waves impact the deck the loads increase rapidly such that the difference in safety factor is largely washed out.

The analyses in Appendices D and G indicate that fatigue is a negligible risk contributor. The detailed analyses in Appendix G indicate that the probability of a fatigue induced failure leading to tendon system collapse of the 2-tendon MCAPS TLP is $1.6 \cdot 10^{-7}$ ($4 \cdot 10^{-8}$ for one leg only) over a 20 year service life, and essentially nil for the 4-tendon system. The fatigue systems analysis in Appendix G shows that the fatigue induced collapse failure probabilities are less for the 4-tendon system than the 2-tendon system, indicating a positive influence of the additional redundancy in the 4-tendon system. However, because of the design philosophy employed, the 4-tendon system experiences higher stress levels. The probability of experiencing fatigue failure of only one tendon (which would have to be repaired or replaced) was calculated to be 0.097 over 20 years for the 4-tendon MCAPS TLP and $2.6 \cdot 10^{-5}$ over 20 years for the 2-tendon MCAPS TLP. These results were obtained without considering inspection. As shown in Appendix G, inspection does help to reduce risk but not very dramatically.

It should be noted that the difference between the 2- and 4-tendon systems is very much a function of the ultimate strength design philosophy utilized in this example to design the 2- and 4-tendon systems, and is not to be construed as a general conclusion. With the particular design philosophy employed, the 2-tendon system appears to be a viable alternative to the 4-tendon system from the risk point of view without considering initial cost differences. A more complete picture of the difference between the 2-and 4-tendon systems is shown in Appendix G, including approximate estimates of initial costs, repair costs, and failure costs.

In addition to the structural systems detailed evaluations, Appendix F includes the development of an advanced model for tendon system inspection, maintenance and repair which includes organizational aspects of reliability. This model was developed but was not applied to the MCAPS TLP. The promise which this model holds warrants its further development and application.

4.7 Comparative Uncertainty Analysis

Uncertainty analysis for the difference between the total expected present values of alternative systems was not performed in the MCAPS project. However, Appendix A illustrates such a comparative analysis, focusing on the risk cost difference between the 2- and 4-tendon systems arising only from the respective wave overload trees. Results clearly show that the epistemic uncertainty (standard deviation) associated with the expected risk cost difference between the two systems is only about 25% of the risk cost standard deviation of either system individually. (Recall from Section 3.5 that the epistemic risk cost standard deviation is about $38 million.) Although seldom quantified, this conclusion is expected since the uncertainties common to both systems wash out when the cost difference is taken. This conclusion enhances the applicability of the MCAPS methodology as a comparative analysis tool.

5.0 MCAPS Process - Observations, Perspectives and Evaluation

5.1 The MCAPS Process

The MCAPS process can be organized into seven basis steps:

1. Define the alternative production systems to be evaluated.
2. Determine the reliability and economic characteristics of the alternative systems.
3. Define system improvements and life cycle requirements.
4. Determine if the system meets goals and objectives.
5. If system does not meet goals and objectives, revise system until it does (or modify goals and objectives.)
6. Choose the alternative which best meets the goals and objectives.
7. Proceed with life cycle implementation.

The above seven steps indicate how the process should work ideally in a real project. The MCAPS project was not real in the sense that it was not an on-going project, with active design teams, intended to culminate in design, fabrication, installation and operation of a tension leg platform. It was a hypothetical case based on previously completed conceptual design work.

A number of complications made the simulation of this process imperfect. The MCAPS team members were geographically separated from one another thereby complicating the communications process. Communications took place during a few meetings, by telephone, facsimile and courier service, rather than the day-to-day and face-to-face communications between members of a typical project team. Due to constraints of time and resources, the interaction with and feedback from active design teams to see how improvements could be implemented in cost-effective ways was missing. Because of these shortcomings, the MCAPS project was not carried out under the most ideal circumstances and therefore does not totally reflect what would take place in a real project. The project was done primarily for illustration.

5.2 General Observations

The MCAPS study team was divided into structural and mechanical systems sub-teams. It became evident that to perform the project good communication had to be maintained between the two groups. As explained in Appendix C, some of the mechanical/operational event trees culminated with structural event trees. The terminal events in all trees included both mechanical and structural consequences. This is an indication of how interface problems between various groups on a design team are handled and documented. Accounting for the interdependencies between the various types of event trees is essential.

While the basic MCAPS format was the binary event tree, fault trees were also used to supplement the analysis as illustrated in Appendix E. Typically, fault trees were used to define the conditional probability at critical branch points in an event tree. In Appendix F structural reliability analyses were performed to assess the conditional probabilities at some branch points.

The MCAPS risk analysis was not easy to perform and is no panacea. It became clear that the risk analysts and the project design engineers had to develop a common understanding of the system to be analyzed. Good communication was essential, and even though the MCAPS team enjoyed such communication it still took several iterations between the MCAPS team members to arrive at the MCAPS analysis results. Interdisciplinary teamwork among the project team members is the key to performing a satisfactory analysis. Checks and balances between the risk analysts and the team members who really understand the system are essential.

The process of risk assessment is intended to impose a degree of discipline upon the responsible parties to thoroughly consider the behavior of the system in all of its failure modes. The process does not guarantee that all scenarios with potential negative consequences will be included. Without the process, however, one can almost be assured of missing several important scenarios. The complexity of large technological systems is such that engineering intuition alone cannot be relied upon to evaluate the adequacy of a system or to compare one system with another.

The effect of the Mideast crisis on oil prices and the cost of the Valdez oil spill cleanup are additional data not considered in the cost estimates used in this study. These effects on costs illustrate that cost estimates are no less fuzzy than probabilities, yet cost analyses are always done. The uncertainty of cost estimates does not invalidate cost estimating activities. Similarly, the uncertainties associated with probability estimates should not invalidate the MCAPS comparisons at the time they are made. In both cases, one does the best with what one has at the time.

One important topic identified for possible further consideration is the issue of topsides layout discussed in Section 10.4 of Appendix C. The MCAPS topsides layout is different from topsides layouts which emerged from application of safety principles developed by the Norwegian offshore industry. A study to see if the MCAPS layout can be improved merits consideration.

5.3 Quantitative Perspectives

The following observations concerning the illustrative quantitative aspects of the MCAPS analysis are intended to convey a further understanding of the analysis process and results.

5.3.1 Present Worth Values

The total expected present worth risk cost for Case II, the base case, is $84 million, of which $43 million is due to direct damage of the production structure and facilities, $39 million is due to deferred production, and $2 million is due to hydrocarbon spills. The yearly breakdown of these present worth risk costs is shown in Table 5.1.

These risk costs can be compared to other present worth values including the present worth investment of $421 million in platform, drilling and production facilities, and predrilling operations during the first four years of the project life cycle, $814 million in revenues from production, $153 million in operating costs, and $16 million in availability costs (from MIRIAM analysis, Appendix H), as shown in Table 5.2. The present worth of the project discounted at 10% is $140 million, but this figure does not include tax considerations. It can be seen that the total risk cost of $84 million is nearly the same value as the net present worth of $140 million. The purpose of the full scope, life cycle risk analysis is to identify the hazards and to design the production system so as to bring the risk costs down to the lowest practical level. It should be observed that the $84 million risk cost arises primarily from high consequence, low frequency events as discussed next.

5.3.2 Risk Costs

The lifetime frequency of exceeding $N million in accident losses is shown in Figure 5.1 for Case II, the base case. The losses range in value from nearly zero with very high frequencies to more than $1.6 billion with very low frequencies. These results were obtained by plotting the frequencies and consequences from the leaves of all of the trees (consequences not discounted) and generating the exceedance diagram.

The flat portion of the diagram, from $100 million to $900 million, has a lifetime frequency of about 0.15. This means that the frequency of exceeding the loss of $100 million is about the same as exceeding the loss of $900 million. In other words, the frequency of having losses in the range of $100-900 million is negligible. This is, of course, a direct reflection of the discrete type modelling in the event trees and the conditional expected consequences assumed in the analysis. The distributions associated with the terminal event consequences were not included because expectations are adequate for our expected value analysis. The distributions would, however, smooth out the jumps in the lifetime exceedance frequency curves.

To obtain an average annual exceedance frequency, the lifetime frequency of 0.15 is divided by 19. This yields 0.008, which can be thought of as the annual frequency of exceeding a $900 million loss, i.e., the loss that would be exceeded once every 125 platform years on the average.

Let us consider a typical set of accidental events for a platform, with reference to Design Accidental Events (DAE) and Residual Accidental Events (RAE) as defined in Reference 1. The requirement of a DAE is that hazardous effects to personnel shall be limited, but there are no similar requirements for protection against negative economic impact. Let us further consider DAEs and RAEs in broad groups, as in Reference 2. A typical picture regarding frequencies for these events is shown in Table 5.3, which shows, broadly speaking, that RAEs fall below the 0.0001 cutoff frequency, but that the DAEs present a frequency of serious economic impact of around 0.005 per year. While the present result of 0.008 per year for MCAPS is slightly higher, it is similar in magnitude seen in other studies. (Further discussion of DAEs and RAEs can be found in Section 6.)

5.3.2 Fatal Accident Rate (FAR)

The FAR is defined as the number of fatalities per $1{\cdot}10^8$ hours of exposure. Analysis of FAR in various industrial activities yields values in the range of 1-50.

The expected number of lives lost over the life of the project is 6.4 for Case II (Table 4.1). The FAR for this case, assuming 120 lives at risk for 19 years, is

$$\text{FAR} = \frac{6.4 \times 10^8}{120 \times 19 \times 365 \times 24} = 32$$

Values in this range have been considered acceptable for some major offshore development projects in the North Sea. Typical values for the North Sea fall in the range of 10-50 and can be as high as 100, under certain conditions.

Figure 5.2 shows the frequency of exceedance diagram of lives lost for Case II. It shows that the greatest contributions to the FAR value of 32 arise from severe accidents involving a large number of lives at risk but small frequencies of occurrence.

5.3.4 Uncertainties and Notional Probabilities

The risk numbers in this report are the results of the risk calculations. These include statistical and judgmental inputs to models, both physical and probabilistic. In performing an analysis such as MCAPS, the engineer tries to develop the best estimates he is able to provide with the information and resources available to him, and attempts to provide estimates which he thinks of as actuarial (as close to the truth as possible).

In some cases, e.g., wave height frequencies, the input probabilities can be accompanied by formal, quantified confidence bands describing the uncertainty in the estimated probabilities. At the other extreme, the frequency input cannot be based on empirical data because the appropriate historical experience is missing or undocumented; the estimates are then professional judgments based on experience with like components or similar situations. In this case, the uncertainty in the frequency estimate is itself at best another judgment. While it is possible (and practice in, for example, the nuclear field) to assess and propagate these uncertainties in the inputs to produce quantitative confidence bands on the outputs (frequencies of major accidents, expected costs, etc., see Appendix A), it must be recognized that the final probabilities may be subject to significant (and at best only weakly quantified) uncertainty.

In some safety analyses, it is possible under these circumstances to use the calculated probabilities in a purely relative sense. This is the case, for example, in structural code calibration such as the 1989 API RP2A LRFD draft recommended practice (Reference 3). These probabilities are sometimes called 'notional' for that reason. In risk analyses involving comparison of alternatives using an expected cost basis, however, notional probabilities are not sufficient. The probabilities must be considered best estimates (strictly 'mean estimates') of frequencies (e.g., actuarial frequencies).

The process of performing probabilistic risk analysis, even when the risk estimates are uncertain, provides a method for rational evaluation and comparison that is technically superior to methods which are deterministic in nature and do not formally account for probabiliites of events and their consequences. In short, there does not seem to be a rational alternative to operating with uncertain estimates.

Some concern was expressed by the MCAPS participants about quantitative results. Quantitative results should be viewed as a by-product of the analysis. The objective is to make wise decisions on the basis of the quantitative results. The interpretation of the quantitative results in absolute terms must also be considered, but this should be done with great circumspection since the quantitative results are understood to be uncertain, representing the engineer's available information and best judgment, and are only current estimates of hard actuarial quantities.

5.4 Applicability, Benefits and Costs

The MCAPS technology is applicable to all types of systems, whether conventional or novel, simple or complex. It has been in use in the Norwegian offshore industry for more than 10 years, and it is being heavily employed now in the United Kingdom. The MCAPS technology is most effective when applied to large, technologically complex systems, or when there is significant novelty in design, construction, or operation. The benefits of applying MCAPS technology are an improved understanding, both qualitatively and quantitatively, of the system behavior, identification and mitigation of hazards, improved cost effectiveness of designs, and improved safety. Its use on new, routine systems which have a history of satisfactory performance and which involve off-the-shelf technology may produce only limited benefits. Its use on requalification of conventional platforms can provide important insights on extension of their useful service lives.

The cost of applying the technology depends on the complexity and novelty of the project. but has been found to fall in the range of 0.2% to 0.5% of the field development cost (excluding drilling costs). This figure also includes internal company resources needed to monitor the work of external risk analysis consultants. A detailed engineering risk assessment of a $1 billion project would require 2000 to 4000 man-hours and would be conducted over a period of 2 to 4 months. Typically, the risk assessment study would be conducted parallel with project design such that the results can be used to influence the design without any negative impact on the overall project time schedule. The cost/benefit ratio of applying the MCAPS methodology is often less than 1 over 10, based on experience, when the MCAPS methodology is applied in a 'non-prescriptive' regulatory environment (i.e., where there are no prescriptive standards that must be fulfilled, but where risk assessment can be used to identify the most cost-effective alternatives).

5.5 Limitations

Throughout the MCAPS analysis, probabilities and associated consequences were frequently established on the basis of engineering judgement. In many cases, analysis experience with previous similar analyses was invoked as the basis. Although data bases exist (as described in Appendix C), little direct data exists for novel systems such as the MCAPS TLP. For example, blowouts, boat collisions, and dropped objects are events that cause significant risk. These events are not easily modeled and the applicability of existing data for novel systems is in doubt. The risk attributable to such events is a judgement and an estimate open for debate.

The subjective elements of the analysis can be considerable. There is as yet no complete professional agreement or consensus on the means and uncertainties to be used, for example, in the analysis of structural reliability, and it remains for each individual designer, analyst, company or consultant to do the best he knows how to do. Different analysts will come up with different results.

While risk assessment technology is being applied, especially in offshore operations in Norway, the United Kingdom, and various industries, many of the issues being confronted in MCAPS are still being researched. Consequently, many aspects of the MCAPS technology will undergo further development and implementation.

Not only is there a lack of data, but tools for reliability analysis are not readily available nor are they easy to use. Tools for mechanical/operational systems seem more available and developed, probably because the modelling involved is simpler. In structural reliability there is considerable mechanical interaction between members of the system which complicates the analysis.

5.6 Discussion and Evaluation

Should the lack of data or tools hinder the application of risk analysis? The answer to that is NO. If data are not available, risk analysis still provides insight to the behavior of the system and allows the engineers to express their degree of belief in a systematic and orderly way. It provides documentation of the thought processes that lead to particular design decisions. Furthermore, it provides the impetus for data collection. In order to see the future, one must have an idea of the past. For this reason, collection of data on accidents and failure rates and the development of data bases are extremely important activities.

Where tools are not available, they need to be developed and used. The increasing demand for risk analysis will bring tools to the forefront as required. At this time there is a pressing need for development of risk analysis guidelines to assist analysts in developing consistently accurate and compatible results.

The time for application is now. One astute individual at the MCAPS final meeting said, "If the time for application is not now, when will it ever be?" That point is well taken. The only requirement in proceeding forward is that the limitations must be recognized so that unwarranted conclusions are not reached.

Risk assessment facilitates a check on the engineer's intuition of how a system should behave. If the analysis goes against the engineer's intuition, this forces the engineer to think more clearly and deeply about the problem. The result may be a modified intuition or a revised risk assessment.

Risk assessment provides a framework in which teamwork can be done. It provides opportunities to handle interface problems between various members of the teams or design groups. Perhaps most important, it provides management with additional oversight and decision-making capabilities.

The objectives of risk assessment are to help identify the best alternative and to make the best alternative safe and economic. The process of performing the risk assessment is the primary vehicle for achieving these objectives. It does this by facilitating teamwork, communication, and by focusing attention on those components having the greatest risk and indicating where cost-effective risk reduction measures can be implemented.

Risk assessment should be embraced because of its technical merit. It is a tool that can be used to bring about long term benefits, i.e., reducing risk and also increasing profitability. The cost of performing risk assessment is small when compared to the adverse consequences that are possible for large, complex, and novel technological systems. The MCAPS TLP falls into that class of systems.

6.0 Governmental Requirements for Risk Assessment

Use of risk assessment in association with offshore operations has been required by Norwegian authorities (Norwegian Petroleum Directorate) since 1981. The United Kingdom has informally adopted a risk assessment policy, prompted by the "Piper Alpha" accident, and is expected to institute a requirement for formal risk assessment in the next 12-24 months. Canada is developing similar requirements for offshore concept safety analysis of production installations.

6.1 The Norwegian Approach

The Norwegian requirement for Concept Safety Evaluations (which is the specific terminology used for risk assessments) stems from Reference 2, which is a guideline and not actually law (although all concerned responded as if it were law). The scope of the 1981 guidelines was limited to new production platforms during concept and development engineering. This document has been replaced by a formal regulation for use of risk analyses in all offshore operations (Reference 4).

The effect of the use of risk assessments for production installations on the Norwegian continental shelf has been clearly demonstrated through developments of platform designs, where today's platforms provide better separation of hazardous sources from areas of main occupancy and primary shelter. This is achieved through spatial separation (to the extent possible) combined with the use of passive and active safety protective measures.

One of the main changes that may be observed by comparing the old guidelines with the new regulations is that the so-called limit of 0.0001 per year has disappeared. This may at first seem odd and may give rise to the impression that the NPD is abandoning the approach taken in the past, possibly admitting that the procedure has not been effective. But this is not the case. According to the NPD, there are other reasons for this change, of which one is the possible political implication of having an accepted target risk level cited explicitly in the regulations. The most important reason, however, is that the NPD wants all users of risk assessments to focus on the process of applying these techniques, rather than on the quantification of risk levels to be compared to the 0.0001 per year limit. It is thus clear that the Norwegian experience underlines the risk assessment process as the most important aspect for safety improvements. This seems to be a general consensus among all involved in the execution of these studies in Norway. This approach is also consistent with that recently discussed by Seiler (Reference 5).

A further amplification of this issue is provided by the fact that most of those concerned with risk assessments consider definition of the Design Accidental Events (DAE) and the associated loads to be the primary value of the risk assessments. The distinction between Design Accidental Events and Residual Accidental Events (RAE) is based on a combination of accidental event probability and consequence of the event. A line is drawn between the DAEs and RAEs based on these considerations. The residual risk implied by the RAE should not be too high. If it is too high, then either the consequences will have to be reduced (by creating a DAE) or the frequency will have to be reduced to bring the frequency of the event to a level below a predetermined target, formerly specified as 0.0001 per year, into the residual event category. The most common actions are often a combination of these two approaches.

The process of risk assessment and its input to the design process is maximized by a consistent application of DAEs and associated loads to define the design basis for all platform systems. This is valued as the most important application of the Concept Safety Evaluation methodology in Norwegian offshore operations, and is really what Norwegian authorities are focusing on for future use of this approach.

Use of risk assessment in Norwegian offshore operations (with some few exceptions, especially in the early days of applying the technique) has been successful in avoiding mathematical manipulation of numbers without any technical meaning (i.e., when manipulation of numbers is performed to reduce the frequency below 0.0001 per year, without corresponding technical or operational changes). This was probably due to the fact that there were no experience or existing habits concerning the use of risk assessment prior to the introduction of the offshore guidelines. Therefore, the authorities were able to influence the industry to carry out these studies with focus on technical and operational aspects, instead of manipulation of numbers. This experience in Norway may be contrasted with experiences in other countries, where there may be relatively strong emphasis on using risk assessments in a "verification mode." This mode leans on the risk assessment to demonstrate that the risk level is acceptably low, and therefore may encourage numbers manipulation to arrive at acceptable results.

Such application of risk assessment can be adversative in nature as it may be difficult to obtain a complete consensus on absolute risk values for acceptability purposes. It is very easy to let the process of risk assessment, from which insight into important mechanisms can be gained, to be subverted such that the quantification and evaluation of absolute risk values become the major focal points. This has led to misapplication and mistrust concerning the use of risk assessment in the past, but it is slowly being overcome in view of the widening interest in this subject matter in many disciplines.

6.2 The United Kingdom Approach

The U.K. Department of Energy has issued a discussion document (Reference 6) which calls for "Formal Safety Assessments" (FSA) to be provided for new and existing installations on the U.K. continental shelf. The FSA as currently proposed is a broad presentation of the safety case for the installation, with a formal risk assessment as one of the corner stones. The discussion document spells out in some detail how the risk assessments should be carried out. The studies are intended to be quantitative assessments with emphasis on the process of applying the approach in seeking safety improvements.

The United Kingdom Offshore Operators has endorsed the objectives of Formal Safety Assessment described in Reference 6. The E&P Forum position paper (Reference 7) suggests that experience shows the application of quantitative risk assessment can contribute to both increased safety and improved cost effectiveness. Caution, however, was expressed concerning the setting of absolute values for risk acceptance criteria.

6.3 Canadian Requirements

Canada has developed draft regulations (Reference 8) for oil and gas installations. A concept safety analysis of the offshore production installation, which considers all components and all activities associated with each phase in the life of the production installation including the construction, installation, operation and removal phases of the production installation, is expected to become a requirement.

7.0 Conclusions

The MCAPS project has provided considerable technical material in depth and breadth. Specifically, the following were accomplished:

1. A full scope, life cycle risk analysis of a novel offshore system, the MCAPS TLP, was illustrated.
2. Comparative risk analyses were illustrated for three alternative production riser concepts. The comparisons have identified possible design improvements that may be cost-effective in reducing risk.
3. Comparative risk analyses were illustrated for two alternative tendon systems, i.e.; a 2- and 4-tendon system. The differing design philosophies made the comparison difficult. However, it was concluded that a 2-tendon system can be a viable alternative from a risk standpoint. It was shown that fatigue was a negligible contributor to risk for both systems, and that the ultimate strength difference between the two systems only made a marginal difference in the final analysis.
4. Uncertainty of the difference in risk costs between alternative systems was shown to be significantly less than uncertainty associated with each system individually, thus enhancing the applicability of comparative risk assessment.
5. Topsides layout differences between European and US offshore conceptual design practices were identified and would warrant further investigation.
6. An advanced model for tendon system inspection, maintenance and repair was developed which includes organizational aspects of reliability.

The MCAPS team found that some design scenarios only come to light when design is thought of in reliability terms which requires consideration of the interaction among components and subsystems and the complete range of design parameters. A good illustration of this is TLP design for wave impact. Deterministic design to the 100-year criterion would not have identified the need for proper consideration of this overload condition.

The subjective elements involved in risk assessment can be considerable, and professional consensus or agreement on characterization of uncertainty is lacking. While risk assessment is being applied, many of the issues confronted in the MCAPS project are still being researched, but this fact should not hamper its future development and application.

The general conclusion from the MCAPS experience is that risk assessment is not a simple process. It requires extensive familiarity with the system. Knowledge of the system and its deterministic behavior are paramount. For that reason, risk assessment is an intensive interdisciplinary effort requiring good teamwork.

The most important benefit of an analysis such as MCAPS is the process that is involved in carrying out the analysis, the teamwork that is facilitated, and the communication that is established among the various team members and management involved in the project. The specific numbers generated may be less important and should serve only as a guide to focus attention on those aspects of the project which generate the most risk and to indicate where cost-effective risk reduction measures can be taken.

8.0 Recommendations

1. If the MCAPS TLP configuration were presently being actively considered for offshore use, additional risk assessments would be recommended to identify cost-effective risk reducing measures.

2. Given that the MCAPS TLP is not being actively considered at this time, it is recommended that the application of risk assessment technology be encouraged in presently on-going projects and future projects. This recommendation is consistent with the recommendation of References 6 and 7.

3. Risk assessment should be embraced because it is a tool that can be used to bring about long term benefits, i.e., reducing risk and also increasing profitability.

4. Further thought should be given to and plans made for development of risk assessment technology, particularly comparative risk assessment, related software developments to facilitate its application, and failure data collection efforts to give risk assessments greater credibility. At this time there is a pressing need for development of risk assessment guidelines to assist analysts in developing consistently accurate and compatible results.

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10.0 References

1. Vinnem, J. E. and Hope, B., Offshore Safety Management, Tapir Publishers, Trondheim, Norway, 1986.
2. Guidelines for Safety Evaluations of Platform Conceptual Design, The Norwegian Petroleum Directorate, Stavanger, Norway 1.9.1981.
3. Draft Recommended Practice for Planning, Defining, and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design, API RP2A-LRFD, American Petroleum Institute, December 1989.
4. Regulations Concerning Implementation and Use of Risk Analyses in the Petroleum Activities with Guidelines, The Norwegian Petroleum Directorate, Stavanger, Norway, ISBN 82-7257-314-8, 1990.
5. Seiler, F. A., "On the Use of Risk Assessment in Project Management," Risk Analysis, Volume 10, Number 3, September 1990, pp. 365-366.
6. U.K. Department of Energy, "Discussion Document by the Department of Energy, Formal Safety Assessments for Offshore Installations," PEA 89/93/4, October 1989.
7. E & P Forum, "Quantitative Risk Assessment, A Position Paper Issued by the E & P Forum," Report No. 11.2/150, May 1989, E & P Forum, 25/28 Old Burlington Street, London W1X 1LB.
8. Regulations Respecting Oil and Gas Installations Used in Parts of Canada Under the Oil and Gas Production and Conservation Act, Draft, Federal Version as of 21 August 1990.

Table 3.1

Complete Major Initiating Event List for MCAPS TLP

Project Phase	Event*	
Engineering (Phase 1)	1.1.1	Design failure
	1.2.1	Design failure
Construction (Phase 2)	2.1.1	Construction failure
	2.1.2	Failure during towing of equipment
	2.1.3	Failure during lowering of equipment
	2.1.4	Misplacement of template
	2.1.5	Dropped object
	2.1.6	Mating failure/damage
	2.1.7	Collision
	2.1.8	Marine accident
	2.2.1	Construction failure
	2.2.2	Failure during towing of equipment
Predrilling (Phase 3)	3.1.1	Failure during lowering of template
	3.1.2	Anchor/anchor line damage
	3.1.3	Dropped object from moonpool
	3.2.1	Failure during lowering of BOP
	3.2.2	Subsea blowout
Drilling and Production (Phase 4)	4.1.1	Structural damage in extreme condition
	4.1.2	Structural damage in less than extreme condition
	4.1.3	Collision
	4.1.4	Difference in maintenance/inspection
	4.1.5	Mudslide
	4.2.1	Dropped object from moonpool
	4.2.2	Platform blowout at BOP level
	4.2.3	Subsea blowout
	4.2.4	Significant equipment malfunction
	4.2.5	Large leak from flowline
	4.2.6	Gas leak surface origin
	4.2.7	Oil leak surface origin
	4.2.8	Gas leak subsea origin
	4.2.9	Oil leak subsea origin
	4.2.10	Utility systems fire
	4.2.11	Fire in living quarter
	4.2.12	Production regularity difference
	4.2.13	Offtake systems difference
	4.2.14	Difference in maintenance/inspection
Decommissioning (Phase 5)	5.1.1	Difficulties involved in removal
	5.1.2	Actual value of reuse reduced
	5.1.3	Marine accident
	5.2.1	Actual value of reuse reduced

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*Key to Numbering System:

1.1.1 -Phase No.
1.1.1 -if 1, = Structural - if 2, = Nonstructural
1.1.1 -Initiating event number.

Table 3.2

Reduced Initiating Event List for Coarse Quantitative Evaluation

Project Phase	Event*	
Engineering	1.1.1	Design failure
	1.2.1	Design failure
Construction	2.1.1	Construction failure
	2.1.2	Failure during towing of equipment
Drilling (Predrilling)	3.1.1	Failure during lowering of template
	3.2.1	Failure during lowering of BOP
	3.2.2	Subsea blowout
Operational Drilling and Production	4.1.1	Structural damage in extreme condition
	4.1.2	Structural damage in less than extreme condition
	4.1.3	Collision
	4.2.1	Dropped object from moonpool
	4.2.2	Platform blowout at BOP level
	4.2.3	Subsea blowout
	4.2.4	Significant equipment malfunction
	4.2.5	Gas leak surface origin
	4.2.6	Oil leak surface origin
	4.2.7	Gas leak subsea origin
	4.2.8	Oil leak subsea origin
Decommissioning	5.1.1	Marine accident

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*Key to Numbering System:

1.1.1 -Phase No.
1.1.1 -if 1, = Structural - if 2, = Nonstructural
1.1.1 -Initiating event number.

Table 3.3

Consequences Associated with Initiating Events and Paths

	Severe Injuries	Damage/ Repair Cost (mill US$)	Deferred Production (m=month) (y=year)	Hydrocarbons Released (1000 BBL)
Template damage due to falling object (BOP)	0	50- 100	6-12 m	0
Template damage due to cratered blowout	0	130- 280	23 m-53 m	500 - 1500
Repair to template	0	13	0.15 m	0
Wellhead damaged beyond repair capability	0	15	3 m	0
Repair of tensioner	0	0.3	0.3 m	0
Failure of riser/wellhead	0	13	3-20 m	0
Redesign of compressors prior installation	0	2	0	0
Redesign of compressors after installation	0	5	1-3 m	0
Global hull failure due to burning/exploding platform blowout	20-120	500-1000	4-6 y	500-1500
Nonglobal hull failure due to burning/exploding platform blowout	0-40	60- 180	1-2 y	500-1500
Global hull failure due to explosion on platform deck	30-120	500-1000	4-6 y	250-750
Nonglobal hull failure due to explosion on platform deck	0-40	60- 180	1-2 y	250-750
Global hull failure due to explosion on platform deck	20-120	500-1000	4-6 y	250-750
Nonglobal hull failure due to explosion on platform deck	0-40	60- 180	1-2 y	250-750
Local platform damage due to jet fire on platform deck	0-10	12- 36	3-9 m	0

Table 3.3 (Cont'd.)

	Severe Injuries	Damage/ Repair Cost (mill US$)	Deferred Production (m=month) (y=year)	Hydrocarbons Released (1000 BBL)
Local platform damage due to pool fire on platform deck	0-10	12- 36	3-9 m	0
Total loss due to loss of buoyancy	20-120	500-1000	4-6 y	500-1500
Global hull failure due to fire on sea surface	20-120	500-1000	4-6 y	500-1500
Nonglobal hull failure due to fire on sea surface	0-40	60- 80	12-24 m	250-750
Global hull failure due to tether failure	0	500-1000	4-6 y	500-1500
Local hull failure due to tether failure	0	10	0	0
Global hull failure due to foundation failure	0	500-1000	4-6 y	500-1500
Local failure due to foundation failure	0	5- 10	0	0
Global hull failure due to wave slamming deck	0	500-1000	4-6 y	500-1500
Local failure due to wave slamming deck	0	15- 25	3-9 m	0
Global hull failure due to collision	20-120	500-1000	4-6 y	500-1500
Local hull failure due to collision	0	15-25	3-9 m	0
Wellhead damage by BOP	0	15	3 m	0

Table 3.4

Calculation of Expected, Economic Risk Cost for Subsea Blowouts in Drilling and Production Phase

EXPECTED ANNUAL LOSS				
TERMINAL EVENT NUMBER	LIVES	COST % of platf. val.*	DEFER. PRODUCT. days of tot. prod.	SPILL (1000 bbl)
1	0.0067	0.017%	0.17	0.07
2	0.0076	0.011%	0.21	0.19
3	0	0.003%	0.06	0.56
4	0.0896	0.228%	2.33	0.96
5	0.0256	0.036%	0.70	0.64
6	0	0.022%	0.42	1.92
TOTAL	0.130	0.32 %	3.90	4.34

* platf. val. = $421 MM

Table 3.5

Mechanical Systems Coarse Evaluations Expected Consequences Summary

INITIATING EVENT	FATALITY RISK	ECONOMIC RISK (million USD)			
		DIRECT COST	DEFERRED PRODUCTION	OIL SPILL	TOTAL COST
Design failure	0	0.04	1.67	0	1.72
Failure during lowering of BOP	0	0.73	2.23	0	2.96
Subsea blowout in pre-drilling phase	0**	0.104	0.37	0	0.48
Dropped object from moonpool	0.001	0.012	0.004	*	0.016
Secondary Subsea Blowout	0.001	0.005	0.005	*	0.01
Platform blowout at BOP level	0.67	3.89	3.29	0.120	7.30
Subsea blowout in production phase	1.60	6.56	6.02	0.490	13.07
Significant equipment malfunction	0	2.40	7.58	0	9.98
Gas leak surface origin	0.23	0.412	0.719	0.010	1.141
Oil leak surface origin	0.22	0.882	0.743	0.016	1.64
Gas leak subsea origin	0.040	0.101	0.128	0.009	0.24
Oil leak subsea origin	0.018	0.039	0.058	0.004	0.101
TOTAL FOR PLATFORM	2.8	15.18	22.82	0.65	38.65

* Value less than 0.001
** Affects personnel other than on TLP

Table 3.6

Structural Systems Coarse Evaluations Expected Consequences Summary

EVENT NO.	DESCRIPTION	DIRECT COST ($MM)	DEFERRED PRODUCTION COST ($MM)	SPILL COST ($MM)	TOTAL COST ($MM)
1.1.1	Design Flaw	2.05	1.51	0.08	3.64
2.1.1	Construction Flaw - Fabrication	3.68	2.75	0.15	6.57
2.1.2	Construction Flaw - Transportation	0.00	0.01	0.00	0.01
3.1.1	Construction Flaw - Installation	0.04	0.07	0.00	0.11
4.1.1	Storm Overload	10.54	7.97	0.42	18.93
4.1.2	Fatigue Failure	0.01	0.00	0.00	0.01
4.1.3	Collisions	1.98	1.46	0.08	3.53
5.1.1	Salvage Accident	0.06	0.00	0.00	0.67
	TOTAL STRUCTURAL	18.36	13.78	0.73	32.87
	Constant Structural*-CS	7.82	5.81	0.31	13.94

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* Total Structural minus Storm Overload

Table 3.7

Constant Mechanical (CM) Event Trees from Coarse Evaluation

FILE	TOP EVENT
BOPLOWER	Failure during lowering of BOP
DESFAIL	Design Failure
DROPMOPL	Dropped objects from moonpool
PREDBLOW	Predrilling blowout
SUBSBLOW	Subsea blowout drill/production phase
SUBSECBL	Secondary subsea blowout
SUBSGAS	Large gas leak subsea origin
SUBSOIL	Large oil leak subsea origin
SURFOCAS	Gas leak surface origin
SURFOIL	Oil leak surface origin

Table 3.8

MCAPS Coarse Analysis, Case I

Event Tree	Lives	Cost $MM	Def. Prod. $MM	Spill $MM	Total Cost $MM
CM	2.11	8.89	11.97	0.53	21.39
E&B	0.67	6.29	10.87	0.12	17.28
CS	0	7.82	5.81	0.31	13.94
OL	0	10.54	7.97	0.42	18.93
Total	2.78	33.54	36.62	1.38	71.54

Table 4.1

Summary of MCAPS Cases

Case	Event Trees	Lives	Cost $MM	Def. Prod. $MM	Spill $MM	Total Cost $MM
Case I	CM	2.11	8.89	11.97	0.53	21.39
	E&B	0.67	6.29	10.87	0.12	17.28
	CS	0	7.82	5.81	0.31	13.94
	OL	0	10.54	7.97	0.42	18.93
	Total	2.78	33.54	36.62	1.38	71.54
Case II Base Case Altern. 1 4 tendons	CM	2.11	8.89	11.97	0.53	21.39
	E&B	3.62	24.91	19.91	0.83	45.65
	CS	0	7.82	5.81	0.31	13.94
	OL	0	1.77	1.34	0.07	3.18
	Total	6.40	43.39	39.03	1.74	84.16
Case III Altern. 2 4 tendons	CM	2.11	8.89	11.97	0.53	21.39
	E&B	3.97	24.18	20.57	0.77	45.52
	CS	0	7.82	5.81	0.31	13.94
	OL	0	1.77	1.34	0.07	3.18
	Total	6.08	42.66	39.69	1.68	84.03
Case IV Altern. 3 4 tendons	CM	2.11	8.89	11.97	0.53	21.39
	E&B	5.46	31.90	25.73	1.08	58.71
	CS	0	7.82	5.81	0.31	13.94
	OL	0	1.77	1.34	0.07	3.18
	Total	7.57	50.38	44.85	1.99	97.22
Case V 2 tendons	CM	2.11	8.89	11.97	0.53	21.39
	E&B	4.29	24.91	19.91	0.83	45.64
	CS	0	7.82	5.81	0.31	13.94
	OL	0	1.18	0.91	0.05	2.14
	Total	6.40	42.80	38.60	1.72	83.11

Case I - Coarse Analysis of Base Case
Case II - Surface tree riser + 4 tendons (Base Case)
Case III - Split Tree + 4 tendons
Case IV - Subsea BOP + 4 tendons
Case V - Surface tree riser + 2 tendons

CM - Constant Mechanical
CS - Constant Structural
E&B - Equipment Malfunction & Blowout at BOP Level
OL - Storm Overload

Table 4.2

Events Evaluated for Alternative 1

FILE	TOP EVENT
FLEXFAIL	Failure of Flexible Flowline
RCONFAIL	Failure of Riser Connector
RISFAIL	Failure of Riser
TENSFAIL	Failure of Tensioner
BOPSECBL	Secondary Blowout at BOP level
BOPBLOW	Blowout at BOP Level
TREEFAIL	Failure of Surface Tree

Table 4.3

Events Evaluated for Alternative 2

FILE	TOP EVENT
FLEXFAIL	Failure of Flexible Flowline
RCONFAIL	Failure of Riser Connector
RISFAIL	Failure of Riser
STREFAIL	Failure of Subsea Tree
TENSFAIL	Failure of Tensioner
BOPSECBL	Secondary Blowout at BOP level
BOPBLOW	Blowout at BOP Level
TREEFAIL	Failure of Surface Tree
WOONFAIL	Failure of Wellhead Connector

Table 4.4

Events Evaluated for Alternative 3

FILE	TOP EVENT
FLEXFAIL	Failure of Flexible Flowline
RCONFAIL	Failure of Riser Connector
RISFAIL	Failure of Riser
SBOPFAIL	Failure of subsea BOP
TENSFAIL	Failure of Tensioner
BOPSECBL	Secondary Blowout at BOP level
BOPBLOW	Blowout at BOP Level
TREEFAIL	Failure of Surface Tree
WCONFAIL	Failure of Wellhead connector

Table 5.1

Expected Present Worth Risk Costs

(Discount rate = 10%)

Year	Damage Cost	Deferred Prod	Spill	Total
1	0	0	0	0
2	306686	868382	0	1175068
3	278805	868382	0	1147188
4	253459	868382	0	1121842
5	2532144	4536631	100729	7169504
6	4972478	6149502	223764	11345744
7	5003081	6104924	219869	11327874
8	4880499	5648317	211212	10740028
9	3514049	3712523	138040	7364612
10	3193295	2817552	125462	6136310
11	2902996	2017575	114057	5034627
12	2639087	1296275	103688	4039050
13	2399170	1323595	94262	3817027
14	2181064	869853	85693	3136609
15	1982785	672572	77902	2733260
16	1802532	516576	70820	2389928
17	1638665	374761	64382	2077809
18	1489696	245839	58529	1794064
19	1417128	134066	55690	1606884
Totals:	$43,400,000	$39,030,000	$1,740,000	$84,100,000

Table 5.2

Present Worth Values
(Discount rate = 10%)

Investment 1. year:	42,100,000
Investment 2. year:	84,200,000
Investment 3. year:	168,400,000
Investment 4. year:	126,300,000
Present Worth of Investment:	$421,000,000

Year	Revenue	Expenses	Unavailability
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	42613060	18298551	860784
6	88442955	16635047	1786548
7	101963102	15122770	2059655
8	115048137	13747972	2323972
9	116421175	12498157	2351708
10	108811196	11361961	2197986
11	86943974	10329055	1756490
12	55764341	9390050	1126440
13	29526096	8536409	596427
14	15257631	7760372	308204
15	12742173	7054884	257392
16	11583794	6413531	233993
17	10530722	5830482	212721
18	9573383	5300439	193382
19	8703076	4818580	175802
Total	$813,930,000	$153,100,000	$16,440,000

Summary	
Revenues	$814 MM
Investment	421
Expenses	153
Unavail	16
Risk Cost	84
Net Present Worth	$140 MM

Table 5.3

Typical Frequencies* Associated with Residual and Design Accidental Events

HAZARD CATEGORY	FREQUENCY OF EVENTS WITH SIGNIFICANT PERSONNEL AND ECONOMIC IMPACT (RAE)	FREQUENCY OF MAJOR DAEs (i.e. LIMITED PERSONNEL EFFECT BUT SEVERE ECONOMIC IMPACT)
BLOWOUT	$2 \cdot 10^{-4}$/yr	$2 \cdot 10^{-3}$/yr
FIRE & EXPLOSION	$8 \cdot 10^{-5}$/yr	$2 \cdot 10^{-3}$/yr
COLLISION	$5 \cdot 10^{-5}$/yr	$5 \cdot 10^{-4}$/yr
EXTREME ENV. LOAD	$6 \cdot 10^{-5}$/yr	$1 \cdot 10^{-4}$/yr
FATIGUE, etc.	$5 \cdot 10^{-5}$/yr	$1 \cdot 10^{-4}$/yr

* based on private communications with J. E. Vinnem

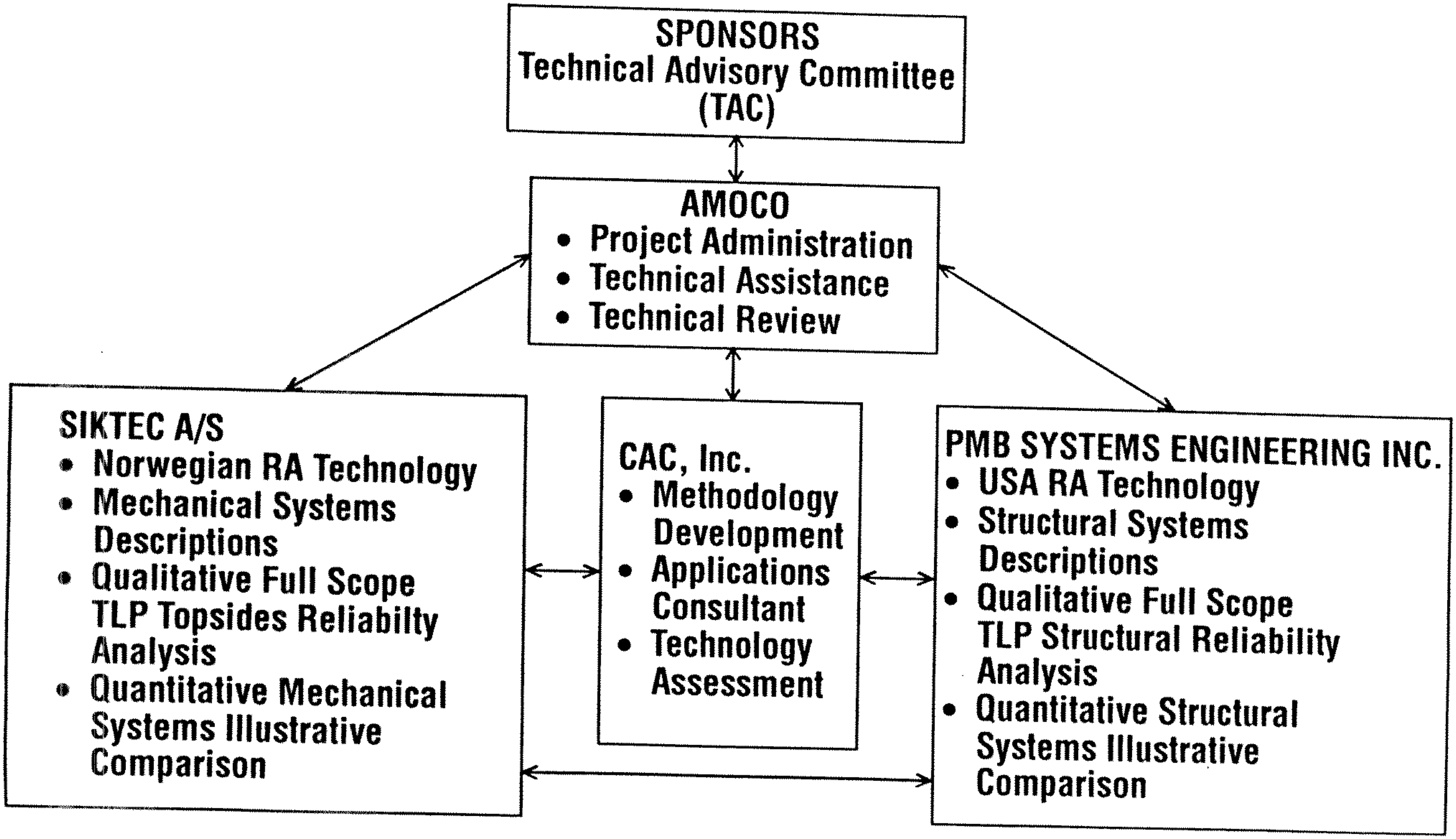


Figure 1.1 Project Organization

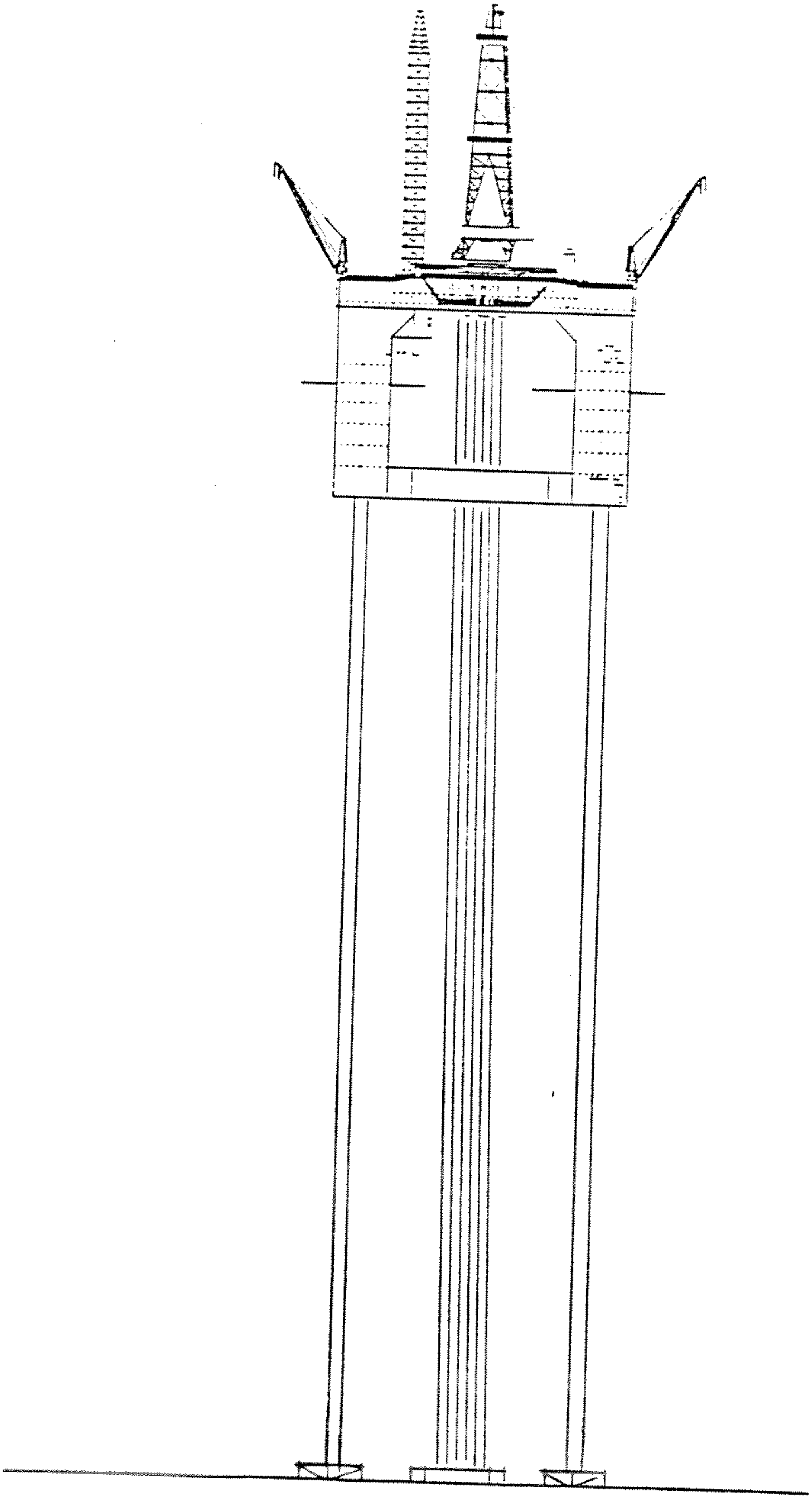


Figure 3.1 MCAPS TLP Configuration

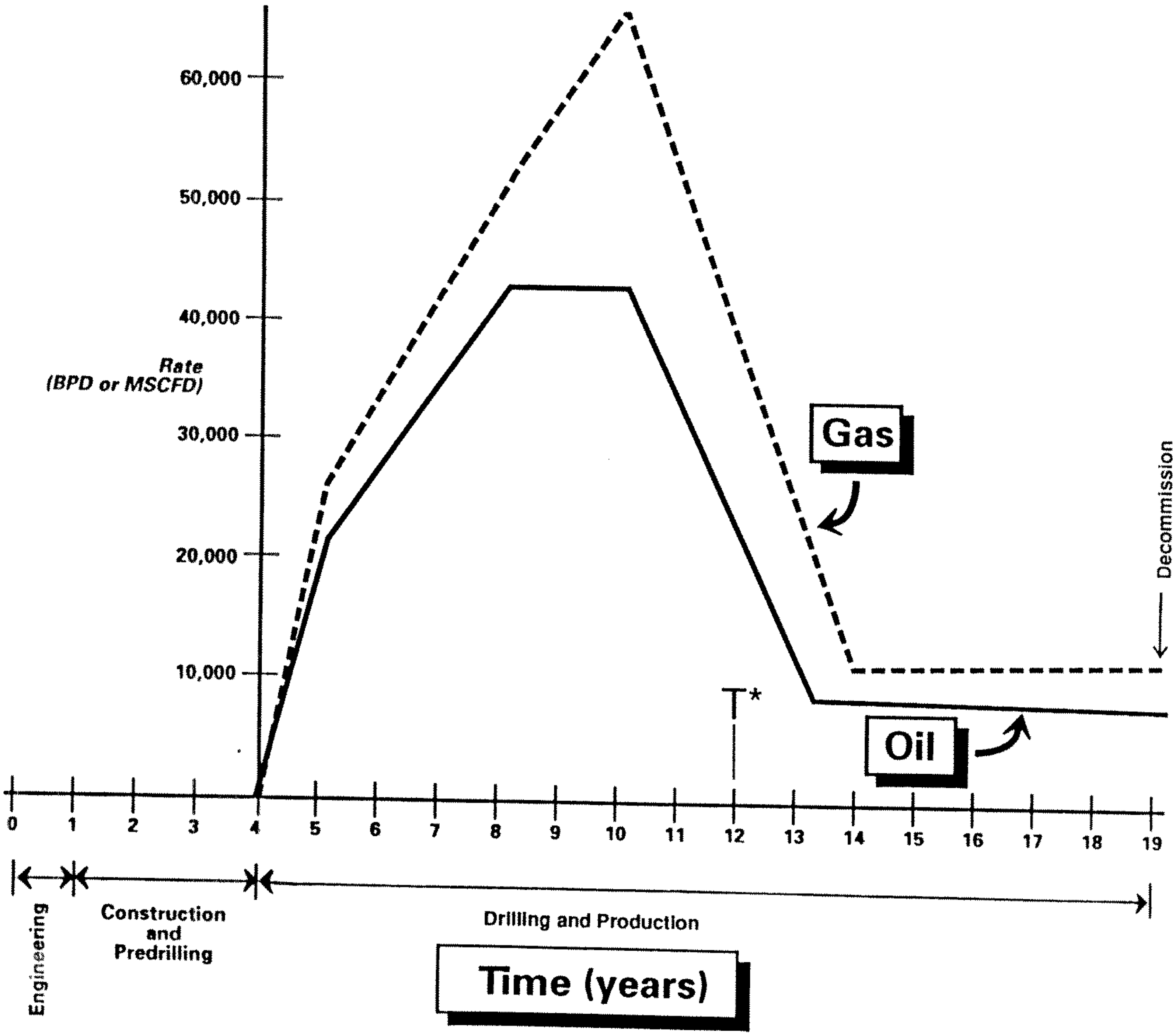
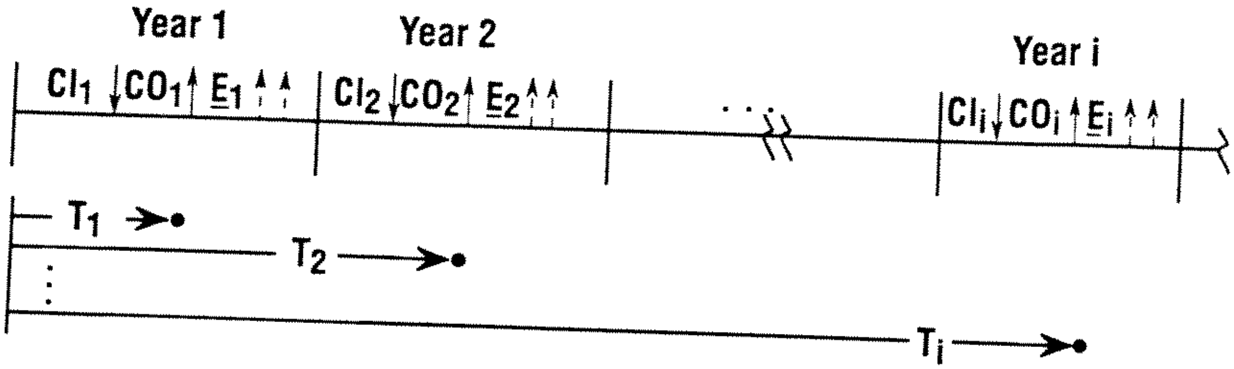


Figure 3.2 Life-Cycle Phases and Production Profile

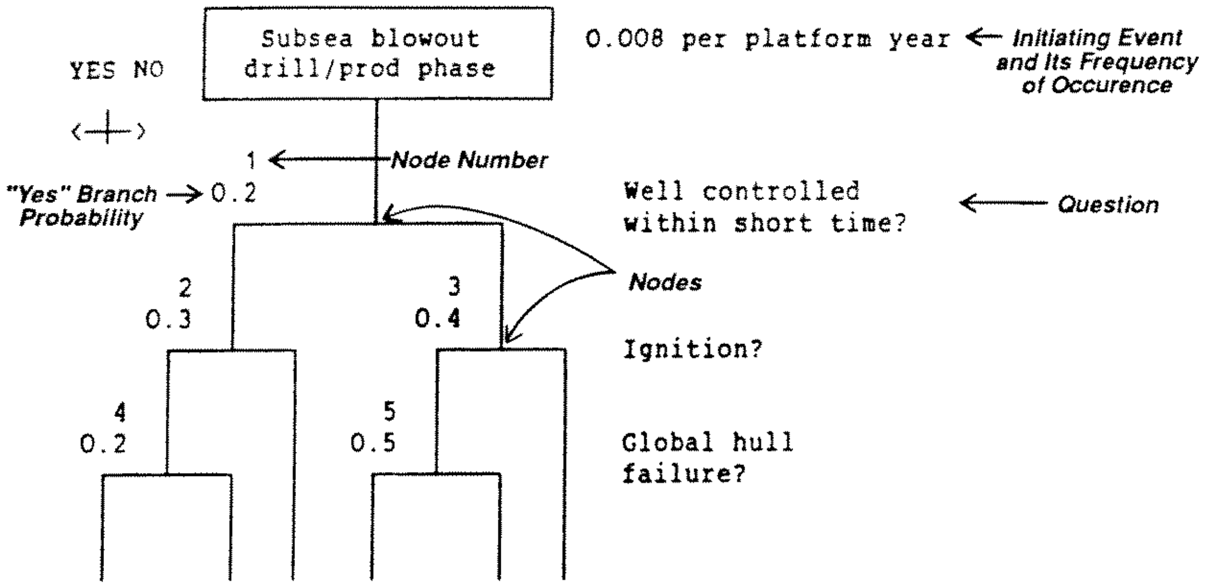


Definitions:

CI_i	cash flow in, year i
CO_i	cash flow out (costs), year i (including "unmodeled" events)
$\underline{E}_i$	set (vector) of possible (random) costs, year i ("modeled" events).
T_i	representative time (e.g., mid point) of year i
r	discount rate
PW	present worth

$$PW \cong \sum_{i=1}^{n} (CI_i - CO_i - \sum_{j} E_{ij})\, e^{-rT_i}$$

Figure 3.3 Time Stream of Cash Flow Including Random Events

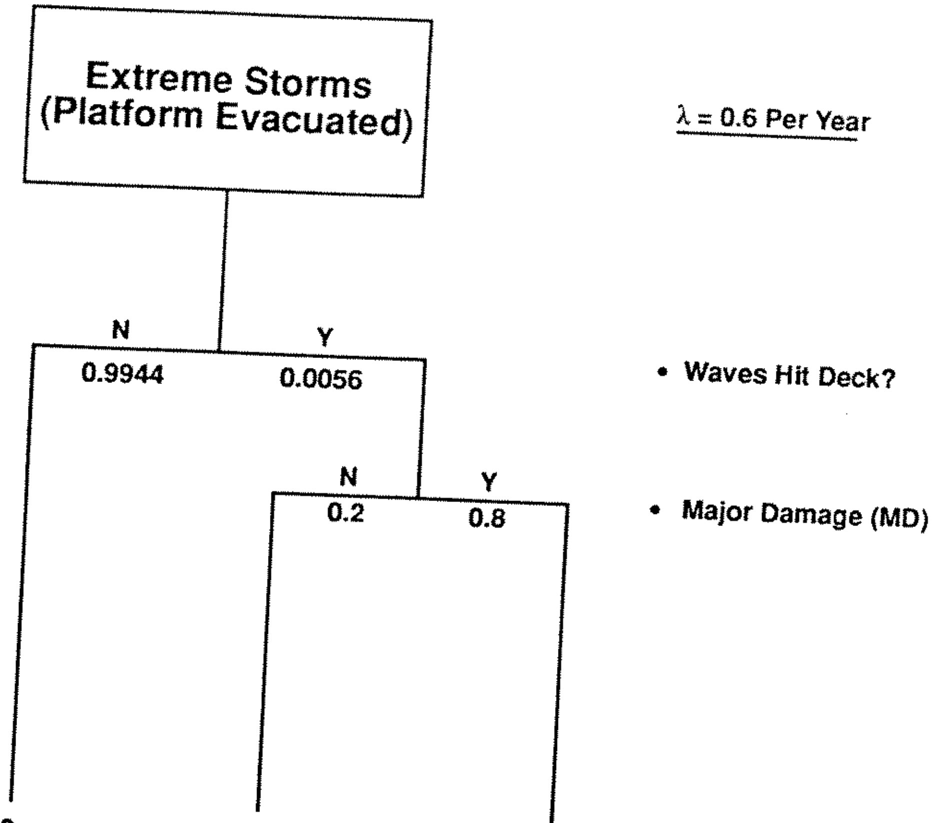


1	2	3	4	5	6	Event no *(Terminal events)*
0.012	0.048	0.14	0.16	0.16	0.48	Conditional probability ***(Conditional on initiating event)***
70	20	0	70	20	0	Expected value: lives
178%	29%	3%	178%	29%	6%	Expected value: cost (% of tot. platf. value)
5	1.5	0.15	5	1.5	0.3	Expected value: deferred prod. (years)
750	500	500	750	500	500	Expected value: spill (1000 bbls.)

DESCRIPTIONS OF TERMINAL EVENTS

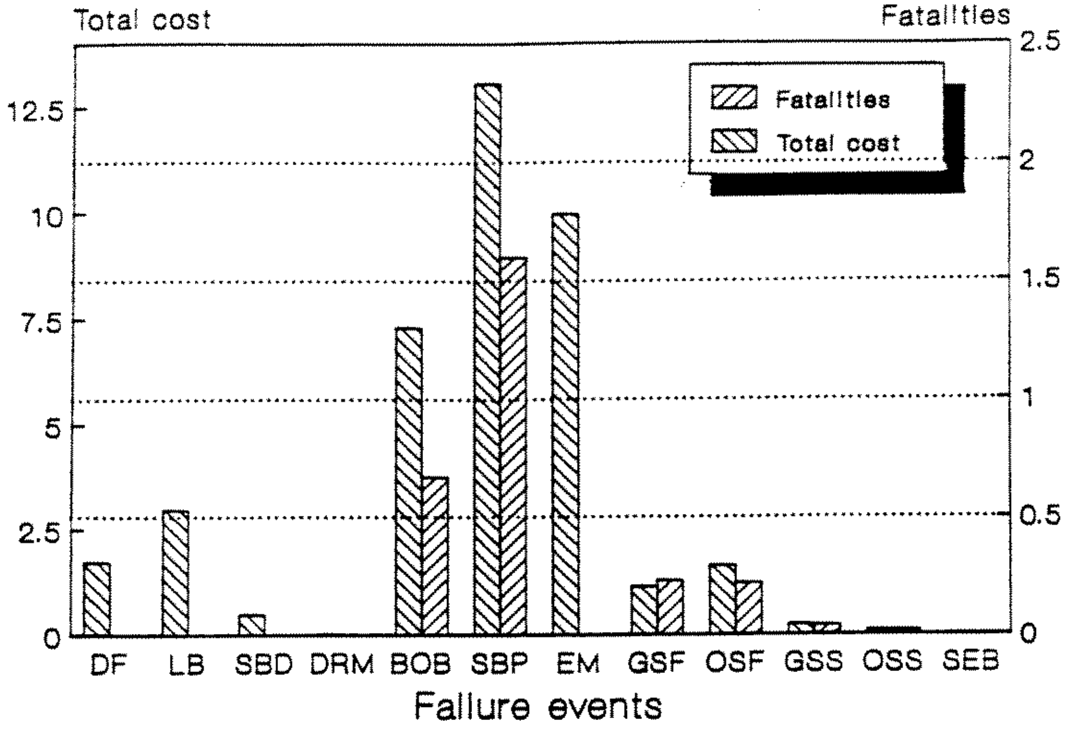
1 Controlled blowout, burning, global hull failure
2 Controlled blowout, burning, but no global hull failure
3 Controlled blowout, nonignited
4 Uncontrolled blowout, burning, global hull failure
5 Uncontrolled blowout, burning, but no global hull failure
6 Uncontrolled blowout, nonignited

Figure 3.4 Event Tree for Subsea Blowout in Drilling and Production Phase



0	LD (Local Damage)	MD	
994.4	1.12	4.48	Conditional Probability x 10^3
0	0	0	Serious Injuries
0	20.0	750.0	Damage/Repair Costs (mill US$)
0	183	1825	Deferred Production (days)
0	0	1000	Spill (1000 BBLS)

Figure 3.5 Storm Overload Event Tree



Terminology:

- DF - Design failure
- LB - Failure during lowering of BOP
- SBD - Subsea blowout in predrilling phase
- DRM - Dropped object from moonpool
- BOB - Platform blowout at BOP level
- SBP - Subsea blowout in production phase
- EM - Significant equipment malfunction
- GSF - Gas leak surface origin
- OSF - Oil leak surface origin
- GSS - Gas leak subsea origin
- OSS - Oil leak subsea origin
- SEB - Secondary subsea blowout

Figure 3.6 Contributions to Total Risk Cost in Coarse Evaluation

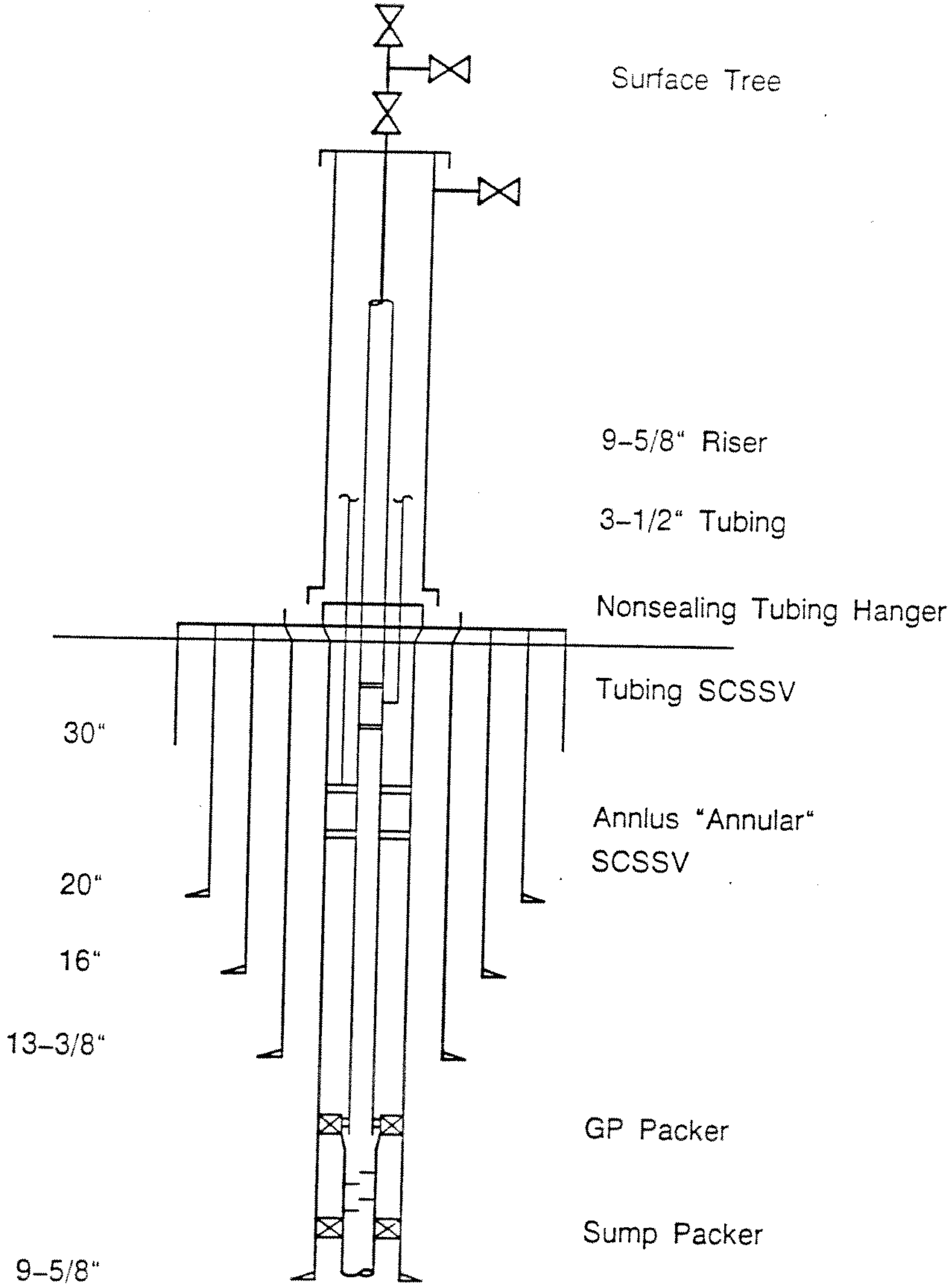


Figure 4.1 Surface Tree Riser Concept (Base Case)

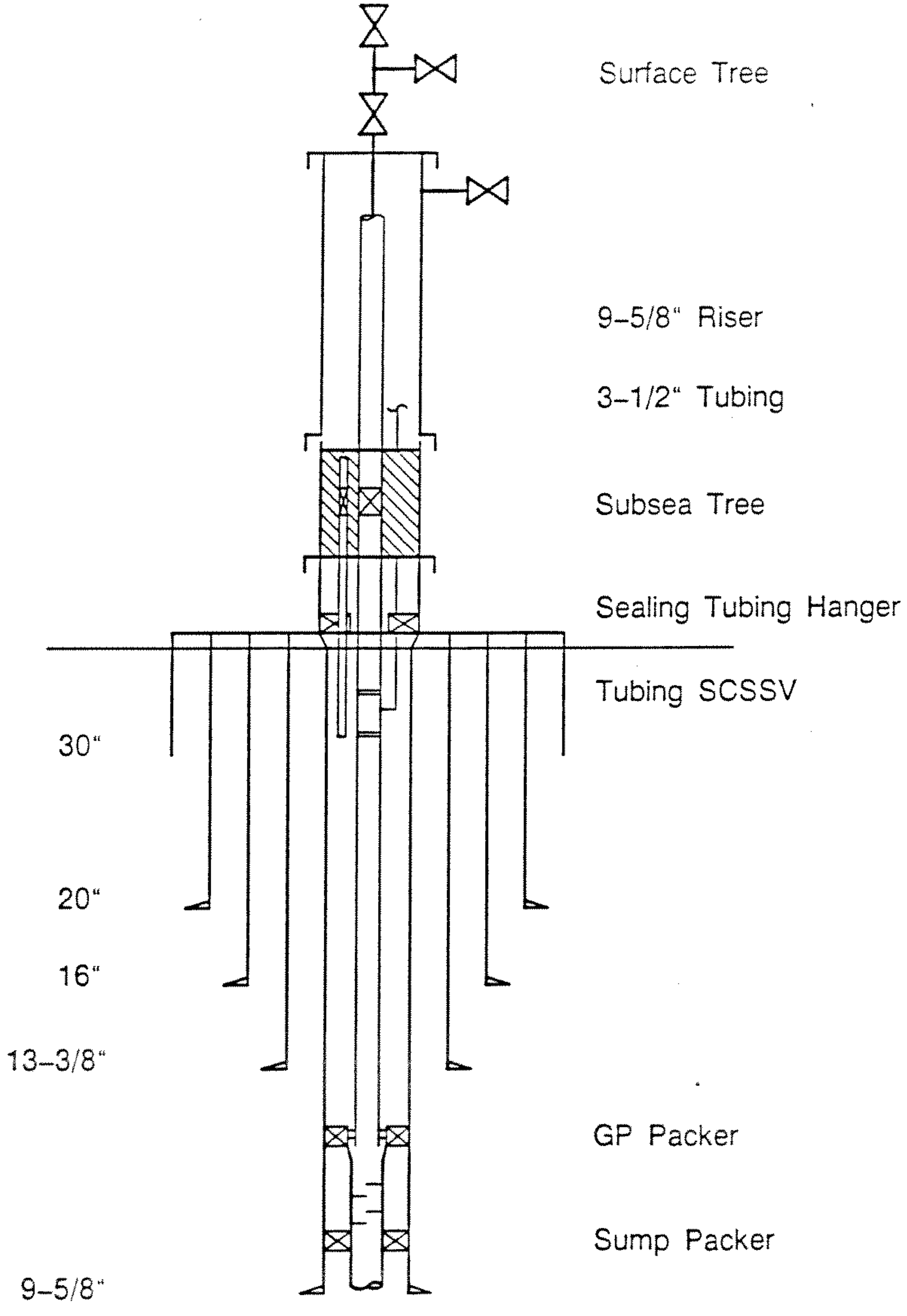


Figure 4.2 Split Tree Riser Concept

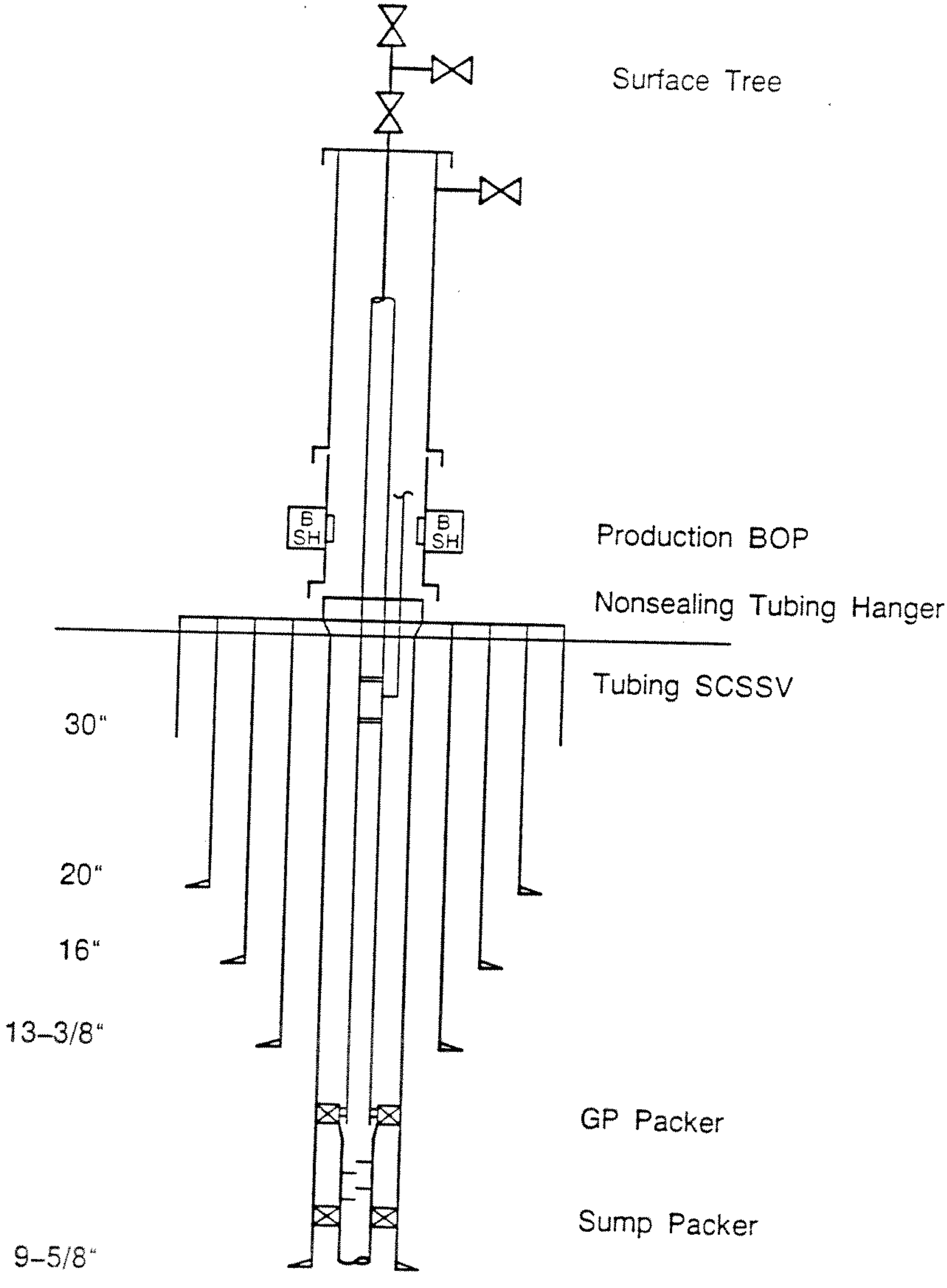


Figure 4.3 Subsea BOP Riser Concept

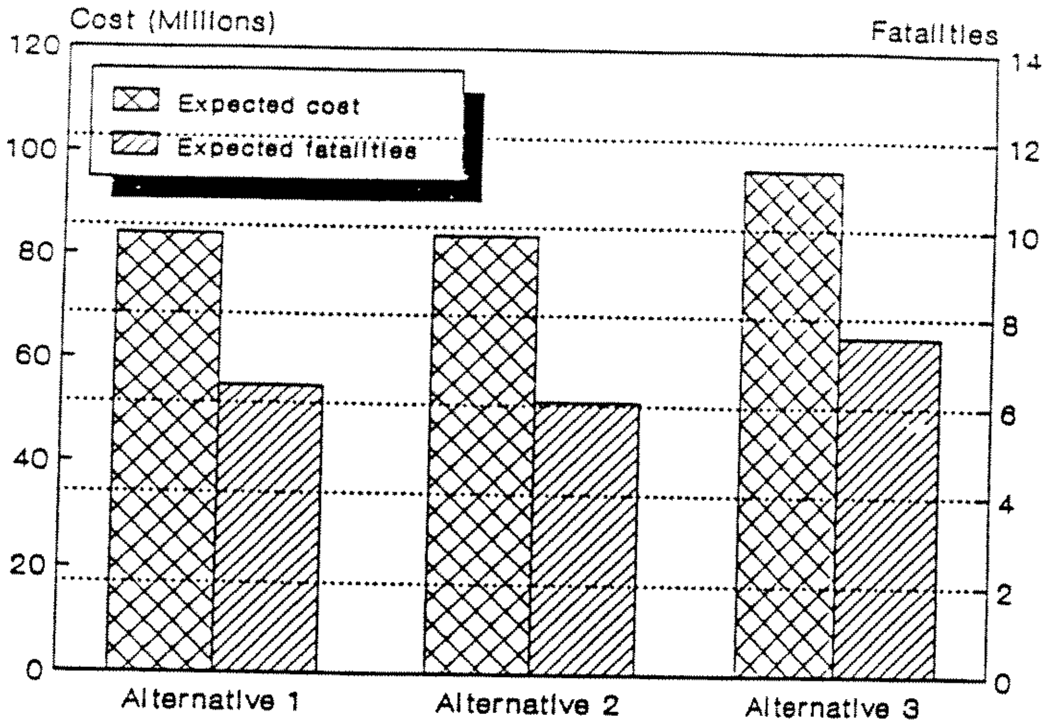


Figure 4.4 Overall Comparison of Riser Alternatives with Respect to Total Risk Cost and Fatality Risk

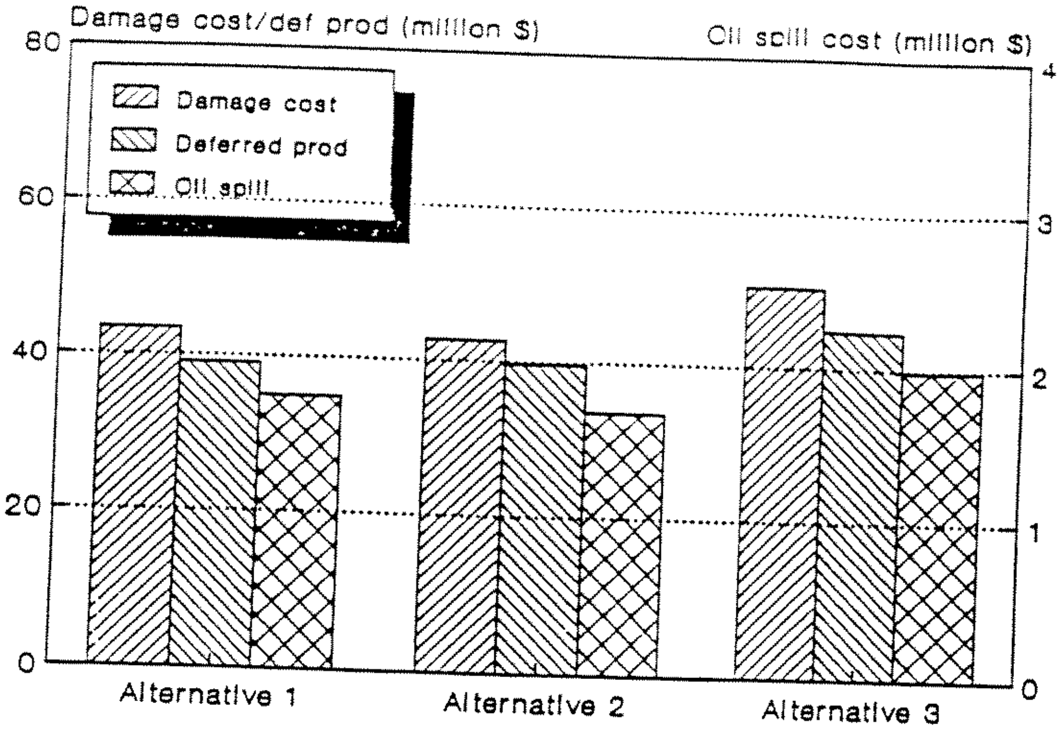
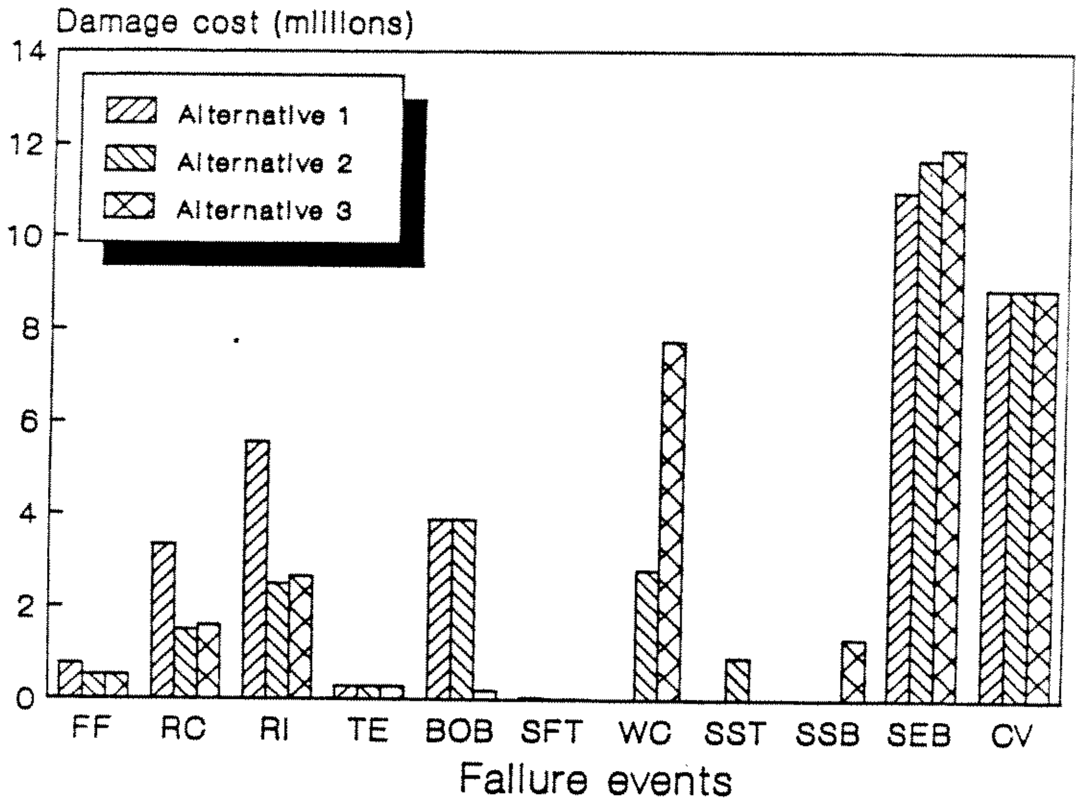


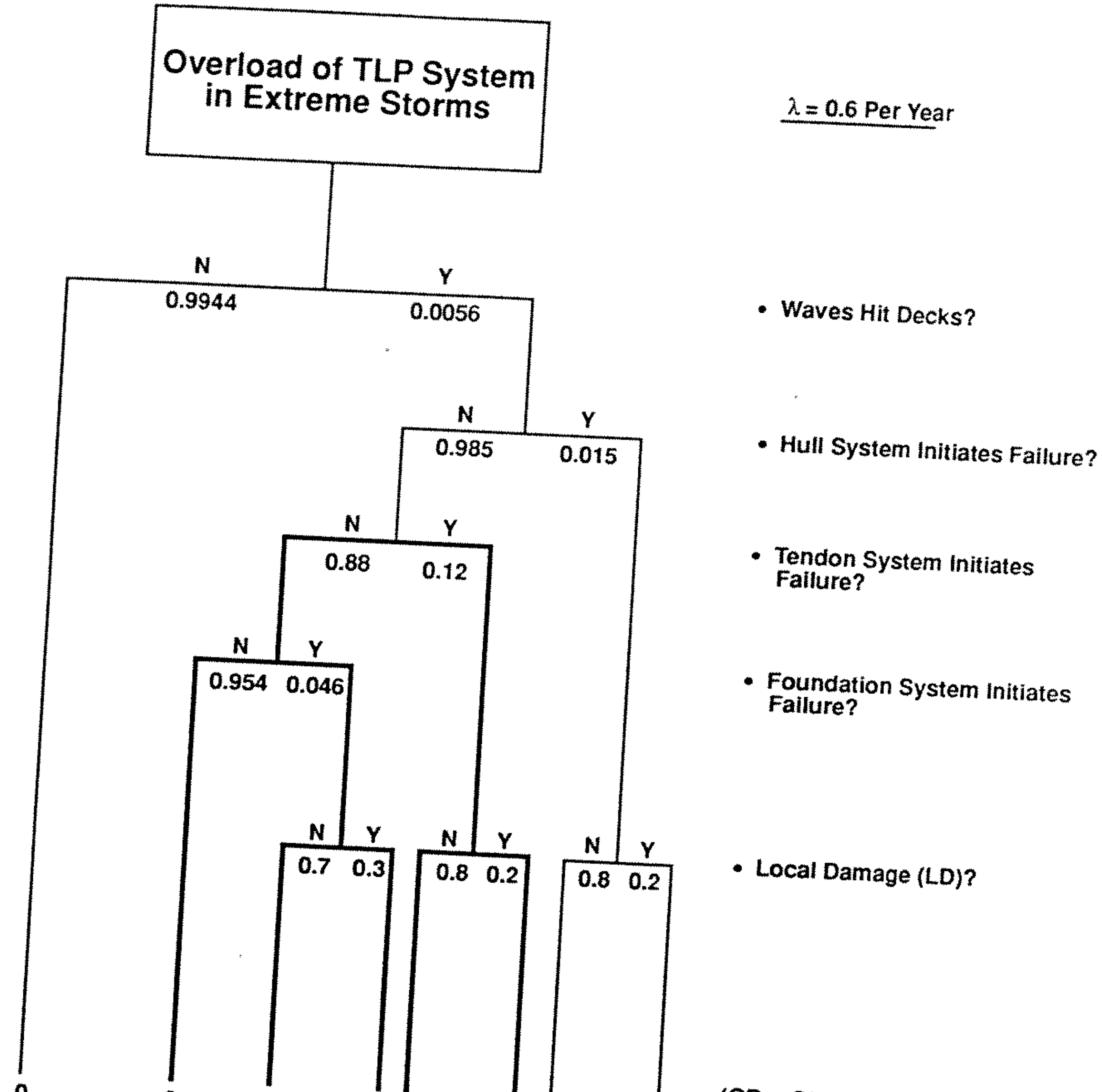
Figure 4.5 Comparison of Risk Costs of Riser Alternatives with Respect to Different Consequence Categories



Terminology:

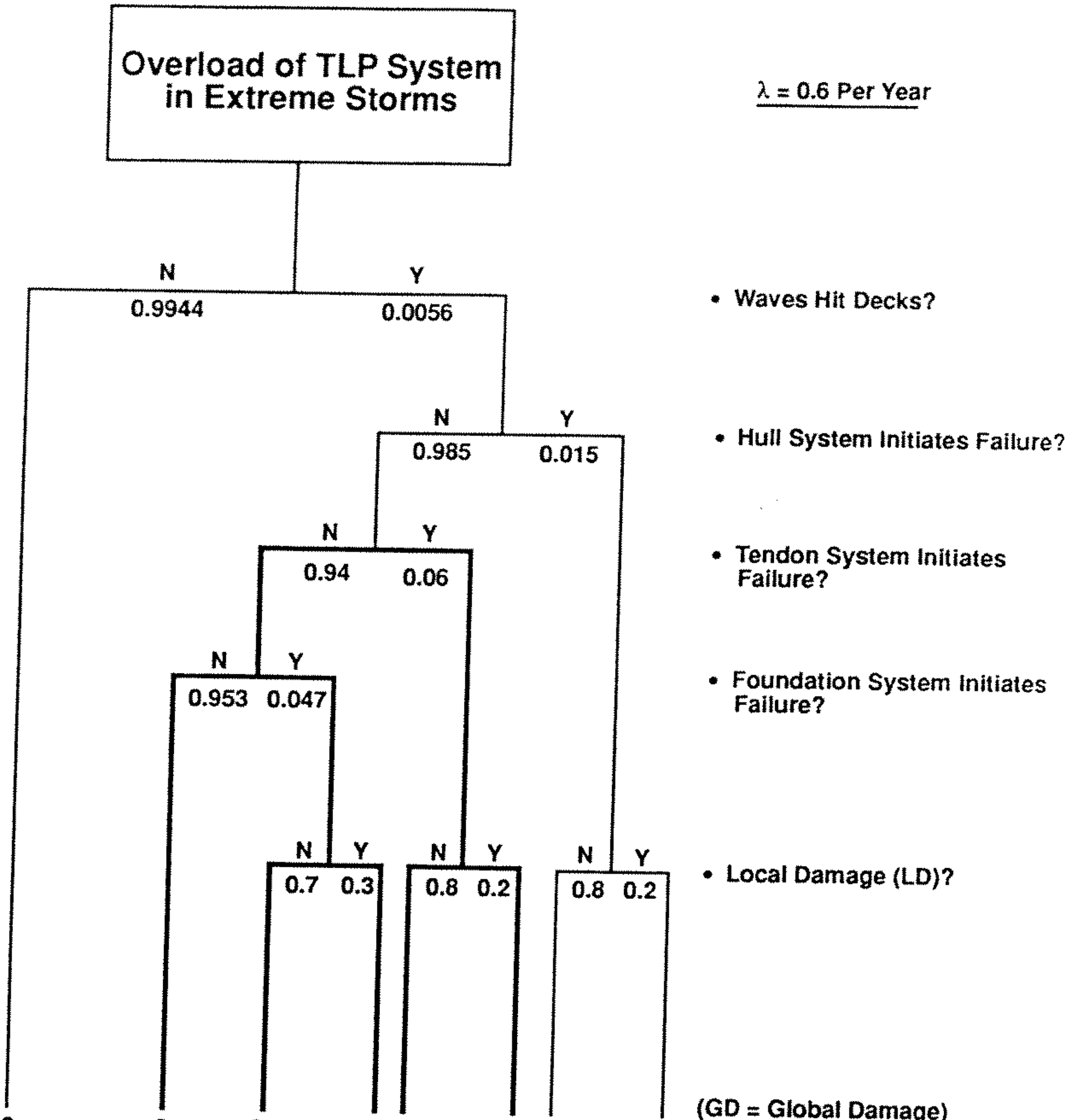
FF - Flexible flowline failure
RC - Riser connector failure
RI - Riser failure
TE - Tensioner failure
SFT - Surface tree failure = ZERO
WC - Wellhead connector failure
SST - Subsea tree failure
SSB - Subsea BOP failure
SEB - Secondary BOP blowout
CV - Constant values (from coarse evaluation)
BOB - Blowout at BOP Level

Figure 4.6 Comparison of Riser Alternatives with Respect to Different Initiating Events



0	0	GD	LD	GD	LD	GD	LD	(GD = Global Damage)
994.4	4.63	0.156	0.067	0.53	0.132	0.067	0.017	Conditional Probability x 10^3
0	0	0	0	0	0	0	0	Serious Injuries
0	0	750.0	20.0	750.0	20.0	750.0	20.0	Damage/Repair Costs (mill US$)
0	0	1825	183	1825	183	1825	183	Deferred Production (days)
0	0	1000	0	1000	0	1000	0	Spill (1000 BBLS)

Figure 4.7 Storm Overload Event Tree for 4-Tendon System



0	0	GD	LD	GD	LD	GD	LD	(GD = Global Damage)
994.4	4.94	0.166	0.073	0.265	0.066	0.067	0.017	Conditional Probability x 10^3
0	0	0	0	0	0	0	0	Serious Injuries
0	0	750.0	20.0	750.0	20.0	750.0	20.0	Damage/Repair Costs (mill US$)
0	0	1825	183	1825	183	1825	183	Deferred Production (days)
0	0	1000	0	1000	0	1000	0	Spill (1000 BBLS)

Figure 4.8 Storm Overload Event Tree for 2-Tendon System

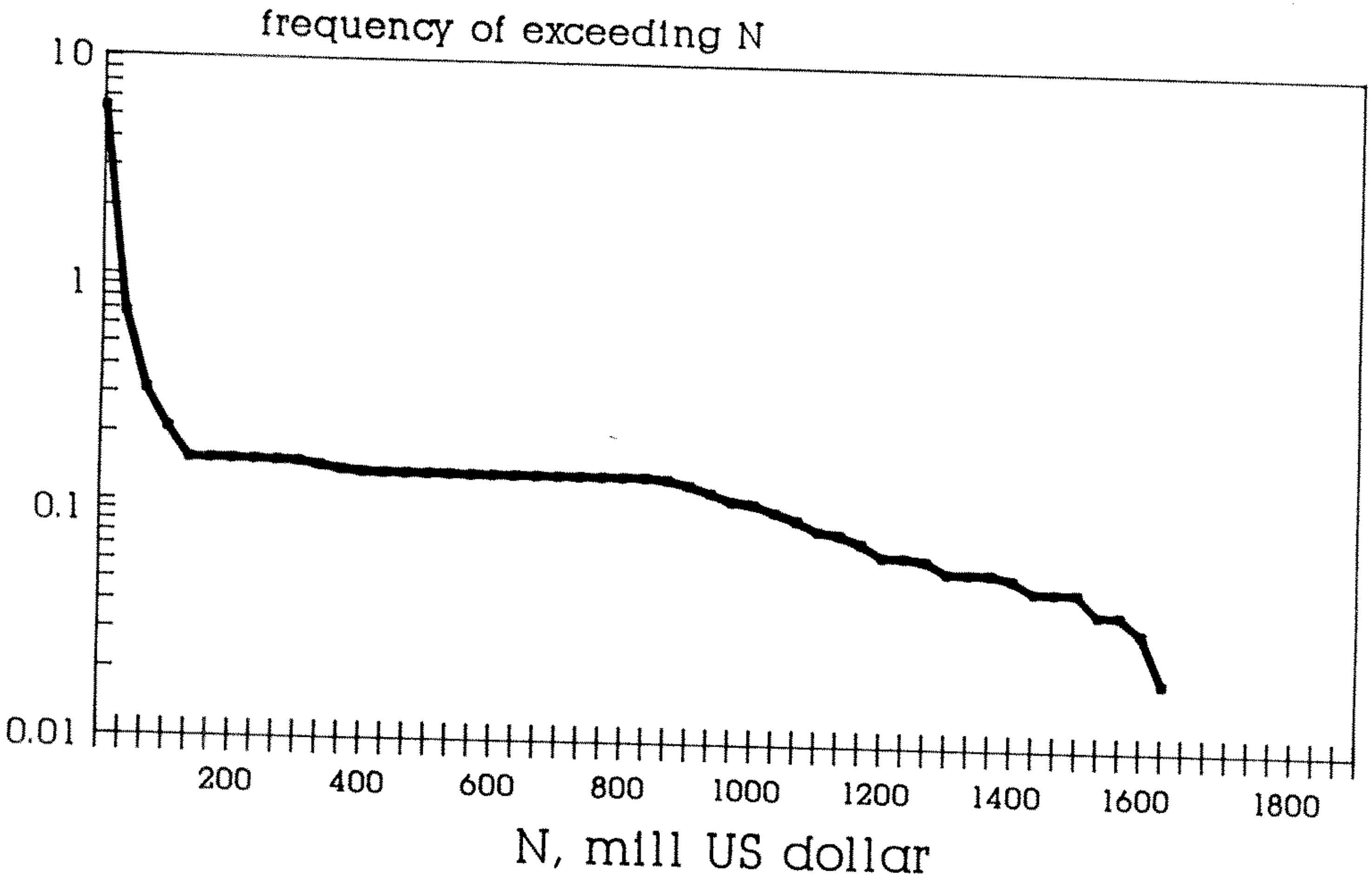


Figure 5.1 Lifetime Exceedance Frequency of Total Risk Cost (not discounted) for Base Case, Case II

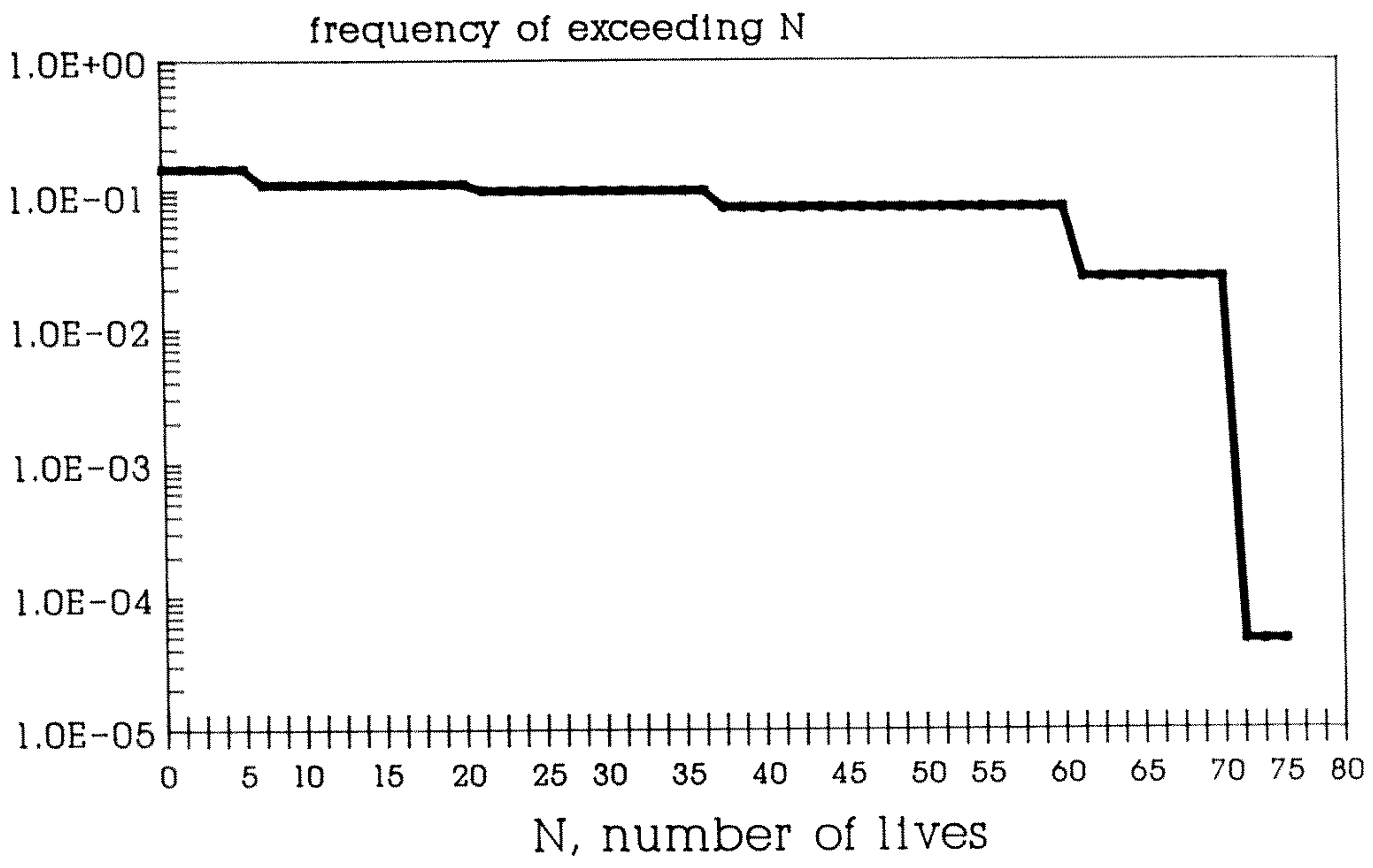


Figure 5.2 Lifetime Exceedance Frequency of Lives Lost (Not Discounted) for Base Case, Case II