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Human and Organizational Factors in Reliability Assessment and Management of Offshore Structures

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Today, there is a worldwide infrastructure of offshore structure systems that include fixed, floating, and mobile platforms, pipelines, and ships. Background on current and future trends in development of comprehensive programs to help improve the quality and reliability of offshore structure systems are discussed. A combination of proactive, reactive, and interactive risk assessment and management approaches have been developed and applied. Two risk assessment and management instruments are detailed in this article: a qualitative Quality Management Assessment System (*QMAS*), and a quantitative System Risk Analysis System (*SYRAS*). Application of *QMAS* to produce human and organizational performance shaping factors that are used as input to *SYRAS* is discussed.

KEY WORDS: Offshore structures; risk assessment; risk management; probabilistic risk assessment; quantitative risk assessment; structure risk analysis; qualitative risk assessment; human and organizational factors

1. INTRODUCTION

Reliability Assessment and Management (RAM) for offshore structures has been founded primarily on experience. This approach has resulted in more than 10,000 fixed, floating, and mobile offshore structures presently cited in the world's oceans in water depths approaching 1,000 m (Fig. 1). In addition, there are more than 200,000 miles of pipelines and 5,000 ships that form an infrastructure that provides support and facilities for exploration, drilling, production, and transportation of hydrocarbons.

Experience with these structures has clearly shown that the primary hazard is not the ocean environment itself; the industry has learned how to engineer, build, operate, and maintain structures that can survive the extreme storms, earthquakes, ice and sea floor soil movements that frequent this environment. The primary hazard is associated with human and organizational factors (HOF) that develop during their lifecycles. Studies have shown that while the majority of the structure failures occur during operations and maintenance, a majority of these failures have sources that are founded during the design phase. Structures are engineered and designed that have inherent flaws; they cannot be built as intended and they are difficult to operate and maintain. While they may have the requisite strength or capacity, they lack the required durability, serviceability, and compatibility.

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2. QUALITY AND RELIABILITY

One of the important developments in structural reliability analysis (SRA) and probabilistic risk analysis (PRA) for offshore structures[1] has been redefinition of the terms "quality" and "reliability" in a holistic context that addresses the primary functions and life-cycle phases of offshore structure systems. These definitions have proven to be very

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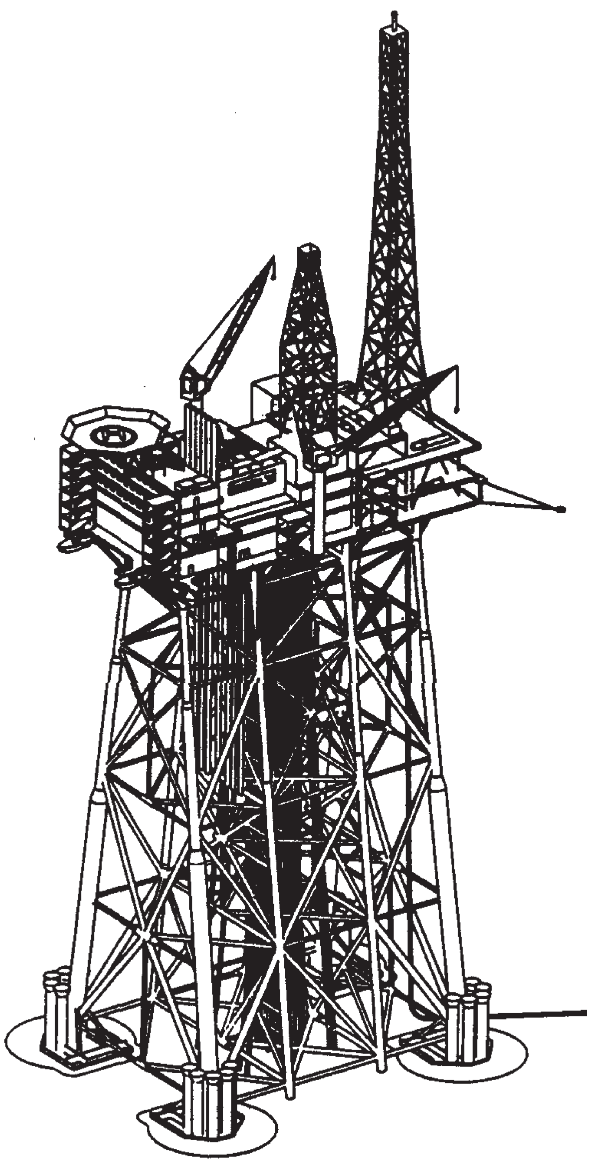

Fig. 1. Deep water offshore oil and gas drilling and production platform.

important in applications of PRA and SRA to the design and requalification of offshore structures; the definitions help focus the efforts on a balanced and comprehensive understanding of the potential performance characteristics of a given offshore structure system.

Quality has been defined as freedom from unanticipated defects in offshore systems. Quality is fitness for purpose.[2,3] Quality is meeting the requirements of those that own, operate, design, construct, and regulate offshore structures. These requirements include those of *serviceability, safety, compatibility*, and *durability*. Quality is taken to be *freedom from unanticipated defects in the serviceability, safety, durability, and compatibility of the offshore structure system.*

Serviceability is suitability for the proposed purposes, i.e., functionality. Serviceability is intended to guarantee the use of the system for the agreed purpose and under the agreed conditions of use. Safety is the freedom from excessive danger to human life, the environment, and property damage. Safety is the state of being free of undesirable and hazardous situations. The capacity of a structure to perform acceptably during extreme demands and other hazards is directly related to and most often associated with safety. Compatibility assures that the structure does not have unnecessary or excessive negative impacts on the environment and society during its lifecycle. Compatibility is also the ability of the structure to meet economic, time, and environmental requirements.

Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the structure. Durability is freedom from unanticipated maintenance problems and costs. Experience with offshore structures has shown that durability is one of the most important characteristics that must be achieved; if insufficient durability is developed, there are unanticipated and often undetected degradations in the other quality characteristics, and many times these degradations have disastrous results.

Note that concerns for safety have been integrated with the other quality attributes that largely dictate the operability/availability and financial viability of the system. In addition, offshore structure "systems" have been defined in a holistic way to include: operating personnel, organizations (local, corporate), equipment (hardware), structures (supporting facilities), procedures (formal, informal, software), environments (internal, external, social), and the interfaces between the foregoing. The "stop-rule" in the characterization of such systems is to stop the identifications and analyses when the effects of adding more elements/components produces relatively insignificant effects on quality and reliability.

Reliability has been defined as the probability (likelihood) that a given level of quality will be achieved during the design, construction, operating, and maintenance life-cycle phases of an offshore structure. Reliability is the likelihood that the structure system will perform in an acceptable manner. Acceptable performance means that the structure system has desirable serviceability, safety, compatibility, and durability. The complement of reliability is the likelihood or probability of unacceptable quality; the probability of failure. This definition has linked the concepts of probability, uncertainty, and reliability with the holistic definition of quality to reflect upon the likelihoods of achieving acceptable quality in offshore structures.

Compromises in quality of a structure system can occur in the structure itself and/or in the facilities it supports. These failures can be rooted in malfunctions developed by individuals (operators) in design, construction, operation, and/or maintenance. Individuals, the people who design, construct, operate, and maintain the systems, have direct influence on malfunctions developed in these phases. However, the malfunctions developed by the individuals can be and often are caused (contributing factors) or compounded (propagating factors) by malfunction-inducing influences from organizations, hardware, software (procedures), and environment (external, internal).

The quality and reliability of the structure system can be directly influenced by two primary categories of factors: intrinsic and extrinsic. Intrinsic factors are hazards that can result in compromises in the quality of the structure system that are ''natural'' or due to inherent randomness (residual risk elements). Extrinsic factors are hazards that can result in compromises in the quality of the structure system that are ''unnatural'' or caused by human and organizational factors (HOF). HOF can result in human and organizational errors (HOE); these are misadministrations or malfunctions that have unanticipated and undesirable outcomes. Human errors represent outcomes from interactions of a complex series of initiating, contributing, and compounding factors. Experience with the wide variety of offshore structures has clearly shown that while the majority of initiating factors can be identified with malfunctions of individuals and/or ''operating'' teams, the vast majority of contributing and compounding factors represent organizational breakdowns.

3. APPROACHES AND STRATEGIES

Current experience indicates that there are three fundamental, complementary, and interactive approaches that can be implemented to help achieve adequate and acceptable reliability in offshore structures: (1) proactive, (2) reactive, and (3) interactive or real-time. In the context of these three approaches there are three strategies that can be employed: (1) reduce incidence of malfunctions, (2) increase detection and correction of malfunctions, and (3) reduce effects and consequences of malfunctions.

3.1. Proactive Approaches

The proactive approach attempts to analyze the system before it fails in an attempt to identify how it could fail in the future. Measures can then be put in place to prevent the failure or failures that have been anticipated. Proactive approaches include well-developed qualitative methods such as HazOp (Hazard Operability) and FMEA (Failure Mode and Effects Analyses),[5] and quantitative methods such as PRA (Probabilistic Risk Analyses) and QRA (Quantified Risk Analyses).[1] Each of these methods have benefits and limitations and if used wisely can be employed with good results during different phases in the lifecycle of an offshore structure system.

Proactive PRA/QRA/SRA processes have been widely used by the offshore structure industry for more than three decades. Another important proactive approach that has been employed in offshore structures comes from the field of ergonomics: the art and science of interfacing people with the systems that they design, construct, operate, and maintain. This approach is fundamentally one that focuses on a proactive reduction in the likelihoods of malfunctions that develop at people-hardware interfaces.[6] Recent experience has adequately demonstrated that configuration of ''people friendly'' interfaces with the other system components, including procedures, environments, hardware, structure, and, most recently, organizations (macroergonomics), can do much to help assure that desirable and acceptable quality and reliability in offshore structures are realized. Detailed guidelines have been developed for the ergonomic design of offshore structure systems.[7,8]

Experience with RAM during the lifecycle of offshore structures has shown that one of the most important proactive strategies is that of creating robust-damage tolerant and fail-safe (intrinsically safe) structure systems. Robustness in the structure, operating team, and organizational components of offshore structure systems has been shown to be derived from three primary elements: (1) configuration, (2) ductility, and (3) excess capacity.[3] The elements are configured so that backups are provided for conditions in which the system may be defective or damaged; they are configured so that the full potential capacities of the elements can be developed. Frequently, engineers have called this ''redundancy,'' referring to the degree of indeterminacy or existence of parallel/back-up elements. Configuration can involve redundancy, but it also involves many other aspects of the geometry and layout (topology) so that the structure, hardware, or organization can perform acceptably even though defective and damaged. Ductility is the ability (and willingness) to carry overloads and shift the overloads to other parts of the system without loss of basic functionality. Excess capacity is provision of the ability of ''under-loaded'' elements in the system to carry abnormal demands or loads. Intrinsically safe systems are those that fail in ways that do not compromise the basic safety characteristics of the system; following a failure, the system can continue to be safely operated until repairs and/or modifications can be made. Experience and analysis have shown that desirable robustness and intrinsic safety cannot be achieved by developing initial cost minimized-weight optimized systems; unguided cost cutting, downsizing, and outsourcing in the components of an offshore structure system have had disastrous results.[9]

3.2. Reactive Approaches

The reactive approach is based on analysis of the failure or near failures (incidents, near-misses) of a structure system. An attempt is made to understand the reasons for the failure or near-failures, and then to put measures in place to prevent future failures of the structure system.[5]

Attention to failures (accidents), near-misses, and incidents is clearly warranted. Studies have indicated that generally there are about 100+ incidents, and 10 to 100 near-misses, to every accident.[5] The incidents and near-misses can give early warnings of potential degradation in the quality of the structure system. In addition, the incidents and near-misses, if well understood and communicated, provide important clues about how system operators are able to rescue their systems, returning them to a high-quality state. Such insights are very important to the interactive RAM that will be discussed shortly.

Guidelines have been developed for investigating incidents and performing assessments associated with near-misses and accidents.[5,10] Experience with application of these guidelines indicates that the attitudes and beliefs of the involved organizations are critical in developing successful systems, particularly in doing away with ''blame and shame'' cultures and practices. It is further observed that many, if not most, applications focus on ''technical causes,'' including structure, procedures, equipment, and hardware. Human-system failures are treated in a superficial manner and often from a safety engineering perspective that has a focus on outcomes of errors (e.g., inattention, lack of motivation) and statistical data (e.g., lost-time accidents).

A primary objective of incident reporting systems is to identify recurring trends from the large number of incidents with relatively minor outcomes. The primary objective of near-miss systems is to learn lessons (good and bad) from operational experiences. Near-misses have the potential for providing more information about the causes of serious accidents than accident information systems. Near-misses potentially include information on how the human operators have successfully returned their systems to high-quality states. These lessons and insights should be reinforced to better equip operators to maintain the quality of their systems in the face of unpredictable and unimaginable unraveling of their systems.

Inspections during construction, operation, and maintenance of offshore structures are a key element in reactive RAM approaches. Thus, development of IMR (Inspection, Maintenance, Repair) programs is a key element in development of reactive management of the quality and reliability of offshore structure systems.[11–13] Deductive methods involving mechanics-based probability techniques have been highly developed. These techniques focus on ''predictable'' damage that addresses durability (e.g., fatigue damage). Inductive methods involving discovery of defects and damage are focused primarily on ''unpredictable'' elements that are due primarily to unanticipated HOE, such as weld flaws, fit-up or alignment defects, dropped objects, ineffective corrosion protection, and collisions. Experience with a wide variety of types of marine structures clearly indicates that a majority of damage and defects that develop during the lifecycle of an offshore structure is due to the second category of ''causes;''[13] thus, IMR programs must be developed that address both categories of damage and defects. Reliability Centered Maintenance (RCM) approaches have been developed to help address both predictable and unpredictable damage and defects.[14,15]

Experience with offshore structure systems has shown that the reactive approach also has some important limitations. It is not often that one can truly understand the causes of accidents; often, there are important limitations in the selection, training, and motivations of accident-, incident-, and near-miss assessors/investigators. Also, there are important limitations in the processes and ''templates'' that these investigators use in the assessments and in recording the results. Legal, regulatory, punitive, and organizational ''image'' concerns frequently overshadow the assessment and understanding processes.

If one does not understand the true causes, how can one expect to put the right measures in place to prevent future accidents? Further, if the causes of accidents represent an almost never to be repeated collusion of complex actions and events, then how can one expect to use this approach to prevent future accidents? Further, the usual reaction to accidents has been to attempt to put in place hardware and equipment that will help prevent the next accident. Attempts to use equipment and hardware to fix what are basic HOF problems generally have not proven to be effective. It has been observed that progressive application of the reactive approach can lead to decreasing the accepted ''safe'' operating space for operating personnel through increased formal procedures to the point where the operators have to violate the formal procedures to operate the system.[10]

3.3. Interactive Approaches

Experience with RAM in the quality and reliability of offshore structures has shown that there is a third and very important approach that needs to be recognized and further developed. This approach is interactive (real-time) assessment and management of degradations in which danger builds up in a system and it is necessary to actively intervene with the system to return it to an acceptable quality state. Until recently, this approach was largely ignored; it was contended that proactive and reactive approaches were the only two fundamental RAM approaches.

The interactive approach is based on the contention that many aspects that influence or determine the failure of structure systems in the future are fundamentally unpredictable and unknowable. These are the incredible, unbelievable, complex sequences of events and developments that unravel a system until it fails or malfunctions. This approach is based on providing systems (including the human operators) that have enhanced abilities to detect potential degradations and rescue themselves. This approach is based on the observation that people more frequently return systems to high-quality states (incidents, near-misses) than they do to states that result in accidents and failures.

Engineers can have important influences on the abilities of people to rescue systems, and on the abilities of the structure systems to be rescued, by providing adequate measures to support and protect the operating personnel and the system components that are essential to their operations. Quality control (QC) is an example of the real-time approach that is frequently employed in the design and construction phases. Quality assurance is done before the activity (proactive), but QC is conducted during the activity (interactive). The objective of QC is to be sure that what was intended is actually being carried out and that the activity is developing the desirable results.[5] Current experience indicates that much of what is presently done in QA/QC is not effective; a false sense of security is developed by what are frequently perfunctory processes that even more frequently focus on the elements that rarely are responsible for major compromises in the quality and reliability of offshore structures (e.g., checking calculations and not verifying assumptions).

Two fundamental approaches to improving interactive RAM performance are: (1) providing people support, and (2) providing system support.[16] People support strategies include such things as selecting personnel well suited to address and perform the necessary activities, and then training them so they possess the required skills and knowledge. Retraining is important to maintain skills and achieve vigilance. The cognitive skills developed for interactive RAM degrade rapidly if they are not maintained and used.

Interactive RAM teams can be developed that have ''requisite variety;'' variety in the team members' backgrounds and experience matches the variety of issues that need to be addressed. Such teams need to have well-developed teamwork processes so the necessary awareness, skills, and knowledge are mobilized when they are needed. Auditing, training, and retraining are needed to help maintain and hone skills, improve knowledge, and maintain readiness. Interactive RAM teams need to be trained in problem ''divide and conquer'' strategies that preserve situational awareness through organization of strategic and tactical commands and utilization of ''expert task performance'' (specialists) teams that utilize ''migrating decision making.''[17] Interactive RAM teams need to be provided with practical and adaptable strategies and plans that can serve as useful ''templates'' in helping manage each unique situation. These templates help reduce the amount and intensity of cognitive processing that is required to manage the situation.

Improved system support includes factors such as improved maintenance of the necessary critical equipment and procedures so they are workable and available as the situation unfolds. Data systems and communications systems are needed to provide and maintain accurate, relevant, and timely information in ''chunks'' that can be recognized, evaluated, and managed. Systems need to be provided to slow the escalation of the situation, and to restabilize the system. Structures need to be designed that will promote quality and reliability in design, construction, operations, and maintenance; life-cycle design of human friendly systems.

4. RAM INSTRUMENTS

Two instruments have been developed recently to help promote more effective application of RAM process in proactive, reactive, and interactive approaches. The first instrument is identified as a Quality Management Assessment System (QMAS); this is fundamentally a qualitative process to help guide assessment teams to examine the important parts of offshore structure systems at different times during their lifecycle. These assessment teams include members of the offshore structure system being assessed. The instrument has been designed to elicit the insights and information that only these people can have.

The second instrument is a System Risk Analysis System (SYRAS); this is a PRA/QRA/SRA instrument to help develop quantitative results that are often required by engineers and managers. Traditional event tree and fault tree analysis methods have been used in SYRAS. The analytical templates in SYRAS enable analyses of each of the lifecycles of an offshore structure (design, construction, operation, maintenance) and address each of the quality attributes. A link has been developed between the results from QMAS and the input required for the SYRAS instrument. This link is based on translating the ''grades'' developed from application of QMAS to performance shaping factors (PSF) that are used to modify normal rates of human/operator malfunctions. The link has been developed, verified, and calibrated from QMAS-SYRAS analyses of failures and successes of offshore structure systems during their different life-cycle phases.[18] While PSF have been used by a variety of industries to modify ''standard'' rates of malfunctions,[5] their verification/validation has been very limited. Using results from case history studies to provide such validations does not appear to be extensively developed. Due to the specific types of systems that have been used in the developments, the PSF used in the QMAS-SYRAS link may be valid only as to the types of systems and their particular life-cycle phases. Research is continuing on these PSF.

Both QMAS and SYRAS are generic in that they can be and have been applied to a wide variety of different types of structure systems (onshore and offshore). However, it has been learned that every system brings with it unique aspects that must be reflected in these instruments. Particular hardware, structure, software, organizational, operating team, environments, and interface elements must be incorporated into the generic frameworks. Such flexibility has been intentionally incorporated in these elements. System-specific modifications generally are developed by the assessment teams that use these instruments.

5. QUALITY MANAGEMENT ASSESSMENT SYSTEM

QMAS is a method that is intended to provide a level of detail between the qualitative/less detailed methods (e.g., HazOps, FMEA) and the highly quantitative/very detailed methods (PRA, QRA). QMAS encompasses two levels of safety assessment: coarse and detailed qualitative. The objective of QMAS is to, with the least effort possible, identify those factors that are not of concern relative to quality and reliability, to identify those mitigation measures that need to be implemented to improve quality and reliability, and to identify those factors that are of concern that should be relegated to more detailed quantitative evaluations and analyses. QMAS has been designed to facilitate applications in operational settings in which the ''domain experts'' do not have extensive or formal RAM backgrounds; this is an instrument that is intended to help empower those that have daily responsibilities for the quality and reliability of offshore structure systems.

5.1. Components

The QMAS system is comprised of three primary components: (1) a laptop computer program and documentation that is used to help guide platform assessments and record their results, (2) an assessor qualification protocol and training program, and (3) a three-stage assessment process that is started with information gathering and identification on Factors of Concern (FOC), then proceeds to observe operations, and is concluded with a final assessment and set of recommendations.

The surveying instrument is in the form of a laptop computer program that contains interactive algorithms to facilitate development of consistent and meaningful evaluations of existing facilities. The instrument includes evaluations of the categories of facility factors defined earlier: operating personnel, organizations, hardware (equipment, structure), procedures (normal, emergency), environments, and the interfaces between the categories of factors. Standardized and customized written, tabular, and graphical output reporting and routines are provided. This instrument is intended to help identify alternatives for how a given facility might best be upgraded so that it can be fit for the intended purposes.

5.2. Evaluation Steps

There are five major steps in the QMAS. Step 1 is to select a system for assessment. This selection would be based on an evaluation of the history of quality and reliability degradation events and other types of high-consequence accidents involving comparable systems, and the general likelihood and consequences of potential quality and reliability degradations.

Step 2 is to identify an assessment team. This team is comprised of qualified and trained QMAS assessors indicated as Designated Assessment Representatives (DARs). These DARs normally come from the organization/s and operation/s being assessed, regulatory or classification agencies, and/or consulting engineering service firms. DAR appointment is based on technical and operations experience. Integrity, credibility, and deep knowledge are key DAR qualification attributes. DARs are qualified based on QMAS-specific training and experience that includes development of in-depth knowledge of human and organizational factors and their potential influences on the quality and reliability of offshore structure systems. To avoid conflicts of interest, DARs are allowed to request replacement when such conflicts arise. It is desirable that the assessment teams include members of management and operations/engineering. The DAR teams include experienced ‘‘outsiders’’ (counselors) who have extensive HOF background and QMAS applications experience.

Step 3 consists of a coarse qualitative assessment of the seven categories of elements that comprise an offshore structure system. This assessment is based on the general history of similar types of facilities and operations and details on the specific system. These details would consist of current information on the structure, equipment, procedures (normal operations and maintenance, and emergency/crisis management), operating personnel (including contractors), and organizations/management. Discussions are held with representatives of the operator/system organization and the operating/engineering teams.

The product of Step 3 is identification of the FOC that could lead to degradations in quality and reliability of an offshore structure system. As a part of the assessment process, which will be described later, the assessment team records the rationale for identification of the FOC. The assessment may at this stage also identify suggested mitigations. The results are reported in user-selected standard textural and graphical formats and in user-defined textural and graphical formats (that can be stored in the computer or produced each time). For some systems, the information at this stage may be sufficient allow the system to exit the QMAS with the implementation of the mitigations, recording the results, and scheduling the next assessment.

If it is deemed necessary, the QMAS proceeds to Step 4: development of scenario/s to express and evaluate the FOC. These scenarios or sequences of events are intended to capture the initiating, contributing, and compounding events that could lead to degradations in quality and reliability. These scenarios help focus the attention of the assessors on specific elements that could pose high risks to the system. Based on the FOC and the associated scenarios, Step 5 proceeds with a detailed qualitative assessment. Additional information is developed to perform this assessment and includes more detailed information on the general history of the structure system, its details, results from previous studies, and management and operating personnel interviews. In recording results from the interviews, provisions are made for anonymous discussions and reporting.

The product of Step 5 is a detailing of the mitigation measures suggested for mitigation of the FOC confirmed in Step 5. The rationale for the suggested mitigations are detailed, together with projected beneficial effects on the FOC. As for the results of Step 3, the results of Step 4 are reported in
1 standard and user-defined formats. At this point, the assessment team could elect to continue the QMAS in one of two ways. The first option would be to return to the FOC stage and repeat Step 5 based "new" FOC and the associated scenarios. The second option would be to proceed with some of the FOC and the associated scenarios into coarse quantitative analyses and evaluations. If the assessment team elected, the QMAS could be terminated at the end of Step 5. The results would be recorded, and the next assessment scheduled.

5.3. Evaluations Processes

The QMAS evaluation is organized into three sections or "levels" (Fig. 2). The first level identifies each of the seven structure system components: 1.0 – operators, 2.0 – organizations, 3.0 – procedures, 4.0 – equipment, 5.0 – structure, 6.0 – environments, and 7.0 – interfaces. These seven components comprise "modules" in the QMAS computer program. The structure and equipment factors are modified to recognize the unique characteristics of different offshore structures.

The second level identifies the factors that should be considered in developing assessments of the components. For example, for the operators (1.0), seven factors are identified: communications (1.1), selection (1.2), knowledge (1.3), training (1.4), skills (1.5), limitations/impairments (1.6), and organization/coordination (1.7). If in the judgment of the assessment team, additional factors should be considered, such can be added. Using a process that will be described later, the assessment team develop grades for each of these factors.

The third level identifies attributes associated with each of the factors. These attributes are observable (behaviors) or measurable. These attributes provide the basis or rationale for grading the factors. For example, for the communications factor (1.1), six attributes are included: clarity (1.1.1), accuracy (1.1.2), frequency (1.1.3), openness/honesty (1.1.4), verifying or checking—feedback (1.1.5), and encouraging (1.1.6). Again, if in the judgment of the

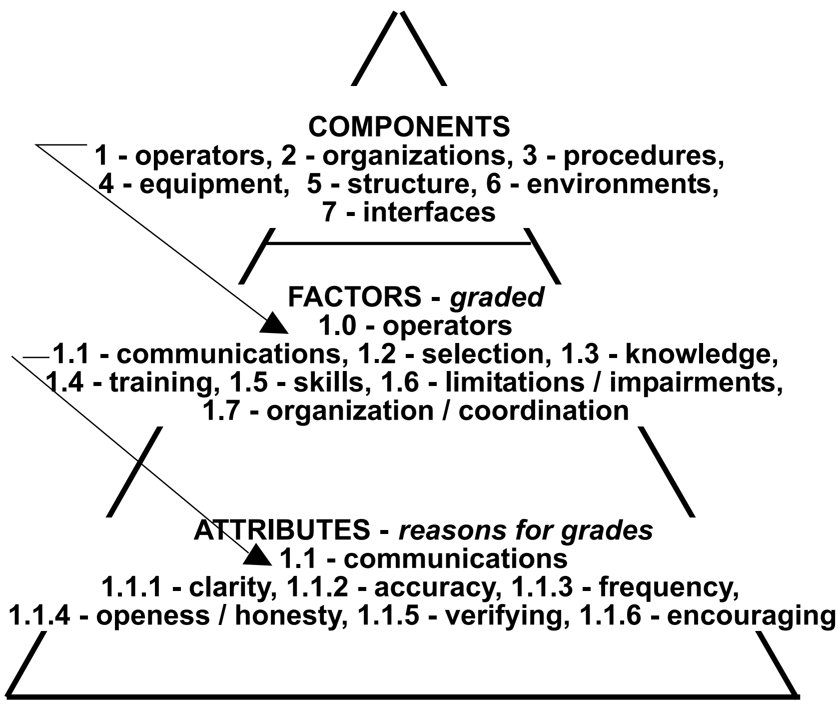

Fig. 2. Safety components, factors, and attributes.

assessment team, additional attributes are needed, they can be added to the QMAS.

The factors and attributes for each of the system components have been based on results from current research on these components with a particular focus on the HOF-related aspects.[5,17,19–28] This approach avoids many of the problems associated with traditional "question-based" instruments that frequently involve hundreds of questions that may be only tangentially applicable to the unique elements of a given structure system.

5.4. Factors Grading

The QMAS assessment team assigns grades for each component factor and attribute. Three grades are assigned: the most likely, the best, and the worst. These three grades help the assessors express the uncertainties associated with the gradings. Each of the attributes for a given factor are assessed based on a seven-point grading scale (Fig. 3). An attribute or factor that is average in meeting referent standards and requirements is given a grade of 4. An attribute or factor that is outstanding and exceeds all referent standards and requirements is given a grade of 1. An attribute or factor that is very poor and does not meet any referent standards or requirements is given a grade of 7. Other grades are used to express characteristics that are intermediate to these. The reasons for the attribute and factors grades are recorded by the assessment team members. This process develops a consensus among the system or domain experts, allowing for expressions of dissenting opinions. The expression of the reasons for the gradings provides some of the most important insights into the potentially important challenges to the quality and reliability of offshore structure systems.

The grades for the attributes are summed and divided by the number of attributes used to develop a resultant grade for the factor. Weightings of the factors and attributes can be introduced by the assessors. The assessors review the resultant grades and if they are acceptable, the grades are recorded.

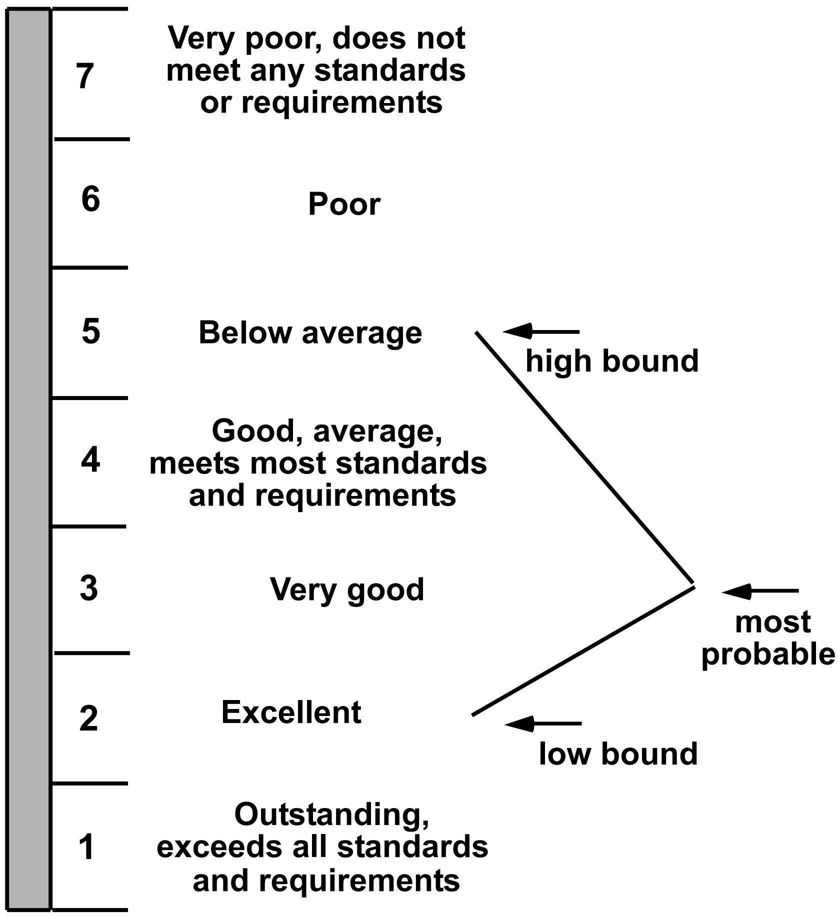

Fig. 3. Scale for grading attributes, factors, and components.

If they are not, they are revised and the reasons for the revisions noted. The uncertainties associated with the grades for the attributes are propagated using a first order statistical method.

In the same manner, the grades for the factors are summed and divided by the number of factors to develop a resultant grade for the component. Again, the assessors review this resultant grade and if it is acceptable, the grade is recorded. If it is not, it is revised and reasons for the revision noted. The uncertainties associated with the grades for the factors are propagated using a first order statistical method.

A ''Braille'' chart is then developed that summarizes the mean grades (and, if desired, their standard deviations) developed by the assessment team for each of the factors (Fig. 4). The ''high'' grades (those above 4) indicate components and the associated factors that are candidates for mitigation.

5.5. Assessors

The most important element in the QMAS system is the team of assessors. It does not matter how good the QMAS assessment instruments and procedures are if the personnel using the instrument do not have the proper experience, training, and motivations. The QMAS assessors must have experience with the system being assessed, quality auditing experience, and training in human and organization factors. The assessor team is comprised of members from the system (operators, engineers, managers, regulators) and QMAS ''counselors'' who have extensive experience with the QMAS system and operations—facilities similar to those being assessed.

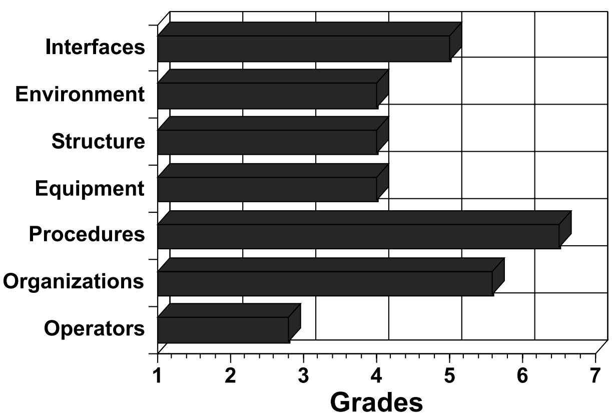

Fig. 4. Example component mean grading results.

An important aspect of the qualifications of assessors regards their aptitude, attitude, trust, and motivation. It is very desirable that the assessors be highly motivated to learn about human and organization factors and safety assessment techniques, have high sensitivity to quality hazards (''perverse imaginations''), be observant and thoughtful, have good communication abilities, and have a willingness to report ''bad news'' when it is warranted. It is vital that both the assessors and the QMAS counselor have the trust and respect of the system operators and managers.

An assessor ''just-in-time'' training program has been developed as part of the QMAS instrument. This program includes training in human and organization factors and the QMAS assessment process. Example applications are used to illustrate applications and to help reinforce the training. A final examination is used to help assure that the assessor has learned the course material and can apply the important concepts.

The assessor training program has two parts: (1) informational and (2) practical exercises. The informational part contains background on the QMAS assessment process and computer instrument, failures involving offshore structures and other types of engineered structures, human and organizational performance factors, and evaluations.

The second part of training is the hands-on use of the computer software. Training exercises are performed to demonstrate the use of the QMAS instrument. Software demonstrations using offshore structures as case studies are walked through. Then the assessors assess another system on their own. Following this, the assessments are compared and evaluated. The assessors are asked for feedback on the QMAS.

This approach has been identified as a ''participatory ergonomics'' approach. The people that participate in the daily activities associated with their portion of the lifecycle of a system are directly involved in the evaluations and assessments of that system. These people know their system better than any outsider ever could. However, they need help to recognize the potential threats to the quality and reliability of their system. These people provide the memory of what should be done and how it should be done. These are the people that must change and must help their colleagues change so that desirable and acceptable system quality and reliability are developed. This is a job that outsiders can never do and should not be expected to do.

QMAS has been applied to a wide variety of offshore structure systems, including marine terminals, offshore platforms, and ships. Multiple assessment teams have been used to assess the same system; the results have shown a very high degree of consistency in identification of the primary factors of concern and potential mitigation measures. QMAS has proven to provide a much more complete and realistic understanding of the human and organizational elements that comprise offshore structure systems than traditional PRA/QRA/SRA approaches.[29]

6. SYSTEM RISK ASSESSMENT SYSTEM

The System Risk Assessment System (SYRAS) has been developed to assist engineers in assessment of system failure probabilities based on identification of the primary or major tasks that characterize a particular part of the lifecycle (design, construction, maintenance, operation) of an offshore structure.

The probability of failure, Pf, is the likelihood of not developing the four defined quality objectives. Each quality attribute can be evaluated with respect to four life-cycle phases: Design, Construction, Operation, and Maintenance (Fig. 5). Acceptable performance means that the structure has desirable serviceability ($i = 1$), safety ($i = 2$), durability ($i = 3$), and compatibility ($i = 4$). The complement of reliability is the likelihood or probability of unacceptable performance; the probability of failure, $P(F_i)$. The probability of failure can be expressed analytically as

$$P(F_i) = P(D_i \geq C_i)$$

where D_i is the demand placed on the system and C_i is the ability or capacity of the system to meet or satisfy the demand. P(X) is read as the probability that the event (X) takes place. F_i represents the event of failure to develop desirable quality of type (i). Demands and capacities are quantified in terms meaningful to define the quality attributes of serviceability (e.g., days available for service), safety (e.g., margin between load resistance and loading), durability (e.g., expected life of structure), and compatibility (e.g., expected initial and future costs).

Failures to achieve desirable quality in an offshore structure can develop from intrinsic (I) or extrinsic (E) causes. Intrinsic causes include factors such as extreme environmental conditions and other similar inherent, natural, and professional uncertainties. Extrinsic causes are due to human and organizational factors—identified here as "human errors." The probability of failure of the structure to develop quality attribute (i), $P(F_{Si})$, is

$$P(F_{Si}) = P(F_{SiI} \cup F_{SiE})$$

where ($\cup$) is the union of the failure events. The probability of failure of any one of the quality attributes (i) due to inherent randomness is $P(F_{SiI})$. The probability of failure of any one of the quality attributes (i) due to the occurrence of human error is $P(F_{SiE})$. The probability of human error in developing a quality attribute (i) in the structure is $P(E_{Si})$. Then

$$P(F_{Si} = P(F_{SiI}|E_{Si})P(E_{Si}) + P(F_{SiI}|\not{E}_{Si})P(\not{E}_{Si}) + P(F_{SiE}|E_{Si})P(E_{Si})$$

The first term addresses the likelihood of structure failure due to inherent causes given a human error

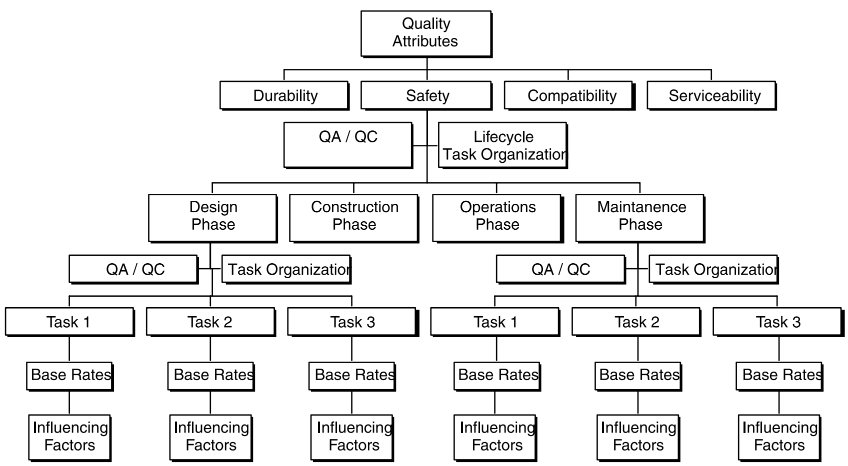

Fig. 5. SYRAS components.

(e.g., structure fails in a storm due to damage from a boat collision). The second term addresses the same likelihood given no human error. This is the term normally included in structural reliability analyses. The third term addresses the likelihood of structure failure directly due to human error (e.g., structure fails due to explosions and fire).

The probability of failure given HOE, $P(F_S \mid E)$, characterizes the ''robustness'' or defect and damage tolerance of the structure to human errors. The shape of the fragility curve (Fig. 6) can be controlled by engineering. *This is explicit design for robustness or defect (error) tolerance and fail-safe or intrinsically safe design.* For the intensities (magnitude) and types of malfunctions that normally can be expected, the structure should be configured and designed so that it does not fail catastrophically (or have unacceptable quality) when these types and magnitude of malfunctions occur. The fragility curve for a particular system is determined using off-line analyses or experimental results and the results input to SYRAS.

The probability of no human error is:

$$P(\not{E}_{Si}) = 1 - P(E_{Si})$$

The probability of insufficient quality in the structure due to HOE, $P(F_{SiE})$, can be evaluated in the (j) life-cycle activities of design (j = 1), construction (j = 2), operations (j = 3), and maintenance (j = 4) as

$$P(F_{SiE}) = P\left(\bigcup_{j=1}^{4} F_{SiEj}\right)$$

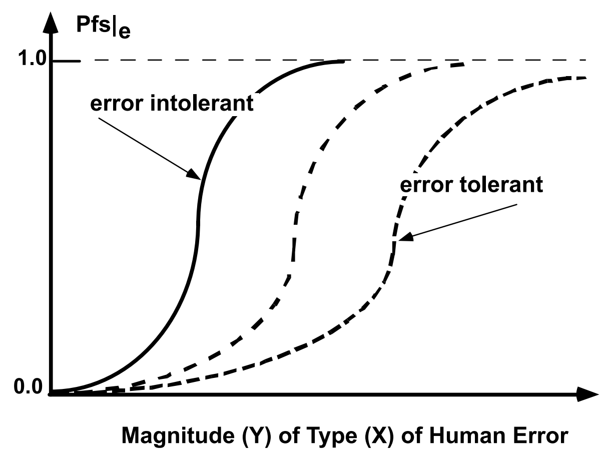

Fig. 6. Likelihood of unsatisfactory quality for error tolerant and intolerant structure systems.

or

$$P(F_{SiE}) = \sum_{j=1}^{4} P(F_{Sij} \mid E_{Sij}) P(E_{Sij})$$

Each of the life-cycle activities (j = 1 to 4) can be organized into (n) parts (k = 1 to n):

$$P(F_{SiEj}) = P\left(\bigcup_{k=1}^{n} F_{SiEjk}\right)$$

This task-based formulation addresses the majority of the functions that are involved in the principal activities that occur during the lifecycle of an offshore platform.

For example, the system design activity (j = 1) can be organized into four parts (n = 4): configuration (k = 1), system demand analyses (k = 2), system capacity analyses (k = 3), and documentation (k = 4). The likelihood of insufficient quality in the system due to human error during the design activity is

$$P(F_{SiE1}) = P\left(\bigcup_{k=1}^{4} F_{SiE1k}\right)$$

If desirable, the primary functions or tasks can be decomposed into subtasks to provide additional essential details.

The likelihood of insufficient quality in the system due to errors that are developed during the life-cycle activities can be based on the eight types of operator errors identified in Table I (heuristic taxonomy) (m = 1 to 8)

$$P(F_{SiEjk}) = P\left(\bigcup_{m=1}^{8} F_{SiEjkm}\right)$$

or

Table I. Classification of Individual Malfunctions

Communications—ineffective transmission of information
Slips—accidental lapses
Violations—intentional infringements or transgressions
Ignorance—unaware, unlearned
Planning & Preparation—lack of sufficient program, procedures, readiness
Selection & Training—not suited, educated, or practiced for the activities
Limitations & Impairment—excessively fatigued, stressed, and having diminished senses
Mistakes—cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis, and action

$$P(F_{SiEjk}) = \sum_{m=1}^{8} P(F_{SiEjk} \mid E_{Sijkm}) P(E_{Sijkm})$$

The method known as Absolute Probability Judgement (APJ) is used to evaluate the "base rates" of operator/human malfunctions (Fig. 7).[5,20–22] Performance shaping factors (PSF)[5,20,24] are used to assist in the evaluation of the influences of organizations, procedures, hardware (structure, equipment), environments, and interfaces among the foregoing on the base rates of malfunctions. QMAS is used to develop the PSF.

Gradings from the QMAS component evaluations ($G_{\varepsilon jkm}$) are developed on a seven-point scale (Fig. 3). The mean value and coefficient of variation of each of the categories of PSF are developed based on an average of the mean values and coefficients of variation of each of the QMAS categories. Evaluation of each of the seven categories of PSF result in a final overall grading ($\overline{G_{\varepsilon jkm}}$) and coefficient of variation ($V_{G\varepsilon jkm}$) on this grading that can be used to quantify a specified PSF.

Each of the seven PSF ($PSF_{\varepsilon jkm}$) can act to increase or decrease the base rates of human errors. SYRAS allows the user to specify the base rates and then scale the base rates by multiplying the base rates by the PSF identified by the user. The scales allow the base rates to be increased or decreased by three orders of magnitude. When quantification of the PSF is based on use of the QMAS instrument and protocol, the PSF is computed from (Fig. 8):

$$\text{Log } PSF_{\varepsilon jkm} = (\overline{G_{\varepsilon jkm}} - 4)$$

The resultant PSF that modifies the base rate of error is computed from the product of the seven mean PSF:

$$PSF_{\varepsilon} = \prod_{i=1}^{7} PSF_{\varepsilon jkm}$$

The resultant coefficient of variation of the PSF is computed from the square root of the sum of the squares of the PSF coefficients of variation:

$$V_{PSF}^2 = \sum_{i=1}^{7} V_{PSFi}^2$$

The PSF provide the important link between the qualitative QMAS assessment process and the quantitative PRA-based SYRAS analysis process.[18,29] Results from QMAS are then translated to input that can be used in the traditional PRA/QRA approach embodied in SYRAS. The QMAS-SYRAS link has been based on a repetitive calibration process involving applications of QMAS

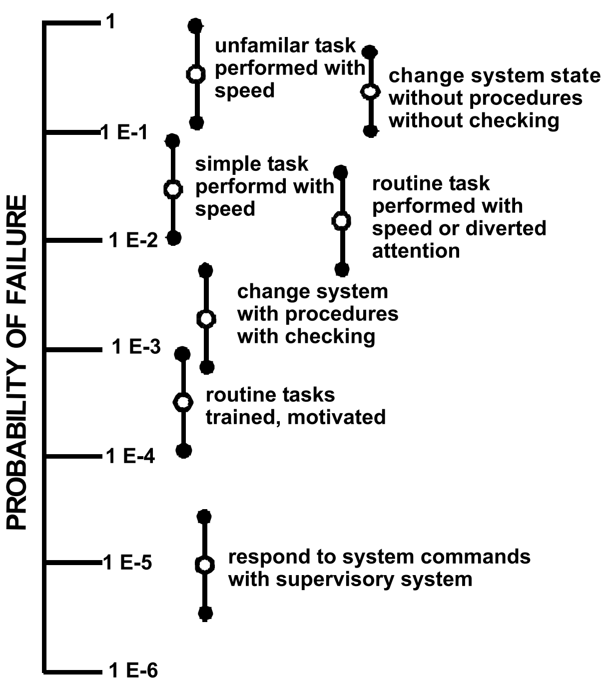

Fig. 7. Nominal human task performance reliability.

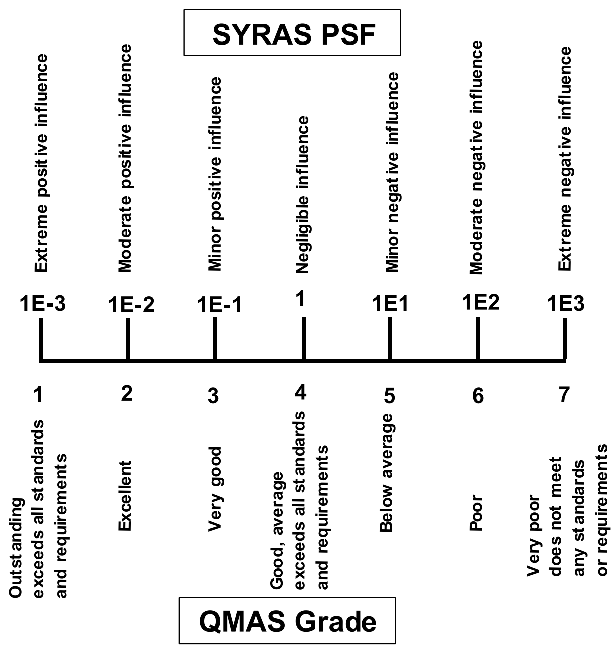

Fig. 8. QMAS qualitative grading translation to quantitative PSF used in SYRAS.

and SYRAS to offshore structures that have failed (very high probabilities of failure) and succeeded (very low probabilities of failure).[18]

The QMAS grades, FOC, and system quality improvement recommendations are intended to help capture the processes that cannot be incorporated into a highly structured quantitative analyses; these are the dynamic, organic processes that characterize most real offshore structure systems. The SYRAS probabilities are intended to provide engineers and managers with quantitative assessments of systems so that the effects of potential mitigation measures can be examined.

Once the tasks are organized into the task structure for the life-cycle phase, correlation among elements is assessed. To facilitate the calculation of the likelihood of failure, the elements can be designated as either perfectly correlated or perfectly independent. Experience has shown that organizational "culture" can provide an important source of correlations in malfunctions and failures.

After determining the overall system task structures, the user has the option of analyzing the effects of Quality Assurance and Quality Control (QA/QC) on the overall system probability. This is done in an "overlay edit-mode." This means that the user is able to go back into the task structures and add in the QA/QC procedures as independent tasks with corresponding influences. The user is presented with both the original system Pf and the QA/QC modified Pf.

Consequently, the next step in the SYRAS development addresses HOF malfunction detection (D) and correction (C). This is an attempt to place parallel elements in the quality system so that *failure* of a component (assembly of elements) requires the failure of more than one *weak link*. Given the high positive correlation that could be expected in such a system, *this would indicate that QA/QC efforts should be placed in those parts of the system that are most prone to error or likely to compromise the intended quality of the system.*

Conditional on the occurrence of type (m) of HOE, E_m, the probability that the error gets through the QA/QC system can be developed as follows. The probability of detection is P(D) and the probability of correction is P(C). The complements of these probabilities (not detected and not corrected) are:

$$P(\bar{D}) = 1 - P(D), \text{ and } P(\bar{C}) = 1 - P(C).$$

The undetected and uncorrected error event, UE_m, associated with a human error of type m is:

$$UE_m = \bigcup_{m=1}^{8} (E_m \cap \bar{D}_m \cap \bar{C}_m)$$

The probability of the undetected and corrected HOE of type m is:

$$P(UE) = \sum_{m=1}^{8} P(E_m|\bar{D}_m \cap \bar{C}_m)(P(\bar{D}_m|\bar{C}_m)P(\bar{C}_m)$$

where A∩7B indicates the intersection of events A
2 and B.

Assuming independent detection and correction activities or tasks, the probability of the undetected and corrected HOE of type m is:

$$\begin{aligned} P(UE_m) &= P(E_m)[P(D_m)P(\bar{C}_m) + P(\bar{D}_m)] \\ &= P(E_m)[1 - P(D_m)P(C_m)] \end{aligned}$$

The probability of error detection and the probability of error correction play important roles in reducing the likelihood of human malfunctions compromising the system quality. Introduction of QA/QC considerations into the developments into the earlier developments is accomplished by replacing $P(E_{Sijkm})$ with $P(UE_{Sijkm})$ into the desirable parts of the *SYRAS* analysis.

7. APPLICATIONS

QMAS and SYRAS have been applied to a wide variety of offshore structures, including offshore drilling and production platforms, ships (including marine terminals), and pipelines. Applications to offshore platforms have involved studies performed during the design, operating (e.g., drilling), and maintenance (e.g., diving inspections-repairs) phases.

Recently, the QMAS-SYRAS combination was applied in an international government-industry-sponsored project to examine the reliability characteristics of "minimum structures."[30,31] While minimum structures have initial costs that are lower than more traditional structures, the questions addressed in this project regarded their life-cycle costs and the effects of the less "redundant" or robust minimum structure systems. QMAS was used to help evaluate the HOF specific to proposed design, construction, operating, and maintenance organizations. Specific life-cycle scenarios were developed based on recent experiences with such structures to help evaluate the HOF reliability implications. This application served to identify how such structures might be used without significant compromises in life-cycle reliability and how modifications in the designs could improve the reliability characteristics.

QMAS and SYRAS have been applied in a recent study of the design of an innovative floating deep water structure. This study involved specific owner-operator and design-engineering-construction organizations. These instruments proved to be very useful in helping identify potential problem areas, how they might best be remediated, and in evaluating the reliability implications of application of various Value Improvement Program (VIP) alternatives. The design organization consisted of the platform owner/operator, a prime EPC (engineer, procure, construct) contractor, and a series of specialist subcontractors. Project managers and lead engineers were assigned from the owner/operator company to the office of the prime EPC contractor. Engineers from the specialist contractors were also assigned to the EPC contractor's office. One of the subcontractors was a leading Classification Society engineer. Engineers from the Classification Society were primarily responsible for QA/QC. Engineers from the owner/operator company performed special risk analyses that involved the topsides, the structure, and drilling and production operations. These risk analyses involved both qualitative and quantitative analyses.

The basic design procedures used were those of the API (American Petroleum Institute). These procedures were augmented with special criteria and guidelines provided by the owner/operator. These procedures were backgrounded with a very thorough study of the unique deep water site conditions (oceanographic, geotechnical). The project management team was led by a very experienced on-shore production manager. The project management-engineering team was staffed with some experienced engineers, but the majority of the engineers were relatively recent graduates.

During the QMAS assessment, four special elements were detected. First, the team was permeated with a confidence that there was nothing unusual or especially difficult about this undertaking, even though this platform would be the world's deepest water drilling and production platform. The platform was regarded as a "conventional drilling island" by the project manager (production geology background). When asked about the possible failure of several critical elements in the structure, the engineers responded that these elements had been designed so they could not fail. Analyses of these components indicated that they had very low probabilities of failure.

Second, the project management team had embarked on a VIP (Value Improvement Program) that involved work intended to lower the project CAPEX (capital expenditures) by 25%. The managers and engineers had all signed a poster that tracked on a monthly basis the "fat" that was being eliminated from the preliminary design. The third special element was a significant "tension" that had developed between the project managers and the lead engineers. The lead engineers believed that management should not question the results from their analyses because the analyses represented the latest technology and knowledge. The fourth element was the complete absence of anyone on the design team that had significant experience in offshore drilling and production operations.

Results from the QMAS assessment team's evaluation of the design system are summarized in Fig. 9. The most probable and ±1 standard deviation results are shown for the seven categories. As indicated by the five case histories, the categories of factors of greatest concern were those of the organization, interfaces, and procedures. In this instance, the structure was indicated to be of concern because of its lack of robustness or damage tolerance.

The SYRAS analysis of the structure design process indicated an intrinsic probability of failure of 1 E-4 per year. The extrinsic probability of failure, given PSF = 1.0 was evaluated to be 1 E-4 per year. The combined PSF were evaluated to be 205, resulting in an extrinsic probability of failure of 2.1 E-2 per year.

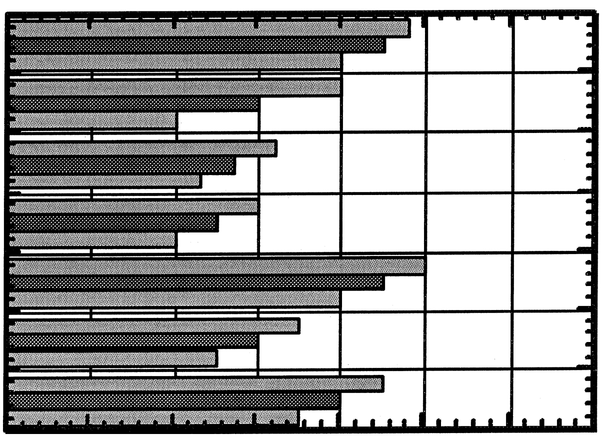

Fig. 9. Results from QMAS assessment team's evaluations.

The commentaries that were developed by the SMAS assessment included the following primary recommendations:

- Implement processes and procedures that would reestablish watchful vigilance and situational awareness (''maintaining the bubble'') by management and engineering of elements that could lead to degradations in the intended quality of this system.
- The VIP needed to include a quantitative process to evaluate the effects of the VIP on the life-cycle quality of the system, including changes in the projected OPEX (operating expenses), and changes in the ''worst''-case economics given a major failure in any of the quality attributes.
- The design process needed to include a constructive ''challenge'' process involving both management and engineering that would involve detailed discussions and sufficiently substantiated justifications for accepting results from the critical analyses performed during the project; these justifications would be based on first principle analytical procedures with verifiable assumptions and results.
- The design team needed to be augmented with additional experienced offshore engineers (in important parts of the design process), periodic independent experienced engineer reviews, and offshore drilling and production operations personnel to help assure the design of a human friendly structure that would facilitate engineering, construction, operations, and maintenance.

Given that these recommendations were successfully implemented, the SMAS evaluation indicated resultant PSF = 1 and a total probability of failure of 1.5 E-4. Assessment of the costs and benefits associated with the implementation indicated a cost benefit ratio in excess of 100. The recommendations were implemented and design of the structure completed successfully.

8. CONCLUSIONS

In the main, the industries that employ offshore structure systems, the associated regulatory agencies, their engineers, managers, and operating staffs have much to be proud of. There is a vast international infrastructure of offshore structures that supply much needed goods and services to the societies they serve. This article addresses some of the issues associated with RAM of offshore structures. The primary challenge that is addressed is not associated with the traditional engineering technologies that have been employed in the creation of these structures. Rather, the primary challenge addressed is associated with the human and organizational aspects of these systems. It is clear that human and organizational factors are the primary challenge in developing offshore structure systems that have desirable and acceptable quality and reliability. Also, it is clear that there is a significant body of RAM knowledge about how to address this challenge. The problem is wise implementation of this knowledge on a continuing basis.

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