Human & Organizational Factors in Design and Operation of Deepwater Structures

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ABSTRACT

This paper summarizes results from a 15 year research and development effort to address human and organizational factors in design and operation of marine structures including floating and fixed platforms, pipelines, and ships (including FPSOs). The focus of this paper is on applications experiences that have been developed in association with innovative deepwater structures.

Proactive, reactive, and interactive engineering and management approaches to achieve desirable and acceptable quality and reliability in deepwater structures are outlined. Quality is defined as the combination of serviceability, safety, durability, and compatibility. Reliability is defined as the likelihood of developing acceptable quality during the life-cycle of the structure (design through decommissioning). Three key strategies are developed that can be employed in the three approaches. These include reduction of likelihoods of malfunctions, reduction of the effects of malfunctions, and increasing the detection and correction of malfunctions.

Application: Application of two instruments developed and employed in the proactive, reactive, and interactive approaches are illustrated with experiences developed during their application to design of an innovative deepwater structure. These instruments include a Quality Management Assessment System (*QMAS*©) and a Structure Risk Analysis System (*SYRAS*©). Techniques to reflect the difficult to capture human and organizational factors in quantitative analyses are summarized.

INTRODUCTION

An important starting point in addressing human and organizational factors (HOF) in the quality (combination of serviceability, safety, durability, and compatibility) and reliability (likelihood of realizing desirable quality) of offshore structures is to recognize that while human and organizational malfunctions are inevitable, their occurrence can be reduced and their effects mitigated by improving how structures are designed, constructed, operated, and maintenance. Engineering can improve the processes and products of design, construction, operations, maintenance, and decommissioning to reduce the malfunction promoting characteristics, and to increase malfunction detection and recovery characteristics. Engineering can help develop systems for what people can and will do, not for what they should do. Engineering can also have important influences on the organization and management aspects of these systems.

Organizations have important and pervasive influences on the reliability of offshore structure systems. High reliability organizations (HRO) have been shown to be able develop high reliability systems that operate relatively error free over long periods of time and in many cases, in very hazardous environments. HRO go beyond Total Quality Management and International Standards Organization certifications in their quest for quality and reliability. They have extensive process auditing procedures to help spot safety problems and they have reward systems that encourage risk mitigating behaviors, They have high quality standards and maintain their risk perception and awareness. Most important, such organizations maintain a strong command and control system that provides for organization robustness or defect tolerance.

Experience clearly indicates that to effectively change the situation, engineers must learn how to address this challenge by analyzing offshore structure 'systems.' In this work, an offshore structure system is defined as consisting of six major interactive components:

- **Operating teams** - people that have direct contacts with the design, construction, operation, maintenance, and

decommissioning of the system,
- **Organizations** - groups that influence how the operating personnel conduct their operations and provide the resources for the conduct of these operations,
- **Procedures** - formal and informal, written and unwritten practices that are followed in performing operations,
- **Hardware** - structures and equipment on which and with which the operations are performed,
- **Environments** - external, internal, and social, and
- **Interfaces** among the foregoing.

APPROACHES

There are three fundamental, complimentary and interactive approaches to achieving adequate and acceptable quality (serviceability, safety, durability, compatibility) and reliability in offshore structures:

- **Proactive** (activities implemented before malfunctions occur),
- **Reactive** (activities implemented after malfunctions occur), and
- **Interactive** or real-time. (activities implemented during occurrence of malfunctions

In the context of these three approaches there are three primary strategies to be employed:

- **Reduce incidence of malfunctions**,
- **Increase detection and correction of malfunctions**, and
- **Reduce effects of malfunctions**.

Proactive Approaches

The proactive approach attempts to analyze the system before it fails (unacceptable quality) 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) and quantitative methods such as SRA (Structural Reliability Analyses), PRA (Probabilistic Risk Analyses) and QRA (Quantified Risk Analyses) [1-5]. Each of these methods have benefits and limitations [6-10].

The author has been an active protagonist and practitioner of the proactive SRA/PRA/QRA approach for more than three decades [12-14]. The author believed that this approach provided an ability to forecast how systems could go bad. Very sophisticated SRA/PRA models could be developed to help foster this belief. The results from these analyses seemed to have value and to enhance his abilities to address some types of variability and uncertainty. This approach was workable as long as he dealt with systems in which the interactions of people with the systems were minimal or minimized. However, the problem changed radically when people began to exert major influences on the quality of the systems and in many cases on the physical aspects of the systems [12]. In this case, his lack of knowledge of the physics and mechanics of the complex behaviors of people that in the future would design, construct, operate, and maintain the system defined an 'unpredictable' system, or certainly one with very limited predictability. The author's analytical models addressed systems that were essentially static and mechanical. Yet the real systems were dynamic, constantly changing, and more organic than mechanical. The analytical models generally failed to capture the complex interactions between people and the systems that they designed, constructed, operated, and maintained.

The author found most data on the reliability of humans in performing tasks to be very limited [15-18]. Existing databases failed to capture or adequately characterize influences that had major effects on human reliability [19,20] Yet, when the numbers were supplied to the very complex analytical models and the numbers were produced, the results were often mistaken for 'reality.' There was no way to verify the numbers. If the results indicated that the system was 'acceptable', then nothing was done. If the results indicated that the system was 'not acceptable', then generally equipment and hardware fixes were studied in an attempt to define a fix or fixes that would make the system acceptable or ALARP (As Low As Reasonably Practicable) [21]. When the author went to the field to compare his analytical models with what was really there, he found little resemblance between his models and what was in the field [12].

The author does not advocate discarding the analytical - quantitative proactive approach. He advocates using different types of proactive approaches to gain insights into how systems might fail and what might be done to keep them from failing [22,13,14]. The marked limitations of analytical models and quantitative methods must be recognized or major damage can be done to the cause of the quality and reliability of offshore structures. The potential for engineers to be 'hyper rational' and attempt to extend the applicability of SRA/PRA/QRA methods beyond their limitations must be recognized and countered [23]. On the other hand, qualitative methods (e.g., HazOp, FMEA), in the hands of qualified and properly motivated assessors (both internal and external) can do much to help the causes of quality and reliability [1,18]. Experience, judgment, and intuition of the assessors needs to be properly recognized, respected, and fully integrated into proactive qualitative and quantitative approaches. Much headway has been made recently in combining the powers of qualitative methods with quantitative RAM methods [13,14]. The qualitative methods are able to more fully capture the dynamic, changing, organic, complex interactions that can not be analyzed [16,20,22]. Given input from the qualitative methods, the quantitative methods are able to provide numbers that can be used to assist development of judgements about when, where, and how to better achieve quality and reliability in offshore structures [13,14]. But, even at this level of development, proactive RAM methods are very limited in their abilities to truly provide quality and reliability in offshore structures. Other methods (e.g. interactive RAM) must be used to address the unknowable and unimaginable hazards.

It is the author's experience in working with and on offshore structure systems for more than four decades, that many if not most of the important proactive developments in the quality and reliability of these systems were originated in a cooperative, trust-based venture of knowledgeable 'facilitators' working with seasoned veterans that have daily responsibilities for the quality of these systems. This cooperative venture includes design, construction / decommissioning, operations, and maintenance / inspection personnel. Yet, it also is the author's experience, that many engineering and many well meaning reliability – risk analysis 'experts' are not developing a cooperative environment. This is very disturbing. The conduct of each operation during the life-cycle of an engineered system should be regarded as the operations of 'families.' Knowledgeable, trained, experienced, and sensitive outsiders can help, encourage, and assist 'families' to become 'better.' But, they can not make the families better. Families can only be changed from within by the family members. SRA/PRA/QRA measures based on casual or superficial knowledge of a system or of an operation of that system should be regarded as tinkering. And, tinkering can have some very undesirable effects and results [12-14,22-26].

The crux of the problem with proactive SRA/PRA/QRA approaches is with the severe limitations of such approaches in their abilities to reasonably characterize human and organizational factors (HOF) and their effects on the performance of a system [6,18-20,27,28]. SRA/PRA/QRA rely on an underlying fundamental understanding of the physics and mechanics of the processes, elements, and systems that are to be evaluated. Such understanding then allows the analyst to make projections into the future about the potential performance characteristics of the systems. And, it is here that the primary difficulties arise. There is no fundamental understanding of the physics and mechanics of the future performance – behavior characteristics of the people that will come into contact with a system and even less understanding of the future organizational influences on this behavior [28,29]. One can provide very general projections of the performance of systems including the human and organizational aspects based on extensive assumptions about how things will be done, but little more. The problem is that engineers and managers start believing that the numbers represent reality.

To the author, the true value of the proactive SRA/PRA/QRA approach does not lie in its predictive abilities. The true value lies in the disciplined process SRA/PRA/QRA can provide to examine the strengths and weaknesses in systems; *the objective is detection and not prediction*. The magnitudes of the quantitative results, if these results have been generated using reasonable models and input information, can provide insights into where and how one might implement effective processes to encourage development of acceptable quality and reliability. The primary problems that the author has with SRA/PRA/QRA is with how this method is used and what it is used to do. Frequently the results from SRA/PRA/QRA are used to justify meeting or not meeting regulatory / management targets and, in some cases not implementing clearly justified – needed improvements in the quality – reliability of an engineered system.

Perhaps the most severe limitation to proactive SRA/PRA/QRA regards 'knowability'. One can only analyze what one can know. Predictability and knowability are the foundation blocks of SRA/PRA/QRA analytical models [1,2,8,30]. But, what about the unknowable and the unpredictable? Can we really convince ourselves that we can project into the future of offshore structure systems and perform analyses that can provide sufficient insights to enable us to implement the measures required to fully assure their quality and reliability? Or are some other processes and measures needed? This fundamental property of unknowability has some extremely important ramifications with regard to application of the ALARP principle [21,31].

The author has concern for some SRA/PRA/QRA analyses that have been and are being used to define IMR (Inspection, Maintenance, Repair) programs for offshore structures [32]. Such analyses can only address the knowable and predictable aspects that influence IMR programs (e.g. fatigue damage at brace joints). Such analyses frequently are used to justify reductions in IMR program frequencies, intensities, and costs [33-35]. But what about the unknowable and unpredictable elements that influence IMR programs? We look for cracks where we do not find them and we find them where we do not look for them [36-39]. What about the host of major 'biases' (differences between reality and calculated results) that exert major influences on the results that come from such analyses [40]? These elements are frequently referred to as being founded in 'gross errors' [32,34,35]. Experience has adequately demonstrated that a very large amount, if not the majority of the defects and damages we encounter in offshore structures are not in any reasonable or practical sense 'predictable'. Other approaches (e.g. inductive information based) must be used to address the unknowable – unpredictable aspects that still must be managed in the operations of offshore structures.

Reactive Approaches

The reactive approach is based on analysis of the failure or near failures (incidents, near-misses) of a system. An attempt is to made to understand the reasons for the failure or near-failures, and then to put measures in place to prevent future failures of the system. The field of worker safety has largely developed from application of this approach.

This attention to accidents, near-misses, and incidents is clearly warranted. Studies have indicated that generally there are about 100+ incidents, 10 to 100 near-misses, to every accident [28,41]. The incidents and near-misses can give early warnings of potential degradation in the safety of the system. The incidents and near-misses, if well understood and communicated provide important clues as to how the system operators are able to rescue their systems, returning them to a safe state, and to potential degradation in the inherent safety characteristics of the system. We have come to understand that responses to accidents and incidents can reveal much more about maintaining adequate quality and reliability than responses associated with successes.

Well developed guidelines have been developed for investigating incidents and performing audits or assessments associated with near-misses and accidents [41,42]. These guidelines indicate that the attitudes and beliefs of the involved organizations are critical in developing successful reactive processes and systems, particularly doing away with 'blame and shame' cultures and practices. It is further observed that many if not most systems focus on 'technical causes' including equipment and hardware. Human – system failures are treated in a cursory 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) [29,41,43].

Most important, most reactive processes completely ignore the organizational malfunctions that are critically important in contributing to and compounding the initiating events that lead to accidents [27,44]. Finding 'well documented' failures is more the exception than the rule. Most accident investigation procedures and processes have been seriously flawed. The qualifications, experience, and motivations of the accident assessors are critical; as are the processes that are used to investigate, assess, and document the factors and events that developed during the accident. A wide variety of biases 'infect' the investigation processes and investigators (e.g. confirmational bias, organizational bias, reductive bias).

In the author's direct involvement with several recent major failures of offshore structures (casualties whose total cost exceeds U.S. $1 billions each), the most complete information develops during legal, regulatory induced, and insurance investigation proceedings. Many of these failures are 'quiet.' Fires and explosions (e.g Piper Alpha), sinkings (e.g. P-36) and collisions / groundings (e.g. Exxon Valdez) are 'noisy' and frequently attract media, regulatory, and public attention. Quiet failures on the other hand are not noisy; in fact, many times overt attempts are made to 'keep them quiet.' These quiet failures frequently are developed during the design and/or construction phases. These represent offshore structure 'project failures.'

The author recently has worked on two major quiet failures that involved international EPC (Engineering, Procurement, Construction) offshore structure project failures that developed during construction. A third major failure involved an EPCO (add Operation) project that failed when the system was not able to develop the quality and reliability that had been contracted for. In both of these cases, the initial 'knee jerk' reaction was to direct the blame at 'engineering errors' and a contended 'lack of meeting the engineering standard of practice.' Upon further extensive background development (taking 2 and 3 years of legal proceedings), the issues shifted from the engineering 'operating teams' to the 'organizational and management' issues. Even though 'partnering' was a primary theme of the formation of the contractors and contracting, in fact partnering was a myth. Even though ISO certifications were required and provided, the ISO QA/QC guidelines (were not followed. The international organizations involved in the work developed severe 'cultural conflicts' and communication breakdowns. Promises were made and not honored. Experienced personnel were promised and not provided ('bait and switch'). There was a continually recurring theme of trying to get something / everything for nothing or next to nothing. As ultimately judged in the courts, these three failures were firmly rooted in organizational malfunctions, not engineering malfunctions. The problem with most legal proceedings is that it is very rare that the results are made public. Thus, the insights important to the engineering profession is largely lost, and in some cases, seriously distorted.

As the result of studying more than 600 'well documented' major failures of offshore structures, some interesting insights have been developed [13,44-46]:

- Approximately 80% of the major failures are directly due to HOF and the 'errors' that develop as a result of these factors ('exherent'); only about 20% can be regarded as being 'natural' or 'inherent' (represent residual risk).
- Of the 80 % of the major failures that are due to HOF, about 80% of these occur during operations and maintenance activities; frequently, the maintenance activities interact with the operations activities in an undesirable way.
- Of the failures due to HOF that occur during operations and maintenance, more than half (50%) of these can be traced back to seriously flawed engineering design; offshore structures may be designed according to 'accepted industry standards' and yet are seriously flawed due to limitations and imperfections that are embedded in the industry standards and/or how they are used; offshore structures are designed that can not be built, operated, and maintained as originally intended; modifications are made 'in the field' in an attempt to make the structure workable, and in the process additional flaws or 'bugs' can be introduced. Thus, during operations and maintenance phases, operations personnnel are faced with a seriously deficient or a defective structure that can not be operated and maintained as intended.
- The accident development process can be organized into three categories of events: 1) initiating, 2) contributing, and 3) propagating. The dominant initiating events are developed by 'operators' performing erroneous acts of commission or interfacing with the hardware – structure components that have 'embedded pathogens' that are activated by such acts of commission (about 80%); the other initiating events are acts or developments involving acts of omissions. The dominant contributing events are organizational; these contributors act directly to encourage or 'cause' the initiating events. In the same way, the dominant propagating events are also organizational; these propagators are generally responsible for allowing the initiating events to unfold into an accident. A taxonomy (classification system) will be developed for this malfunctions later in this paper. It is also important to note that these same organizational aspects very frequently are responsible for development of 'near-misses' that do not unfold into accidents.
- Most accidents involve never to be exactly repeated sequences of events and multiple breakdowns or malfunctions in the components that comprise an offshore structure system. These events are frequently dubbed 'incredible' or

'impossible.' After accidents, it is observed that if only one of the protective 'barriers' had not been breached, then the accident would not have occurred. Experience has adequately shown that it is extremely difficult, if not impossible to accurately recreate the time sequence of the events that actually took place during the period leading to the accident. Unknowable complexities generally pervade this process because detailed information on the accident development is not available. Hindsight and confirmational bias are common as are distorted recollections. Stories told from a variety of viewpoints involved in the development of an accident seem to be the best way currently available to capture the richness of the factors, elements, and processes that unfold in the development of an accident.

- The discriminating difference between 'major' and 'not-so-major' accidents involves the 'energy' released by and / or expended on the accident. Not-so-major accidents generally involve only a few people, only a few malfunctions or breakdowns, and only small amounts of energy that frequently is reflected in the not-so-major direct and indirect, short-term and long-term 'costs' associated with the accident. Major accidents are characterized with the involvement of many people and their organizations, a multitude of malfunctions or breakdowns, and the release and / or expenditure of major amounts of energy; this seems to be because it is only through the organization that so many individuals become involved and the access provided to the major sources of this energy. Frequently, the organization will construct 'barriers' to prevent the accident causation to be traced in this direction. In addition, until recently, the legal process has focused on the 'proximate causes' in accidents; there have been some major exceptions to this focus recently, and the major roles of organizational malfunctions in accident causation have been recognized in court. It is important to realize that the not-so-major accidents, if repeated very frequently, can lead to major losses.

The author has be particularly interested in following the aftermath of the P-36 accident in Brazil. This tragic accident involved one of the, if not the leading deepwater engineering – operator in the world; Petrobras. Thanks to the excellent report issued by the Brazilian National Petroleum Agency and Directorate of Ports and Coasts [47], we have a reasonably complete understanding of the initiating and propagating 'events' that lead to this accident. A very structured process to investigate this accident was developed and followed by the Inquiry Commission [48]. However, the primary focus of this analysis was on the 'onboard' aspects of the accident and of the multitude of structure, equipment, procedure, and human malfunctions and breakdowns that occurred. Key recommendations from the Inquiry Commission Report include:

- Improved coordination of onboard production and stability operations,
- Reduced bureaucracy so personnel have more time to trouble shoot operations,
- Assure adequate crew to perform and supervise operations,
- Restructure maintenance to provide timely operations with qualified personnel,
- Perform risk analyses before any alternations to equipment and structure are made,
- Provide technical training for stability crew operations,
- Provide for retrieval of key information in emergencies,
- Upgrade emergency procedures,
- Eliminate production 'slop tanks' in structure columns.

These are important recommendations to improve future onboard operations and designs. But, do we really understanding the primary contributing and propagating factors that lead to the sinking of this modern offshore structure? Most of the attention has been focused on what the accident disclosed as 'critical flaws' in the design, operation, and maintenance of the unit [49]. But, why and how did these critical flaws get embedded in the system? It seems certain that no one wanted these flaws to be there, but they were there, and they were there in spite of all of the current guidelines and standards that have been developed. And we have seen some of these flaws in previous failures; e.g. compromise of buoyancy when the unit encounters 'beyond the critical point for maximum damage' resulting in a combination of down-flooding and listing (sinking of the Ocean Ranger). Why? How?

It seems fairly certain at this juncture that we will probably never really know. Too many important things are at stake: power, money, reputations, careers; and thus the really important lessons from this experience may be lost. Particularly the ones that go beyond those that triggered the accident including those that contributed to this 'triggering' and those and allowed the initiating events to propagate to the sinking of the unit. It seems reasonably clear that there could have been some major organizational malfunctions that were significant contributing and compounding factors. Quoting from the widely circulated statements from a high ranking Petrobras official that were made before the accident provides some potentially important insights:

> *"Petrobras has established new global benchmarks for the generation of exceptional shareholder wealth through an aggressive and innovative programme of cost cutting on its P36 production facility. Conventional constraints have been successfully challenged and replaced with new paradigms appropriate to the globalised corporate market place. Through an integrated network of facilitated workshops, the project successfully rejected the established constricting and negative influences of prescriptive engineering, onerous quality requirements, and outdated concepts of inspection and client control. Elimination of these unnecessary straitjackets has empowered the project's suppliers and contractors to propose highly economical solutions, with the win-win bonus of enhanced profitability margins for themselves. The P36 platform shows the shape of things to come in the*

unregulated global market economy of the 21st Century."

Unfortunately, this statement also was circulated around the world via the Internet with a dramatic series of pictures that chronicled the sinking of P-36. This sort of blame and shame action helps destroy all hopes of understanding the potentially important organizational issues. It is noteworthy that none of the issues identified in the ANP/DPC Inquiry Commission Report address these 'on-the-beach' organizational issues. Additional industry reports from very credible sources circulated via the Internet add insights into important organizational issues that may not have been recognized:

- *"There were 3 days (!!!) of reports of vent system problems in the area of the column and drain tank. All these were entered in the log of the unit."*
- *"OIM's (Offshore Installation Manager's) onboard did not notify the beach about the vent problems and decided not to shut in the unit. Parts for repair were requested though."*
- *"There are reports of open water tight doors down through the column and even into the pontoon tunnels. This is unbelieveable, but nonetheless very serious!"*
- *"It will be a few more years before we have adequate management and crew attention to water tight integrity, vent systems, and fire fighting plans."*
- *"The control room operator received over 1100 messages and alarms in the 17 minutes they had to take corrective action before it was too late. The fire brigade entered the column without the OIM knowing they were going into the column. They entered the hull which had gas and it ignited killing all of those who entered. The control room turned the firewater pumps on and the water filled the column trough the rupture pipe when they should have closed the sea chest valve."*
- *"The design firm for the topsides performed a HAZOP on the topsides and didn't extend the hazards analysis to the tanks in the column (not in their scope of work). They were converting an existing hull and the hull equipment was the existing equipment. They had identified the need to replace the valves (substandard) and had a 3 year program in place to change them out."*
- *"From what I saw, this was 95% an engineering design problem – human error induced by poor design."*
- *"The P36 (formerly Spirit of Columbus) was completed in Genoa, Italy by the Fincantri yard in 1993/94. It was classed by RINA (Italian classing organization; little experience with semis and no other floating production units). This design was unique for its large center column and (at the time) for it size. The construction was heavily subsidized by the Italian government at a bad time in the business. The yard went into bankruptcy and there was confusion in ownership. The rig never really found a home as a drilling unit. Petrobras finally assembled a deal with all the various parties and took the unit. The conversion to production service was done in Canada."*
- *"We need to stop allowing produced gas and hydrocarbon piping and processing equipment to be inside the columns and pontoons; leaks will happen and fires and explosions in these confined spaces can be expected even with ventilation and detection systems, but it is going to be a very long time before the industry will accept this practice."*
- *"This could never happen to us. We have too many safeguards in place."*

This last statement is particularly chilling. Until the importance of such organizational 'culture' issues are understood and addressed, then we should expect repetitions of this tragic story. Hubris is an enemy of quality and reliability in offshore structures. It was stated recently that achieving desirable quality and reliability in offshore structures is "one damn thing after another' [27]. Constant vigilance and wariness is a price of success.

A primary objective of incident reporting systems is to identify recurring trends from the large numbers 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 safe-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.

Root cause analysis is generally interpreted to apply to systems that are concerned with detailed investigations of accidents with major consequences [41,42]. The author has a fundamental objection to root cause analysis because of the implication that there is a single cause at the root of the accident (reductive bias) [18]. This is rarely the case. This is an attempt to simplify what is generally a very complex set of interactions and factors, and in this attempt, the lessons that could be learned from the accident are frequently lost. Important elements in a root cause analysis includes an investigation procedure based on a model of accident causation. A systematic framework is needed so that the right issues are addressed during the investigation [41,44]. There are high priority requirements for comprehensiveness and consistency. The comprehensiveness needs to be based on a systems approach that includes error tendencies, error inducing environments, multiple causations, latent factors and causes, and organizational influences. The focus should be on a model of the system factors so that error reduction measures and strategies can be identified. The requirement for consistency is particularly important if the results from multiple accident analyses are to be useful for evaluating trends in underlying causes over time.

There is no shortage of methods to provide a basis for detailed analysis and reporting of incidents, near-misses, and accidents. The primary challenge is to determine how such methods can be introduced into the life-cycle RAM of offshore structures and how their long-term support can be developed (business incentives).

Inspections during construction, operation, and maintenance 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 structures [32]. Deductive methods involving mechanics based SRA/PRA/QRA techniques have been highly developed. These techniques focus on 'predictable' damage that is focused primarily on durability; fatigue and corrosion degradations. 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. Reliability Center Maintenance (RCM) approaches have been developed and are continuing be developed to help address both predictable and unpredictable damage and defects. Some very significant forward strides have been made in development and implementation of life-cycle IMR database analysis and communications systems. But, due to expense and cost concerns, and unwillingness or inability of the organization to integrate such systems into their business systems, much of this progress has been short lived.

The reactive approach has some important limitations. It is not often that one can truly understand the causes of accidents. 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 [44]. 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 [27].

Interactive Approaches

Experience with the quality and reliability of offshore structures indicates that there is a third important approach to achieving quality and reliability that needs to be recognized and further developed. Until recently, it was contended that there were only proactive and reactive approaches [28,30]. The third approach is interactive (real-time) RAM in which danger or hazards builds up in a system and it is necessary to actively intervene with the system to return it to an acceptable quality and reliability state. *This approach is based on the contention that many aspects that influence or determine the failure of offshore structures 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. We want to be able to assess and manage these evolving disintegrations. This approach is based on providing systems (including the human operators) that have enhanced abilities to rescue themselves. This approach is based on the observation that people more frequently return systems to safe states than they do to unsafe states that result in accidents.

Engineers can have important influences on the abilities of people to rescue systems and on the abilities of the 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 assurance and quality control (QA/QC) is an example of the real-time approach (Matousek, 1990). QA is done before the activity, but QC is conducted during the activity. The objective of the QC is to be sure that what was intended is actually being carried out.

Two fundamental approaches to improving interactive RAM performance are: 1) providing people support, and 2) providing system support. People support strategies include such things as selecting personnel well suited to address challenges to acceptable performance, and then training them so they possess the required skills and knowledge. Re-training is important to maintain skills and achieve vigilance. The cognitive skills developed for interactive RAM degrade rapidly if they are not maintained and used [23,26,50].

Interactive RAM teams should be developed that have the requisite variety to recognize and manage the challenges to quality and reliability and have developed teamwork processes so the necessary awareness, skills and knowledge are mobilized when they are needed. Auditing, training, and re-training 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. 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 crisis. These templates help reduce the amount and intensity of cognitive processing that is required to manage the challenges to quality and reliability.

Improved system support includes factors such as improved maintenance of the necessary critical equipment and procedures so they are workable and available as the system developments unfold. 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. Adequate 'safe haven' measures need to be provided to allow interactive RAM teams to recognize and manage the challenges without major concerns for their well being. Hardware and structure systems need to be provided to slow the escalation of the hazards, and re-stabilize the system.

One would think that improved interactive RAM system support would be highly developed by engineers. This does not seem to be the case [50,51]. A few practitioners recognize its importance, but generally it has not been incorporated into general engineering practice or guidelines. Systems that are intentionally designed to be stabilizing (when pushed to their limits, they tend to become more stable) and robust (sufficient damage and defect tolerance) are not usual. Some provisions have been made to develop systems that slow the progression of some system degradations.

The research on which this paper is based indicates that system (structure, hardware, operating teams, organizations) robustness is achieved through a combination of configuration (alternative paths to carry the demands), ductility (ability to redistribute demands without compromising quality and reliability), and excess capacity (to carry the redistributed demands) [13]. These guidelines apply to the organizational or people components of systems. Robust systems are not created by over zealous Value Improvement Programs (VIP), repeated down-sizing and outsourcing, and excessive initial cost cutting (reduced CAPEX at the expense of future OPEX).

Effective early warning systems and ‘status’ information and communication systems have not received the attention they deserve in providing system support for interactive RAM. Systems need to be designed to clearly and calmly indicate when they are nearing the edges of safe performance. Once these edges are passed, multiple barriers need to be in place to slow further degradation and there should be warnings of the breaching of these barriers. More work in this area is definitely needed.

Combined Approaches

The results of the experience and work on which this paper is based clearly indicate that a combination of proactive, reactive, and interactive approaches should be used to improve the quality and reliability of offshore structures. Each of these approaches has its strengths and weaknesses and their strengths need to exploited. The results of this work also clearly that in most cases, these approaches are not being used as well as they could be used.

In many instances, the reactive approach has resulted in development extensive rules and regulations that have become so cumbersome that they either are not used or are not used properly. Systems are more normally operated by informal local operating procedures than by following the book. Accident investigations frequently have turned into ‘witch hunts’ many times with the sole purpose of ‘killing the victims.’ Management can mobilize the power to stop accident investigations with identification of the proximate causes and actors. Due to critical flaws in the accident investigation and recording processes, accident databases frequently fail to properly or reasonably capture the essence of how accidents develop or are caused. Near-miss incidents have not received nearly the attention that they should.

In many instances, the proactive approach has developed into a quantitative paper chase that has not yielded the benefits that it could yield. Numbers have been taken to represent the realities of future quality and reliability. Insights about how one might defend the system against unpredictable and unanticipated developments are lost in the complexities of the analyses. Experts are brought in to inspect and analyze the system and many times these experts do not possess the requisite experience or insights about how the system can unravel and fail. The experts are empowered and the system operators are ‘depowered.’ Fixes are general hardware oriented. Rarely do the HOF aspects receive any direct or extensive attention. Frequently, the attitude is ‘this is not an engineering problem, it is a management problem’ (or at least, someone else’s problem).

In general, the interactive approach has not received the attention that it deserves. In some ‘non-engineering’ communities it has received extensive attention [52]. These communities are those that daily must confront crises or the potential for crises. These crises all involve unpredictable and unknowable situations. Many of the communities have learned how to in most cases turn crises into successes. This research has not disclosed one instance in which the interactive approach has been used to address HOF in design engineering activities. Rarely has it been used in operations. Rather, safety meetings, drills and exercises are mistakenly taken to represent this approach.

RAM INSTRUMENTS

Two instruments will be discussed in the remainder of this paper that have been developed recently to help promote more effective application of RAM processes during the life cycle of offshore structures. Development of these two instruments have been concentrated on taking full advantage of the progress cited in this paper while addressing some of the major limitations that have been recognized.

The first instrument (computer program, application protocol) 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 life-cycle. *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 (computer program, application protocol) 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 life cycles of an offshore structure 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 team 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 [13,14].

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 with the least effort possible, to 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.

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.

The *QMAS* process has been developed so that it can be used effectively and efficiently by those that have daily involvement and responsibilities for the quality and reliability of offshore structures. The *QMAS* system is intended to help empower those that have such responsibilities to identify important potential quality and reliability degradation hazards, prioritize those hazards, and then define warranted or needed mitigation measures.

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 by 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) that 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 would be 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. As a part of the assessment process that 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 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.

Evaluations processes

The *QMAS* evaluation is organized into three sections or 'Levels' (Fig. 1). 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, then they 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 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. 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.

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. 2). 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 grades for the attributes are summed and divided by the number of attributes used to develop a resultant grade for

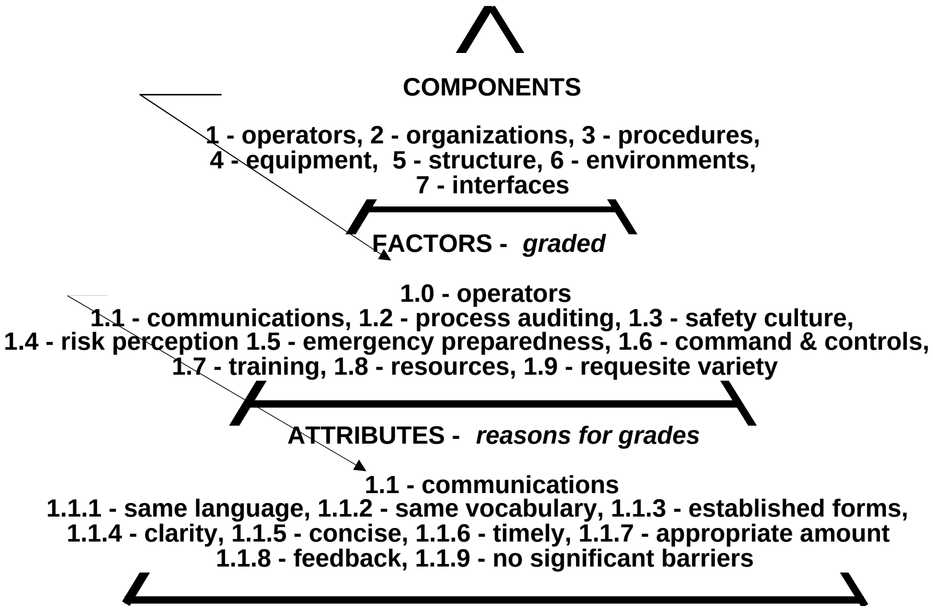

Fig. 1: Safety components, factors, and attributes

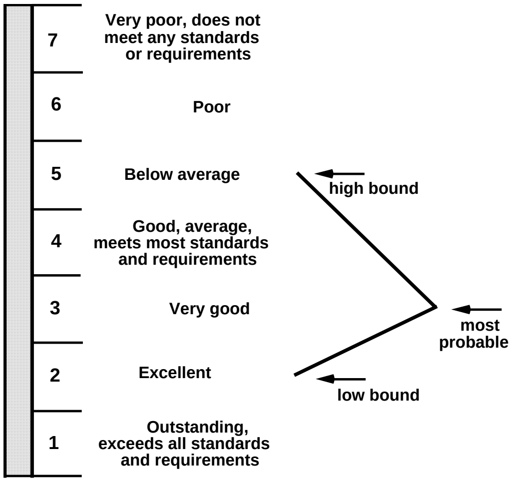

Fig. 2: Scale for grading attributes, factors, and components

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. If it is 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. 3). The ‘high’ grades (those above 4) indicate components and the associated factors that are candidates for mitigation.

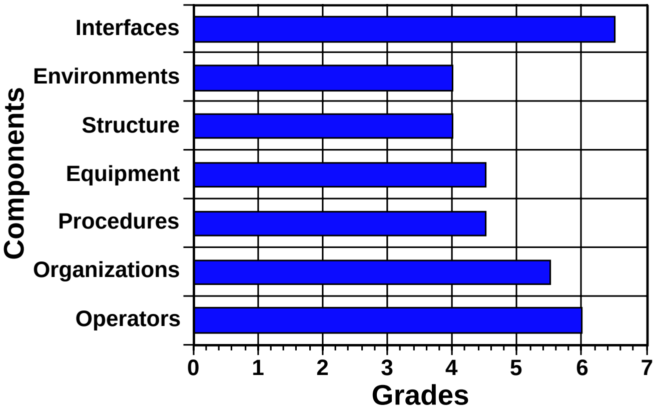

Fig. 3: Example component mean grading results

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.

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 of part 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 is identified as a ‘participatory ergonomics’ approach. The people that participate in the daily activities associated with their portion of the life-cycle 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. Yet, 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 or should be expected to do.

QMAS has been applied to a wide variety of offshore structure systems including marine terminals, offshore platforms, and ships. *QMAS* has been applied in poractive assessments (before operations conducted), in reactive assessments (after operations conducted), and in interactive assessments (during conduct of operations). 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. (Weick, 2000). Frequently, RAM can be conducted solely on the basis of results developed from QMAS, factors important to quality and reliability can be defined and characterized sufficiently to enable effective actions to achieve desirable quality and reliability.

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 life-cycle (design, construction, maintenance, operation) of an offshore structure. This PRA/QRA/SRA instrument has been applied in study of tradeoffs regarding ‘minimum’ platforms, in quality assurance and quality control (QA/QC) of the design of innovative deepwater structures, and the effects of Value Improvement Programs for several major offshore structures [13,53,54]. The *SYRAS* instrument consists of a computer program and an applications protocol [13,14,45,46].

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. 4). Acceptable performance means that the structure has desirable serviceability (i = 1), safety (i = 2), durability (i = 3), and compatibility (i = 4). The compliment 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

$$P(F_i) = P(\boldsymbol{D}_i \geq \boldsymbol{C}_i) \tag{1}$$

where $\boldsymbol{D}_i$ is the demand placed on the system and $\boldsymbol{C}_i$ 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

$$P(F_{Si}) = P(F_{SiI} \cup F_{SiE}) \tag{2}$$

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

$$P(F_{Si}) = P(F_{SiI} \mid E_{Si})\, P(E_{Si}) + P(F_{SiI} \mid \not{E}_{Si})\, P(\not{E}_{Si}) + P(F_{SiE} \mid E_{Si})\, P(E_{Si}) \tag{3}$$

The first term addresses the likelihood of structure failure due to inherent causes given a human error (e.g. structure fails in a storm due to damage from a boat collision). The second

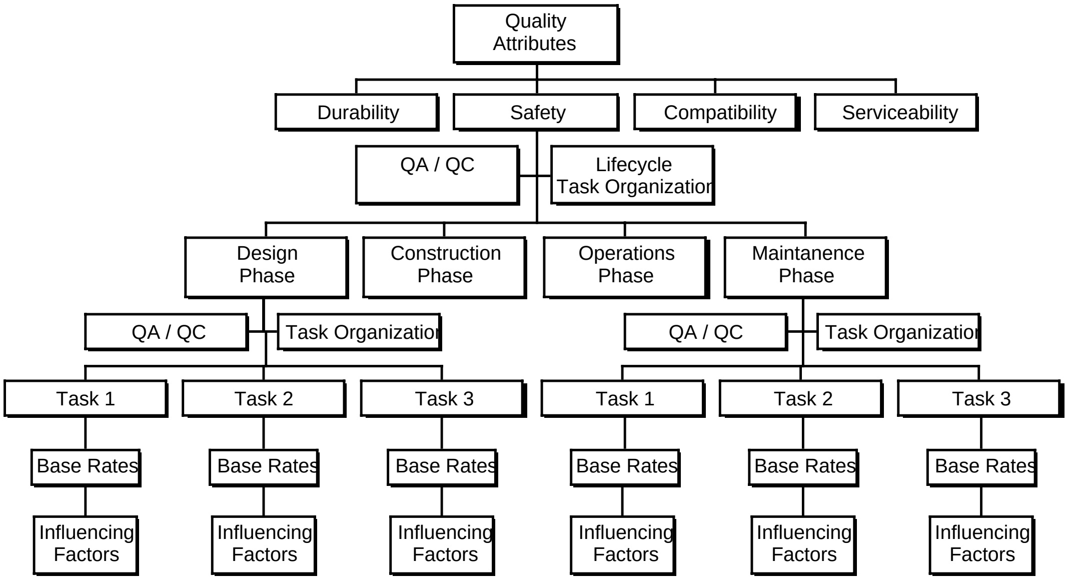

Fig. 4: *SYRAS* components

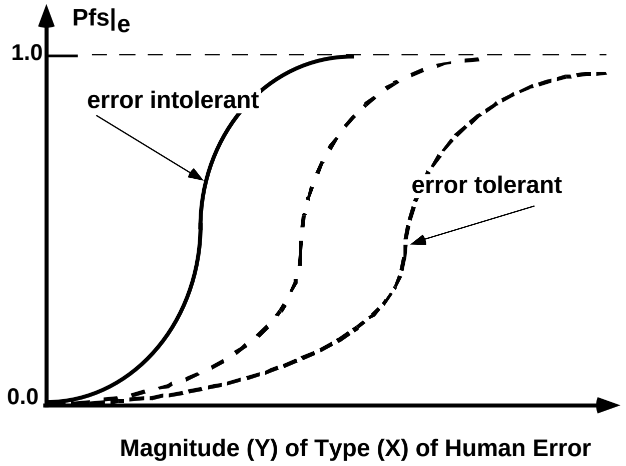

Fig. 5: Likelihood of unsatisfactory quality for error tolerant and intolerant structure systems

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, $P(F_S|E)$, characterizes the 'robustness' or defect and damage tolerance of the structure to human errors. The shape of the fragility curve (Fig. 5) 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:

$$P(\not{E}_{Si}) = 1 - P(E_{Si}) \tag{4}$$

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

$$P(F_{SiE}) = P(\bigcup_{j=1}^{4} F_{SiEj}) \tag{5}$$

or

$$P(F_{SiE}) = \sum_{j=1}^{4} P(F_{Sij} \mid E_{Sij}) P(E_{Sij}) \tag{6}$$

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

$$P(F_{SiEj}) = P(\bigcup_{k=1}^{n} F_{SiEjk}) \tag{7}$$

This task-based formulation addresses the major the functions that are involved in the principal activities that occur during the life-cycle 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

$$P(F_{SiE1}) = P(\bigcup_{k=1}^{4} F_{SiE1k}) \tag{8}$$

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

The base rates of human errors of type 'm', P(E'Sijkm), are based on published information on human task performance reliability (Fig. 6) [15-20]. Performance Shaping Factors (PSF) [15, 16] are used to modify the base or 'normal' rates of human errors, $P(E'_{Sijkm})$, to recognize the effects of organizations, structure, equipment, procedures, environments, and interfaces [14]:

$$P(E_{jkm}) = P(E'_{jkm}) \bullet \prod \mathrm{PSF}_{\varepsilon jkm} \leq 1 \tag{9}$$

As discussed previously, gradings from the *QMAS* component evaluations ($G_{\square jkm}$) are developed on a seven point scale (Fig. 2). 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 ($V_{G\square jkm}$) on this grading that can be used to quantify a specified PSF.

Each of the seven PSF ($\mathrm{PSF}_{\square jkm}$)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. 7):

$$\mathrm{Log\ PSF}_{\square jkm} = (\overline{G_{\varepsilon jkm}} - 4) \tag{10}$$

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

$$PSF_{\varepsilon} = \prod_{i=1}^{7} \mathrm{PSF}_{\varepsilon jkm} \tag{11}$$

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:

$$V^2{}_{PSF} = \sum_{i=1}^{7} V^2{}_{PSFi} \tag{12}$$

The PSF provide the important link between the qualitative *QMAS* assessment process and the quantitative PRA based *SYRAS* analysis process [14,46]. 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* and *SYRAS* to offshore structures that have failed (very high probabilities of failure) and succeeded (very low probabilities of failure) [13]. As would be expected, due to the natural variability in human – organizational performance and the uncertainties associated with the evaluations of such performance, the PSF have very large coefficients of variation (in range of 100% to 200 %).

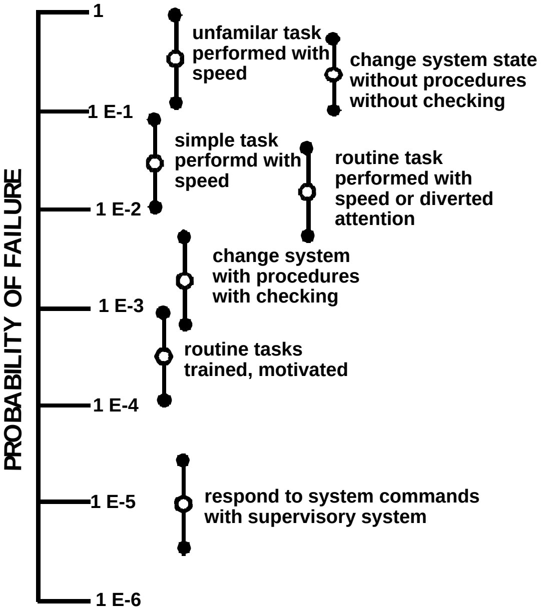

Fig. 6: Nominal human task performance reliability

The *QMAS* grades, FOC, and system quality improvement recommendations are intended to help capture the processes that can not be incorporated into a highly structured quantitative analyses; these are the dynamic, organic processes that characterize most real offshore structure systems. Frequently, the intensive application of the *QMAS* instrument and underlying organizational philosophies (to be discussed in companion paper in this conference) provide the insights essential to help achieve desirable and acceptable quality and reliability. The coupling of the results from *QMAS* with 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 and the effects of management alternatives assessed. Of course, this means that potentially much of the richness of insights provided by *QMAS* can be lost or obscured by intense attention to the numerical results provided by *SYRAS*. The best experiences have been those in which both instruments are diligently applied; thus, capturing both qualitative and quantitative insights.

Once the tasks are organized into the task structure for the life-cycle phase, correlation among elements is assessed. In order to facilitate the calculation of the likelihood of failure, the elements can be designated as either perfectly correlated or perfectly independent.

After determining the overall system task structures, the user has the option of analyzing the effects of Quality Assurance and Quality Control (QA/QC) – checking - 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.

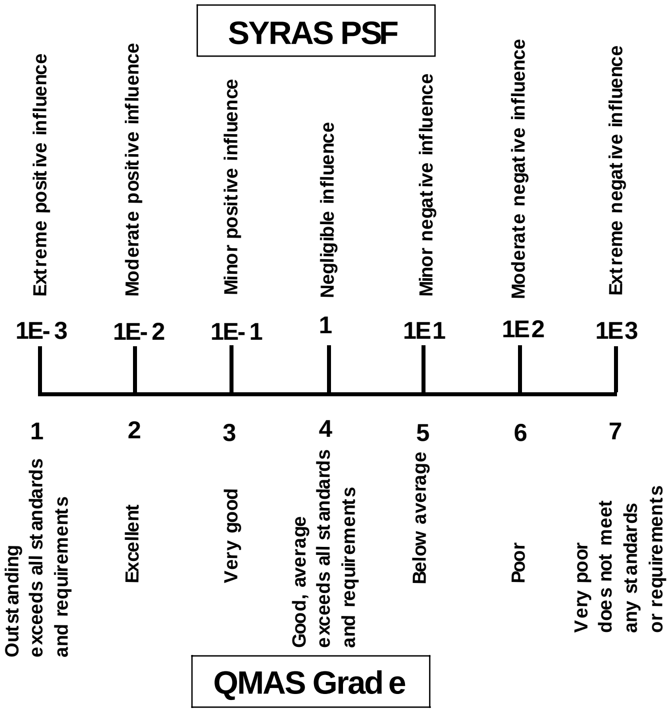

Fig. 7: QMAS qualitative grading translation to quantitative PSF used in SYRAS

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 compliments of these probabilities (not detected and not corrected) are:

$$P(\not{D}) = 1 - P(D), \text{ and } P(\not{C}) = 1 - P(C) \qquad (13)$$

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

$$UE_m = \bigcup_{m=1}^{8} (E_m \cap \not{D}_m \cap \not{C}_m) \qquad (14)$$

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

$$P(UE) = \sum_{m=1}^{8} P(E_m \mid \not{D}_m \cap \not{C}_m)(P(\not{D}_m \mid \not{C}_m)P(\not{C}_m) \quad (15)$$

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

$$P(UE_m) = P(E_m)[P(D_m)P(\not{C}_m) + P(\not{D}_m)] = P(E_m)[1 - P(D_m)P(C_m)] \qquad (16)$$

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.

DESIGN HAZARDS

Reason [27,29] suggests that latent problems with insufficient quality (failures, accidents) in technical systems are similar to diseases in the human body:

> *"Latent failures in technical systems are analogous to resident pathogens in the human body which combine with local triggering factors (i.e., life stresses, toxic chemicals and the like) to overcome the immune system and produce disease. Like cancers and cardiovascular disorders, accidents in defended systems do not arise from single causes. They occur because of the adverse conjunction of several factors, each one necessary but not sufficient to breach the defenses. As in the case of the human body, all technical systems will have some pathogens lying dormant within* them."

Reason developed eight assertions regarding error tolerance in complex systems in the context of offshore structures:

- The likelihood of an accident is a function of the number of pathogens within the system.
- The more complex and opaque the system, the more pathogens it will contain.
- Simpler, less well-defended systems need fewer pathogens to bring about an accident.
- The higher a person's position within the decision-making structure of the organization, the greater is his or her potential for spawning pathogens.
- Local pathogens or accident triggers are hard to anticipate.
- Resident pathogens can be identified proactively, given adequate access and system knowledge.
- Efforts directed at identifying and neutralizing pathogens are likely to have more safety benefits than those directed at minimizing active failures.
- Establish diagnostic tests and signs, analogous to white cell counts and blood pressure, that give indications of the health or morbidity of a high hazard technical system.

The single dominant cause of structure design related failures has been errors committed, contributed, and / or compounded by the organizations that were involved in and with the designs. At the core of many of these organization based errors was a culture that did not promote quality and reliability in the design process. The culture and the organizations did not provide the incentives, values, standards, goals, resources, and controls that were required to achieve adequate quality.

Loss of corporate memory also has been involved in many cases of structure failures. The painful lessons of the past were lost and the lessons were repeated with generally even more painful results. Such loss of corporate memory are particularly probable in these times of down-sizing, out-sourcing, and mega-mergers (take-overs).

The second leading cause of structure failures is associated with the individuals that comprise the design team. Errors of omission and commission, violations (circumventions), mistakes, rejection of information, and incorrect transmission of information (communications) have been dominant causes of failures. Lack of adequate training, time, and teamwork or back-up (insufficient redundancy) has been responsible for not catching and correcting many of these errors (Bea, 2000b).

The third leading cause of structure failures has been errors embedded in procedures. Traditional and established ways of doing things when applied to structures and systems that 'push the envelope' have resulted in a multitude of structure failures. There are many cases where such errors have been embedded in design guidelines and codes and in computer software used in design. Newly developed, advanced, and frequently very complex design technology applied in development of design procedures and design of offshore structures has not been sufficiently debugged and failures (compromises in quality) have resulted.

This insight indicates the priorities of where one should devote attention and resources if one is interested in improving and assuring sufficient quality in the design of offshore structures:

- **Organizations (administrative and functional structures),**
- **Operating teams (the design teams), and**
- **Procedures (the design processes and guidelines).**

DESIGN INTERACTIVE QA/QC

Formalized methods of QA/QC take into account the need to develop the full range of quality attributes in the offshore structure including serviceability, safety, durability, and compatibility.

QA/QC measures are focused both on error prevention and error detection and correction [55,56]. There can be a real danger in excessively formalized QA/QC processes. If not properly managed, they can lead to self-defeating generation of paperwork, waste of scarce resources that can be devoted to QA/QC, and a minimum compliance mentality.

In design, adequate QC (detection, correction) can play a vital role in assuring the desired quality is achieved in an offshore structure. Independent, third-party verification, if properly directed and motivated, can be extremely valuable in disclosing embedded errors committed during the design process. In many problems involving insufficient quality in offshore structures, these embedded errors have been centered in fundamental assumptions regarding the design conditions and constraints and in the determination of loadings or demands that will be placed on the structure. These embedded errors can be institutionalized in the form of design codes, guidelines, and specifications. It takes an experienced outside viewpoint to detect and then urge the correction of such embedded errors. The design organization must be such that identification of potential major problems is encouraged; the incentives and rewards for such detection need to be provided.

It is important to understand that adequate correction does not always follow detection of an important or significant error in design of a structure. Again, QA/QC processes need to adequately provide for correction after detection. Potential significant problems that can degrade the quality of a structure need to be recognized at the outset of the design process and measures provided to solve these problems if they occur. Study of offshore structure design errors and the effectiveness of QA/QC activities in detecting and correcting such errors leads to the checking strategies summarized in Table 1.

Table 1: Offshore Structure Design QA/QC strategies

• What to check?	• How to check ?
- high likelihood of error parts (e.g. assumptions, loadings, documentation) - high consequence of error parts - assumptions - validate complex computer programs & output **• When to check ?** - before design starts (verify process, qualify team) - during concept development - periodically during remainder of process - after design documentation completed	- direct toward the important parts of the structure (error intolerant) - be independent from circumstances which lead to generation of the design - use qualified and experienced engineers - provide sufficient QA/QC resources - assure constructability and IMR **• Who to check ?** - the organizations most prone to errors - the design teams most prone to errors - the individuals most prone to errors

The third implication regards the need for independent (of the situations that potentially create errors), third-party QA and QC checking measures that are an integral part of the offshore structure design process. This checking should start with the basic tools (guidelines, codes, programs) of the structure design process to assure that 'standardized errors' have not been embedded in the design tools. The checking should extend through the major phases of the design process, with a particular attention given to the loading analysis portions of that process. Computer programs used to perform analyses for design of critical parts of the structure should be subjected to verifications and these analyses repeated using independently developed programs.

The intensity and extent of the design checking process needs to be matched to the particular design situation. Repetitive designs that have been adequately tested in operations to demonstrate that they have the requisite quality do not need to be verified and checked as closely as those that are ‘first-offs’ and ‘new designs’ that may push the boundaries of current technology.

DESIGN PROJECT ASSESSMENT

An assessment has been performed by a major Gulf of Mexico operator of a deep water structure design project that involved the use of very innovative design methods and technology. The assessment team was given full access to the design management organization, the engineering organization, and the classification – verification organization. This included reviews of design documentation, specifications, and background information, and interviews – discussions with the members of each of the organizations.

In an attempt to reduce initial costs, the design approach involved very advanced and innovative design procedures and technology. Specific ‘target’ reliabilities were defined by the owner / operator for the structure. A Value Improvement Program (VIP) was instituted. The goal of the VIP was to reduce the initial cost of the project by 25%.

At the time of this review, the design had been underway for two years. The work had included extensive analyses of alternatives, development of computer programs, and performance of experimental work on several of the critical components. A leading classification society was involved in an on-going QA/QC program that included a failure modes and effects analysis of the structure system.

The assessment team included representatives of the management, engineering, and classification organizations (participatory ergonomics approach). The assessment team participated in training workshops that focused on the HOF aspects of the engineering design process and on the HOF considerations in developing successful platform life-cycles.

The application of *QMAS* was preceded by use of a qualitative structure design quality profiling instrument. The consensus results indicated significant concerns for the design procedures, design personnel and management, technology, and quality incentives. The concerns for:

- Design procedures were focused on the very sophisticated and complicated methods that were involved in analysis of a very complex interaction of the structure, the foundation, and the oceanographic environment.
- Design personnel and management were focused on the low level of experience of the lead design engineers and on their on-going debates with the project management’s requirements for verifications and validations of the results from the design analyses.
- Technology were focused in the first-time nature of the engineering methods and analytical tools being used in the design (based on limiting strains and deformations).
- Quality incentives regarded the VIP and the lack of specific guidelines on the effects of VIP on the quality and reliability of the structure.

In the second stage of the assessment, the *QMAS* instrument was applied. A second team of assessors was organized that included representatives of the design organization’s management, engineering, and verification teams. The results are summarized in Fig. 8. The resultant uncertainties are indicated for each of the components (best estimate, ±1σ standard deviation).

The high grades (indicating below average quality attributes) for interfaces, procedures, and operators reflected the same primary issues indicated by the qualitative assessment. Examination of the factors and attributes associated with the gradings indicated that the primary reasons for the high grading of the interfaces referred to the lack of appropriate interfacing between the design and management teams. There was a contention between engineering and management. Engineering felt that once an analysis was completed and verified, then the results should be implemented in the design. Management felt that interpretation and judgement needed to be used as screens to assure that the results ‘made sense’ before they were used.

The reasons for the high grading of the procedures referred to the lack of first principles and experimental verifications of the computer programs that were being used in the design and the lack of any specific guidelines to determine the effects on the structure reliability of the VIP.

The reason for the average grading of the operators (the design team) was due to the relatively low level of structure design experience in the design team and the lack of in-depth construction and operations experience in the team.

The review included five recommendations to improve the *QMAS* gradings:

- Develop and implement definitive guidelines to evaluate the quantitative effects of the VIP alternatives and measures on life-cycle costs and reliability of the structure (these guidelines would be consistent with the background that had been used to develop the reliability targets),
- Develop and implement a ‘challenge’ process in the design procedures that would assure that all results from engineering analyses were validated by alternative analyses, experimental – field data, and experienced

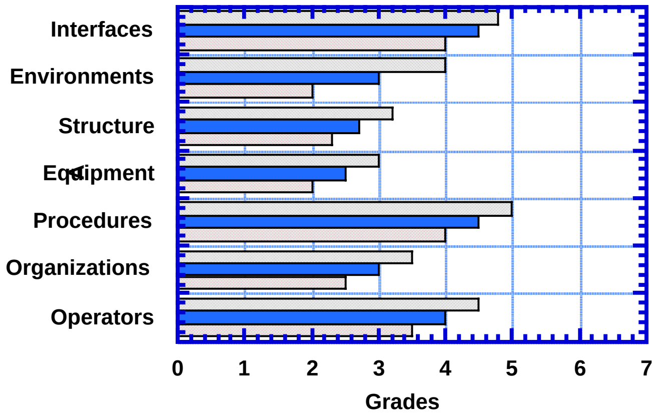

Fig. 8: Grades from interactive application of QMAS to design team, process, and organization

judgement (the ongoing QA/QC process would be replaced),

- Assign additional experienced structural design engineers to the design team (less experienced personnel would be assigned to other projects),
- Temporarily assign construction and operations engineering personnel to the design team to review the construction, operations, and maintenance characteristics being used in the design (these personnel were representatives of the organizations that would build and operate the structure), and
- Develop a structural robustness program and design guidelines that would assure fail-safe design (intrinsic safety) for all of the critical structural and equipment components through the life-cycle of the structure (explicit design for damage and defect tolerance).

The *SYRAS* instrument was used as the approach implemented to evaluate the reliability and life-cycle cost implications of the VIP alternatives. The structural quality profiling instrument and the *QMAS* instrument proved to be effective and efficient. The recommendations developed during the assessment process were implemented by the management, engineering, and classification – verification organizations. The recommendations proved to be practical and cost effective.

CONCLUSIONS

It should be apparent to all engineers that HOF are of fundamental importance in development of offshore structures that will have acceptable and desirable quality and reliability during their life cycles. Design engineers have a fundamental and primary responsibility in addressing HOF as an integral part of the design engineering process.

It should also be apparent to all concerned with the quality and reliability of offshore structures that organizations (industrial and regulatory) have pervasive influences on the assessment and management of threats to the quality and reliability of offshore structures. Management's drives for greater productivity and efficiency need to be tempered with the need to provide sufficient protections to assure adequate quality and reliability.

The threats to adequate quality and reliability in offshore structures in the design office emerge slowly. It is this slow emergence that generally masks the development of the threats to quality and reliability. Often, the participants do not recognize the emerging problems and hazards. They become risk habituated and loose their wariness. Often, emerging threats not clearly recognized because the goals of quality and reliability are subjugated to the goals of production and profitability. This is a problem, because there must be profitability to have the necessary resources to achieve quality and reliability. Perhaps, with present high costs of lack of quality and reliability, these two goals are not in conflict. Quality and reliability can help lead to production and profitability. One must adopt a long term view to achieve the goals of quality and reliability, and one must wait on production and profitability to follow. However, often we are tempted for today, not tomorrow.

The second important thing that we have learned about RAM to help achieve management desirable quality and reliability is organizing the 'right stuff' for the 'right job.' This is much more than job design. It is selecting those able to perform the daily tasks of the job within the daily organization required to perform that job. Yet, these people must be able to re-organize and re-deploy themselves and their resources as the pace of the job changes from daily to unusual (it's improv time!). Given most systems, they must be team players. This is no place for 'super stars' or 'aces.' The demands for highly developed cognitive talents and skills is great for successful crisis management teams. In its elegant simplicity, Crew Resource Management has much to offer in helping identify, train, and maintain the right stuff. If properly selected, trained and motivated, even 'pick-up ball teams' can be successful design engineering teams.

The final part of the15-year stream of research and development on which this paper is based addressed the issues associated with implementation [13]. A case-based reasoning study of seven organizations that had tried implementation for a significant period of time identified five key attributes associated with successful implementation:

- **Cognizance** – of the threats to quality and reliability,
- **Capabilities** – to address the HOF and HRO aspects to improve quality and reliability,
- **Commitment** – to a continuing process of improvement of the HOF and HRO aspects,
- **Culture** – to bring into balance the pressures of productivity and protection and to realize trust and integrity, and
- **Counting** – financial and social, positive and negative, ongoing incentives to achieve adequate and desirable quality and reliability.

It is interesting to note that of the seven organizations that tried implementation, only two succeeded. It is obvious that this is not an easy challenge, and that at the present time, failure is more the rule than success. It is also interesting to note that the two organizations that succeeded recently have shown signs of 'backsliding.' Organizational – management evolution has resulted in a degradation in the awareness of what had been accomplished and why it had been accomplished. The pressures of doing something 'new,' downsizing, outsourcing, merging, and other measures to achieve higher short-term profitability have resulted in cutbacks in the means and measures that had been successfully implemented to reduce the costs associated with lack of adequate and acceptable quality and reliability. Perhaps, all organizations are destined to continually struggle for the balance in production and protection, and accidents represent a map of that struggle to succeed and survive.

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