Submitted in Partial Satisfaction of the Requirements for the degree of Master of Engineering

# Development of a Human and Organizational Factors (HOF) Annex for Underwater Welding

BY

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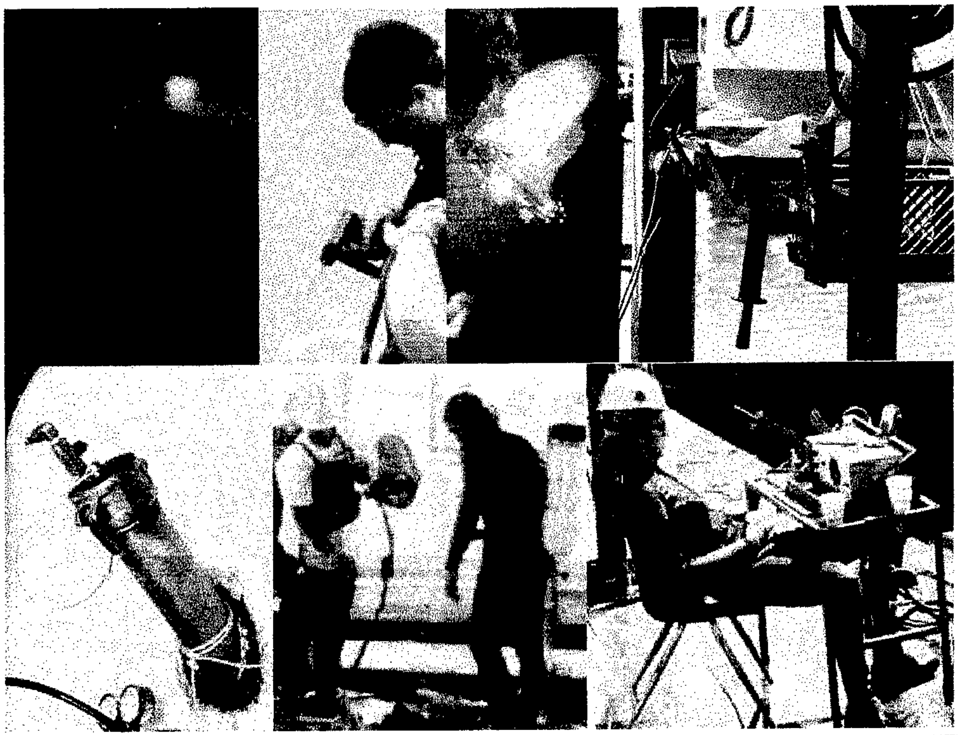

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# 1. Executive Summary

Recent improvements in underwater welding have led to the increased use of wet and dry hyperbaric welding within the marine construction industry. The general acceptance of underwater welding processes has been further advanced by the standardization of methods, procedures, and certification requirements provided by the American National Standards Institute (ANSI)/American Welding Society (AWS) D3.6 Specification for Underwater Welding.

A dedicated effort has been made by the AWS D3B Subcommittee on Underwater Welding to pursue all available means to improve the levels of productivity and safety across the underwater welding industry. One approach which has become a priority of the committee is the inclusion of Human and Organizational Factors considerations within the Specifications in the form of an HOF supplementary annex.

This paper provides a brief summation of HOF principles, a methodology for developing an HOF Annex for underwater welding, recommended content and structure for such an annex, and a combined qualitative and quantitative procedure for determining the utility of recommended HOF improvement applications.

## 2. Literature Review

Research required for the development of a Human and Organizational Factors Annex to the AWS Specification for Underwater Welding began with an in depth literature review. The basic process for conducting the comprehensive literature review is shown in Figure 1. The first step in developing the Annex was to refer to the existing AWS Specifications for Underwater Welding to identify the mission and objectives of the document and to develop applicable content objectives for the new HOF Annex to be added to the document.

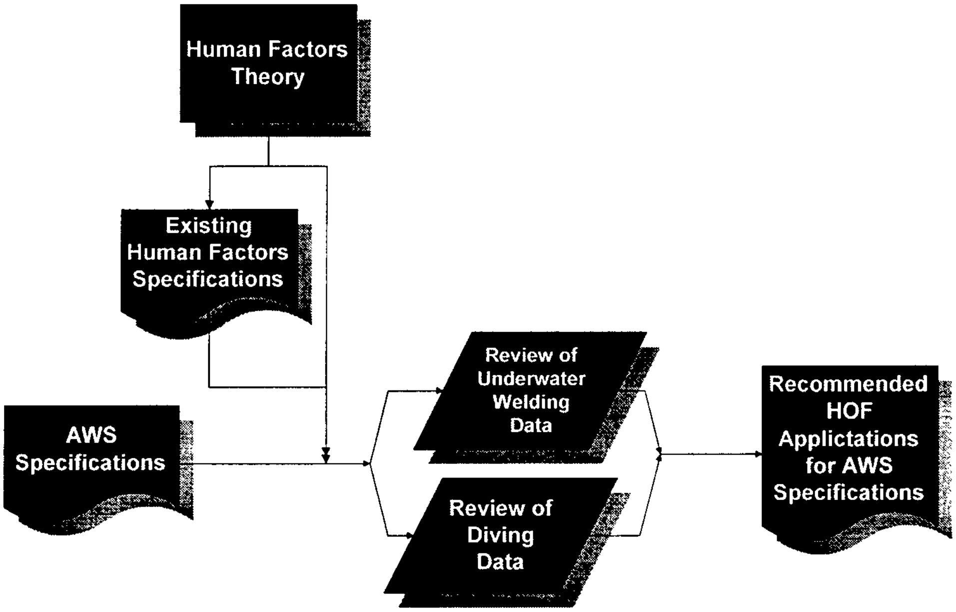

**Figure 1- Literature Review Process**

After a thorough review of the AWS document, existing Human Factors specifications were sought out as benchmarks for the annex. Specifically, the existing specifications provided a starting point for both the content and structure of the annex. Upon the determination that existing specifications were too broad in scope to provide an ideal model for the HOF annex, an intensive human factors study was conducted. By not only researching the human factors theory used to develop the existing human and organizational factors specifications but also the human factors theories not found in the specifications, the development of a more comprehensive annex was possible.

The next step in the literature review was studying all available underwater welding data and general diving data and applying this data to the annex. The final step in the process involved applying human factors theory to the available diving and underwater welding processes in the required AWS specification format.

### 2.1.1 Human and Organizational Factors (HOF)

Any activity that involves people is subject to flaws and defects. The study of Human and Organizational Factors is an attempt to characterize these flaws and defects, determine their causes, and minimize the effects these flaws and defects have on the activity at hand. Since no two people think or react to inputs in exactly the same manner, attempting to understand HOF is a daunting task. Not surprisingly, HOF studies incorporate many specialties which include, medicine, ergonomics, organizational behavior, group dynamics, and human factors engineering (HFE). Likewise HOF techniques have been employed at some level in most industries. Hee provides a summary of the history of HOF studies and a summary of HOF assessment methods which have been used in numerous industries.

### 2.1.2 Probabilistic Risk Assessment and Human Reliability Assessment

Probabilistic Risk Assessment techniques were first used in the nuclear power industry. The general structure of the Probabilistic Risk Assessment (PRA) was established in 1975 with the publication of the U. S. Reactor Safety Study. The PRA involves the following procedural steps:

- Identify the sources of the potential hazard.
- Identify the initiating events that could lead to this hazard
- Establish the possible sequences that could follow from various initiating events using event trees.
- Quantify each event sequence using data or judgment regarding the frequency of the initiating event and the probability of failure on demand of the relevant safety systems.
- Determine the overall system risk. This will be a function of the frequency of all possible accident sequences and their consequences.

While the PRA was one of the first effective methods of assessing risks in critical systems, it failed in one important aspect. It ignored the role of human factors in these systems. For example in studies of nuclear power plant significant event reports conducted independently by Rasmussen and the Institute of Nuclear Power Operations (INPO, 1984), human performance was the cause of 44% and 52% of the incidents, respectively.

Human Reliability Assessment (HRA) techniques have been devised in an effort to better evaluate complicated engineered systems by including the effects of the human interface with the reliability of the hardware and software.

The study of human and organizational factors and their effect on system reliability is still in its relative infancy. Nevertheless, there are many HRA models to chose from. There are several Human Reliability Assessment (HRA) techniques which have evolved in the last decade. A summary of some of these models can be found in Table 1.

The majority of these techniques are quite similar to PRA with human and organizational components included in the system model. HOF is incorporated into most HRA models through four key procedural steps.

- Identification of the system functions that may be influenced by human factors.
- Listing and analysis of the related human operations by performance of a detailed task analysis.
- Estimation of the relevant error probabilities using a combination of expert judgment and available data.
- Estimation of the effects of human errors on the system failure events.

While at first glance application of these procedures may appear simple, further investigation into most

| Model | Author (s) | Description |
|---|---|---|
| Technique for Human Error Rate Prediction (THERP) | Swain | hardware component; handbook of 27 HOE probability tables, event tree with performance shaping factors (PSF) |
| Operator Action Trees (OATS) | Hall, Fragola, Wreathall | Differentiates between procedural and cognitive errors, includes PRA analysis |
| Empirical Technique to Estimate Operators' errors (TESEO) | Bello & Colomari | combined application of five error probability parameters, K1 to K5, including stress, routines, ergonomics |
| Confusion Matrix | Potash | Evaluates errors of operators responding to abnormal plant conditions, seeks to identify various modes of misdiagnosis for a range of possible events. |
| Success Likelihood Index Methodology (SLIM) | Humphreys, Embrey, Rosa, Kirwan, and Rea | Provides a means of eliciting and structuring expert judgements, generates models that connect error probabilities with the factors that influence probability. |
| Systematic Human Action Reliability Procedure (SHARP) | Hannaman | Not a model but a technique for selecting an appropriate HRA model |

**Table 1- Common HRA Techniques**

systems reveals the process of human reliability assessment to be quite complex. There are many theories about how and why people and organizations interact with system hardware and software. Additionally, an accepted standardized HRA procedure which provides objective output does not yet exist. For these reasons it is often necessary to develop system specific human reliability assessments.

Since the complexity of the human and organizational factors problem demands a variety of different HRA techniques an analysis of the most important features of an HRA model is quite useful. Such an analysis was performed by Hannaman and the results are summarized below.

- They should be compatible with and complement current PRA techniques.
- They should be scrutable, verifiable, and repeatable.
- Their application should result in quantification of crew success probability as a function of time.
- They should take account of different kinds of cognitive processing (i. e. skill-based, rule-based and knowledge based levels of performance.)
- They should identify the relationship to the model of various performance-shaping factors.
- They should be comparable to the highest degree possible with existing data from system experience, simulator data, or expert judgment.
- They should be simple to implement and use. They should help to generate insights and understanding about the potential for operators to cope with the situations identified in PRA studies. (Hannaman, 1984.)

### 2.1.2.1 Human Factors Standards

To date several different human factors standards have been developed. In general these standards were established to aid in the development of plans to implement human engineering design criteria for particular high risk systems. A brief synopsis of several Human Factors Standards is provide below.

*IEEE Guide for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations* - This document is designed to provide guidance to management and engineers to develop an integrated program for the application of HFE in the design, operation, and maintenance of nuclear power generating stations. An ongoing program is necessary to ensure that HFE is an equal design consideration with the traditional engineering disciplines in those activities that have a significant human interface.

This standard lists many of the types of factors to be considered when designing human interfaces and a detailed flow chart of the design process for developing systems which include human interfaces. It does not provide guidance in operations of systems. (See Appendix A)

*Standard Practice for F1337-91 HUMAN ENGINEERING Program Requirements for Ships and Marine Systems, Equipment, and Facilities* - This practice establishes and defines the requirements for applying human engineering to the development and acquisition of ships and marine systems, equipment, and facilities. These requirements are applicable to all phases of development, acquisition, and testing and should be integrated with the total system engineering, development, and test effort. These activities should be tailored to meet the specific needs of each program and the milestone phase of the program within the overall life cycle. The criteria provided in this standard should be applied directly to underwater welding systems. This standard does not provide guidance in operations of systems. (See Appendix B)

*ASTM F1166-95a Human Engineering Design for Marine Systems, Equipment, and Facilities* - This standard of practice establishes general Human Engineering Design criteria for marine vessels, marine systems, subsystems, and equipment. It provides a useful tool for the designer to incorporate human capabilities into a design, and it presents specific, detailed human engineering design criteria, principles, and practices. This standard does not provide guidance in operations of systems.

## 2.1.3 Underwater Welding

### 2.1.3.1 The Industry

Since with the first hyperbaric weld in 1965 and the first documented structural wet weld in 1970, underwater welding has become an important tool in the repair of marine structures. The ability to repair these structures in place underwater has saved the oil industry, alone, millions of dollars. These savings, coupled with aging platforms and the trend in the oil industry to go deeper in the search for petroleum has resulted in the growth of the thriving underwater welding segment of the commercial diving market. Grubbs et al. provide a well documented history of underwater welding as well as basic safety requirements, procedures, and three example applications of underwater welding. (Grubbs et al, 1996)

The underwater welding industry has worked diligently over the past three decades to improve the underwater welding processes in an effort to increase business through further promotion of underwater welding. These intense efforts are well documented by the American Welding Society (AWS, 1981) and the American Bureau of Shipping (ABS, 1995)

## 2.1.3.2 Processes

There are several underwater processes currently available for in place welding of ships, platforms, and pipelines. Most of these processes are similar to the corresponding surface processes except they are performed at depth and in some instances in a wet environment.

Brief synopses of the common types of underwater welding as described by Sisman are provided below. (Sisman, 1982)

### 2.1.3.2.1 Manual Metal Arc Or Shielded Metal Arc Wet Welding

The most widely used wet welding method is simply an extension of surface arc welding into the underwater environment. This process is identical to the typical surface manual metal arc welding in which short, flux-coiled electrodes are used. The standard equipment and continuously improving reliability of this procedure have led to the increased use of several underwater arc welding techniques.

Manual metal arc welding utilizes the electric arc created between a flux-covered metal electrode and the workpiece. The electrode is burnt and consumed in the process, providing the metal necessary to fill the weld. The heat developed by the arc melts the parent parts, the core wire, and the flux covering. For use underwater, the surface equipment is insulated at the cable joints and torch and waterproof electrodes are used. The flux covering decomposes under the action of the gas and shields the molten metals from the surrounding water. (Sisman, 1982)

### 2.1.3.2.2 Gas Shielded Arc Welding

Typically tungsten inert gas welding (TIG) in which an arc is struck between a non-consumable tungsten electrode an the workpiece. Filler material in the form of bare metal rod is added into the molten pool by the diver/welder. An alternative method is metal inert gas welding (MIG), in which an arc is struck between a consumable bare metal wire electrode fed from a reel into the weld pool.

### 2.1.3.2.3 Dry Hyperbaric Welding

This method utilizes the flux shielded or the gas shielded methods described above with the welded area enclosed in one of three ways.

Full-sized habitat: an open bottomed chamber enclosing the whole weld are, the welder, and his equipment and filled with an appropriate gas mixture at ambient pressure. The diver/welder may be dressed in either lightweight diving equipment or surface type breathing apparatus.

Mini habitat where inert gas or air displaces water from the upper portion of the diver/welder's body and the weld area. The diver/welder's lower torso remains immersed in water at the open bottom of the habitat.

Portable dry box covers the weld area only. Diver/welder is outside with only his or her hands reaching in. Gas metal arc (GMA) or MIG is normally used. A gas, usually and Argon mixture, is interdicted to displace the water in the box. The diver works from outside the transparent box, reaching into the opening on the underside. A vent in the top of the box is used to clear the welding fumes.

#### 2.1.3.2.4 One Atmosphere Welding

In this type of welding, the welder is transported under pressure in a one atmosphere transfer submersible to an underwater chamber in which the environment is maintained at one atmosphere. Water sealing presents a problem with this method. This type of welding is identical to dry hyperbaric welding with the exception that the welder remains at atmospheric pressure throughout.

#### 2.1.3.2.5 Techniques

There are two principal underwater arc welding techniques. Using the 'touch' or 'drag' technique, the diver/welder maintains constant contact between the electrode covering and the work. The electrode is dragged across the work, and pressure applied by the diver/welder causes the deposit of a small series of beads. This technique is ideal for fillet welding. The more difficult 'manipulative' or 'weave' technique requires maintenance of a constant arc without the application of direct pressure. This procedure calls for a very experienced operator.

The limiting factor for use of either technique is the diminished weld strength resulting from the water's high rate of cooling of the weld pool. As a result of this metallurgical problem, applications of wet welding for structural quality welds are somewhat limited.

### 2.1.4 Current HOF in Underwater Welding

To date there is no publicly available database dedicated solely to the occurrence of underwater welding accidents as a function of human and organizational factors. In fact, limited accident data is available describing either commercial diving casualties or casualties occurring during marine welding operations.

The lack of adequate accident data has been a subject of recurring debate among the commercial diving industry, primarily due to the industry's insurance difficulties. Without the facts and figures necessary to present realistic diving risks to underwriters, diving contractors are unable to convince underwriters to reduce premiums for diving insurance. (MTS, 1978) More importantly, from a safety promotion prospective, better recording and analysis of diving and underwater welding accident data is needed to probabilistically determine the causes of underwater welding accidents in an attempt to focus efforts on accident prevention.

Publicly available actuarial data is limited at best. Such data on commercial diving fatalities is particularly scarce, but data on recreational SCUBA diving is available. It has been estimated that two million SCUBA divers participated in the sport in 1980. As a result of those dives, 116, 128, and 120 accidental deaths were reported in 1978 through 1980, respectively. (National Safety Council, 1989) According to the National Safety Council, the estimate of total divers is crude, and it is impossible to distribute the number of fatalities according to age, location, or diving experience.

The Divers Alert Network (DAN) provides extensive data on recreational SCUBA diving accidents. Generally, DAN does not publish accident data on commercial diving, but one DAN official responded to a request for data on underwater welding accidents by stating that DAN has received reports of two fatalities in the past 8-10 years involving underwater welding/cutting. Both fatalities were the result of the explosion of entrapped hydrogen. (Saxon, 1997)

Elliot and Davis subdivide diving accidents, commercial and recreational, into three broad categories according to circumstances: (1) Accidents that occur while the diver is in the water, (2) Accidents of decompression, and (3) Coincidental illness or physical injury. While a common outcome of the first category of accidents is a fatality by drowning, decompression accidents are normally identified on the surface after the dive and treated successfully using recompression therapy. Elliot and Davis clearly indicate that many of the accidents in all three categories are the result of a succession of causes, each of which might have been corrected had it occurred alone. In combination these causes may render the diver unable to cope, and they often lead to panic or ultimately death. (Elliot and Davis, 1982)

**Table 2- U. S. Diving Fatalities - National Underwater Data Center Statistics**

| Occupational Underwater Diving Fatalities Yearly 1970-1978 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
| 17 | 6 | 9 | 12 | 19 | 17 | 15 | 23 | 13 |

The National Underwater Accident Data Center collected data on diving casualties occurring with in the United States from 1970 to 1978. Results of this study involving occupational divers are summarized in Table 2. This study did not provide a detailed numeric breakout of causes, but case discussions in the narrative demonstrated a high incidence of non-descript human error associated with these fatalities. Furthermore, this study cited the organizational trend in the offshore industry of outsourcing diving operations to private contractors as a factor leading to commercial diving accidents.

The North Sea is the geographic area with the most extensive and accurate data on diving casualties in the commercial diving industry. Results of the study shown in Figure 2, identified main causes of diver fatalities from 1971-1977. 35% of all the 39 fatalities were considered to be caused by human factors. This study also suggests that a fraction of the remaining causes should be classified as human errors because of their dependence on human behavior.

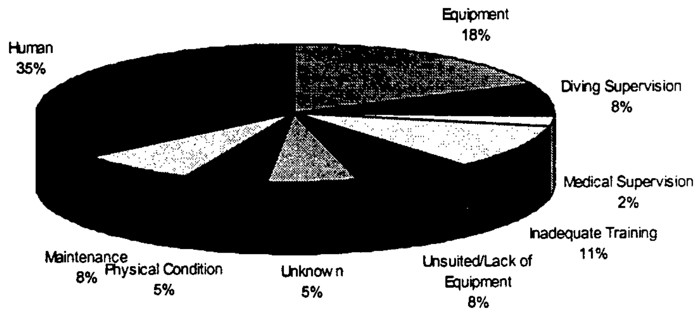

**Figure 2 - Main Causes of Diver Fatalities in the North Sea 1971-1977 based upon 39 Deaths**

Using all the available diver accident data in the North Sea from 1971 to 1983, Jacobsen estimated the overall annual individual fatality rate from a diving accident on the Northern Continental Shelf as 3.9 X 10E-4 as shown in Table 3

**Table 3 Diver Fatality Rate Estimates On The Norwegian Continental Shelf**

| Fatality Measure | Activity Exposure | | |
|---|---|---|---|
| | Surface Oriented Dive | Bell Diving | Chamber Stay |
| No of fatalities | 3 | 7 | 2 |
| Fatalities per dive | 1.80E-04 | 2.80E-04 | - |
| Fatalities per hour activity | 2.70E-04 | 3.00E-05 | 9.60E-07 |
| Annual "individual fatality" rate estimate | 3.90E-04 | | |

Interestingly, other research conducted on North Sea accident figures suggests that at least fifty percent of all North Sea diving accidents occur from air diving as opposed to deeper saturation diving. Research conducted on 47 fatal diving accidents in the North Sea, summarized in Table 4, concluded that most fatal diving accidents are caused by malfunctioning equipment or mistakes in the handling of equipment. In approximately another 10-20% of the accidents a "malfunctioning diver physiology" contributed to the fatal outcome. .

| | |
|---|---|
| Malfunctioning equipment | 15 |
| Inappropriate training and panic | 6 |
| Trauma and surface drowning | 5 |
| Inappropriate equipment | 4 |
| Medico-physiological | 4 |
| Temperature problem | 3 |
| Medically unfit | 2 |
| Unknown Cause | 2 |

**Table 4 - Factors Behind Diving Fatalities in the North Sea 1971-1983 (Ornhagen, 1986)**

A study of all marine welding accidents in the Gulf of Mexico was conducted by the U. S. Minerals Management Service (MMS). Results of this study showed that 70 percent of the 90 reportable welding accidents between January 1, 1967 and September 30, 1983 were caused by "lack of proper site preparation, coordination and supervision (46%)," or "failure to properly isolate potential source of fuel and/or flush inert the work area (34%)." Figure 3 provides a summary of accident causes. (Danos, 1984) Brief descriptions of each of the incidents were included in the study. According to the descriptions provided, only one of the ninety reported welding accidents involved underwater wet welding. This accident resulted in a fatality.

Several attempts have been made to acquire underwater welding safety statistics directly from U. S. commercial diving contractors with limited success. Most companies appear reluctant to release safety statistics for fear of relinquishing a competitive advantage.

Couch et al emphasize the failure of many industry codes to address accident reporting procedures or safety specifics, presumably for reasons of potential liability. Mere reference to safety documents is not considered adequate for most of these documents do not address safety issues specific to underwater welding. (Couch, 1995)

What is the significance of the results of all of the studies cited above? These studies suggest that diving and welding accident and fatality rates are particularly sensitive to human errors; therefore, the application of HOF principles is a necessary tool in improving the reliability of diving and welding systems. Since underwater welding is clearly a direct combination of diving and welding, HOF are extremely important in its success, and any opportunities to decrease the incidence of human error in underwater welding systems should be vigorously pursued.

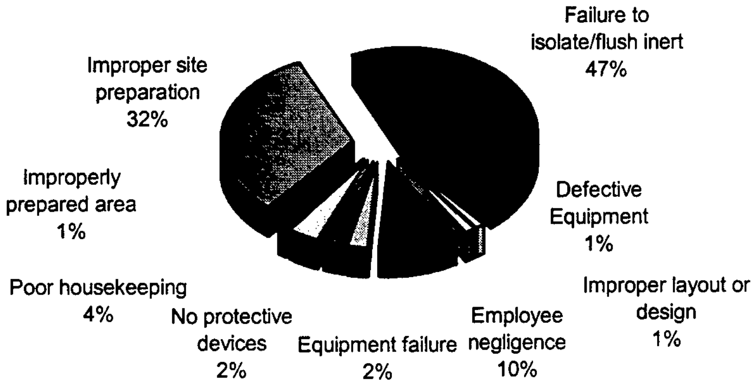

**Figure 3 - Causes of Welding Accidents in GOM 1967-1983**

### 2.1.5 HOF in Productivity, Weld Strength, and Durability

Advances in the study of HOF can also potentially lead to improved productivity in underwater welding operations. Faster processes and more durable welds will be the result of working to decrease incidents of human and organizational errors. To date, attempts to address the human element in underwater welding have been focused on qualification of welder-divers.

Couch, Reynolds and Hanzalek (1994) synopsize various regulatory agencies' present approaches to the qualification of underwater welders and address the difficulties involved in qualifying personnel in this multitude of different procedures in an effort to support work under numerous agencies. As a result underwater welding companies have lost flexibility in carrying out work and have been forced to incur multiple expenses for seemingly redundant qualifications. In an effort to provide solutions to this problem, they explore several approaches to qualification. These approaches include standardized mandatory training, prequalification on the surface, required minimum experience with less difficult procedures, prequalification in NDT, limits on the duration of qualifications, certification by a single agency, and the application of contingency tests.

Holdsworth and Spencer (1994) illustrate the use of systematized certification programs as an effective management tool to measure and improve performance of underwater welding. Certification is one of the most effective methods of lowering risk, improving quality, and enhancing process controls crucial to underwater welding and construction projects.

# 3. Analytical Model

## *3.1 American Welding Society Role*

The organizational structure of the American Welding Society's (AWS) D3b Committee on Underwater Welding is included in Appendix C. The committee meets at least semiannually.

In recognition of the importance of HOF in underwater welding, D3B has recently begun an effort to include an informative annex on HOF in underwater welding in the 2003 edition of the *Specification for Underwater Welding*. This specification includes the requirements for welding structures or components under the surface of water. It includes both dry and wet hyperbaric welding and is primarily dedicated to specific performance requirements of the four individual classes of weld. (AWS, 1997)

The overall goal of development of the HOF annex is to provide specific guidance to underwater welding operators for the improvement of human and organizational factors inherent in underwater welding. Because diving is such an integral component of the underwater welding process, human and organizational factors involved in diving are discussed. However, an attempt is made not to duplicate or, more importantly, contradict any directives or recommendations of recognized commercial diving authorities. Though heavily weighted toward the improvement of underwater welding safety, the annex also includes recommendations for the improvement of human and organizational factors pertaining to the attributes of weld strength and durability.

Format of the annex is governed by the AWS guidelines (AWS, 1994) and subject to the approval of the D3b subcommittee. It is the hope of D3B that the HOF annex will set a precedent for a specific HOF annex to be included in all AWS specifications.

During a joint AWS/International Institute of Welding (IIW) meeting in July 1997, the HOF effort was begun. At the November 1997 meeting, the an initial draft of the HOF Annex was presented to the committee chairman for review and comment, and the HOF concept was formally submitted to the entire committee.

Furthermore, efforts are currently underway to combine the European Standard (EN) and AWS specifications for acceptance as an International Standards Organization (ISO) standard and to incorporate a design section into the AWS document qualifying it as a "standard" rather than a specification. At the November 1997 meeting, a formal request was drafted for the authority to develop an ISO document for Safety, Environmental, Health, Human and Organizational Factors in underwater welding.

## 3.2 Initial Information Collection

### 3.2.1 Underwater Welding Industry Defined Research Needs

In 1994, experts in the field of underwater welding developed the Prioritized List of Research and Development Needs in Underwater Welding (ABS, 1995) which provided specific conditions, goals, and recommendations pertaining to research in underwater welding. Many of the recommended research topics included a focus on HOF. The following conditions, goals, and recommendations which were taken directly from this consensus document, formed the initial guidelines for the collection of information for the development of the HOF Annex:

**Conditions**

- There is a need to depart from traditional approaches and to "break circle."
- All possible, even uncommon, designs and incident technologies at hand should be integrated in the development process.
- A comprehensive, multi-disciplinary and systematic, scientifically-oriented approach is likely to lead to real significant process.
- There is a need for coordination and direction in the investigation and development of techniques for underwater welding.

**Goals**

- Evaluation of processes from the standpoint of operation in wet and/or dry environment.
- Development of recommended procedures and specifications based on data obtained through use and qualification of selected processes, technical development, experience of users and operators, and input from regulating bodies.

**Recommendations**

- Third party certifications for wet welders to prevent entrance of diving companies with little welding experience.
- Modification of codes and standards to include training and experience as a basis for certification.
- Consideration of the effects of restraint. For example restraint can be greater under production conditions than training conditions.
- Incorporation of wet welding into design standards.
- Development of guidelines for damage inspection and repair.
- Improvement of equipment: torch design (gtaw, gmaw, and plasma).

### 3.2.2 Benchmarking HOF Efforts of Other Industries

Across many industries HOF approaches consider the system failure causes resulting from human and organizational errors. These so-called extrinsic causes have been traditionally and incorrectly absent from failure analyses. The study of HOF has identified proactive and real time approaches to improving safety. By focusing on extrinsic causes rather than intrinsic causes of system failures, it has been possible to drastically increase system safety with minimal effort and expense. Many of the same HOF lessons learned can be applied across numerous engineered systems without the high cost associated with predicting, measuring, or simulating extreme intrinsic causes.

HOF program efforts in several industries have proven successful in increasing system safety and reliability. Excellent examples of HOF applications are found in the nuclear power industry (Swain and Guttman, 1975), in the marine industry. (Moore and Bea, 1993), and in the commercial airline industry in the form of Crew Resource Management (CRM). (Merrit and Helmreich, 1996) Many of the tools utilized by these programs have been incorporated into the underwater welding HOF annex where applicable.

### 3.2.3 Field visits

The lack of readily available research data on HOF and safety in underwater welding led to an effort to collect field data. Three field visits to underwater welding training and operations organizations were conducted. The three organizations visited were the College of Oceaneering, Global Divers, and Oceaneering Incorporated. Lessons learned from these field visits are included in Appendices B, C, D and were included in the HOF annex.

The field visits were designed to gain an in-depth knowledge of underwater welding industry standards. A thorough knowledge of the underwater welding system and corresponding HOF system relationships was necessary prior attempting to improve system safety. It was realized early on that the only way to improve the HOF aspects of the system were to approach the problem with humility and to understand that the seeds for success or failure lie with those that have daily responsibilities for the operations and safety of their systems.

### 3.2.4 Organization of HOF Information in the Annex

During the initial information collection phase, the format was developed for the organization of the HOF annex. Information was gathered based on this organization in which human and organizational factors were classified based on influence types. In this classification system, subheadings of influence type were broken down into influence attributes and HOF applications.

### 3.2.4.1 Influence Types

The common categories of human error which can cause underwater welding accidents are directly affected by many types of internal and external influences on the underwater welding system. It has been assumed that there are seven broad influence types affecting underwater welding: 1) individual, 2) team, 3) organizational, 4) procedural, 5)structural, 6) equipment, and 7) environmental.

While all of these influence types are significant, the initial focus of the annex is on the first three influence types, individual, team, and organizational influences. Procedures affecting underwater welding are thoroughly covered in the body of the specifications; therefore, they were omitted from the HOF Annex. Additionally, structural, equipment, and environmental influences on HOE were excluded from the scope of the annex due to their intrinsic nature. These influence factors shall be considered at a later date during the future development of the design section of the D3B standard.

### 3.2.4.2 Influence Attributes

Given that the seven influence types are found within every underwater welding system to some degree, it can be deduced that certain attributes within each of these broad categories lead to success in underwater welding operations. In other words, specific HOF qualities can be identified as common in successful underwater welding systems. Identifying the most successful influence attributes within underwater welding systems was the next step toward implementing useful HOF tools which can ensure success across the entire industry.

### 3.2.4.3 HOF Applications

The ultimate aim of the annex development process is to determine specific HOF applications or recommended practices which, if applied, will result in safe and successful underwater welding operations. These recommended practices are being developed to instill the successful influence attributes in the overall system.

The HOF applications are provided as "nonmandatory recommended practices" within the *Specification for Underwater Welding*. Within the specification, the HOF applications are grouped within the influence attributes, and, likewise the influence attributes are grouped by influence types.

During the analysis each recommended practice was supported with a justification based on information gathered from the literature review, industry benchmarking, or field visits. Since the annex is intended to be utilized as a field document, it should be concise and focused on providing clear directives for underwater welding operators. In order to meet these conciseness and clarity constraints, the final draft of the annex will not include detailed justifications. Instead these justifications shall be included in the document's commentary section. Directives and supporting justification are provided together to facilitate ease in reading this document. Directives which shall be included in the annex are provided in bold.

#### 3.2.4.4 Interfaces

Often systems comprised of quality components are unsuccessful due to the failure of interfaces between these components. To eliminate this phenomenon, the annex considers interfaces as a separate category. Within the interface category, the interfaces of all seven influence types with the three HOF influence types are investigated. (Appendix G)

## *3.3 Deterministic Phase*

The next phase in developing the HOF annex was to determine the value of each recommended HOF practice. Ideally, this would be done through a sensitivity analysis of the effect of each HOF on the probability of system failure. As noted in the literature review, there is a lack of probabilistic underwater welding data on which to base this sensitivity analysis; therefore, a step back to a deterministic approach was necessary.

The deterministic phase involved defining causal relationships of system failures and then developing a system model which could be used to test these relationships. The sequence of tasks involved in developing such a model for the underwater welding system is provided in Figure 4. As shown in the figure, the initial data gathering was followed by determining the quality attribute to be studied and defining a system failure.

Next a system life cycle model and a process for developing HOF tools were implemented in parallel. Finally, several tools were tested using the model. A given tool was evaluated by comparing the risk of system failure in the tool implement to a baseline risk of system failure. If a tool significantly reduces the risk of failure, it should be incorporated into the annex. The next section describes the detailed development of the system model.

### 3.3.1 Quality and Risks in Underwater Welding Systems

Quality in any engineered system consists primarily of four requirements: (1) servicibilility - suitability for the proposed purpose; (2) safety - freedom from excessive danger to human life and property damage; (3) compatibility - the lack of excessive negative impact on the system's surroundings; and (4) durability - the maintainability of the other three quality measurements during the system's intended life.

Due to the significant risk of injury to the welder-diver, the safety aspect of the underwater welding system was often the system characteristic of greatest initial concern. Failure to develop acceptable safety to the welder-diver has the potential to result in a serious injury or fatality. Consequently, there is a limited acceptable margin for error in a safety component in any underwater welding system. Ideally, this margin for error or risk can be determined for each potential failure of the system under consideration in order to provide a means of comparison between safety risks.

Safety risks associated with underwater welding can be expressed as the product of the likelihood of a hazardous event, e.g. an explosion resulting in a diver casualty and the consequences that could be associated with that event. (Bea, 1997) First a simple comparison was used to determine the consequences of a safety failure. Then a life cycle approach for determining likelihood of system failure is discussed.

There are various ways to measure the consequences of an underwater welding accident. Perhaps the most pragmatic approach is to utilize a financial measurements. Though it was nearly impossible to determine the value of a welder-diver's life, it was possible to estimate the potential financial costs to a diving contractor

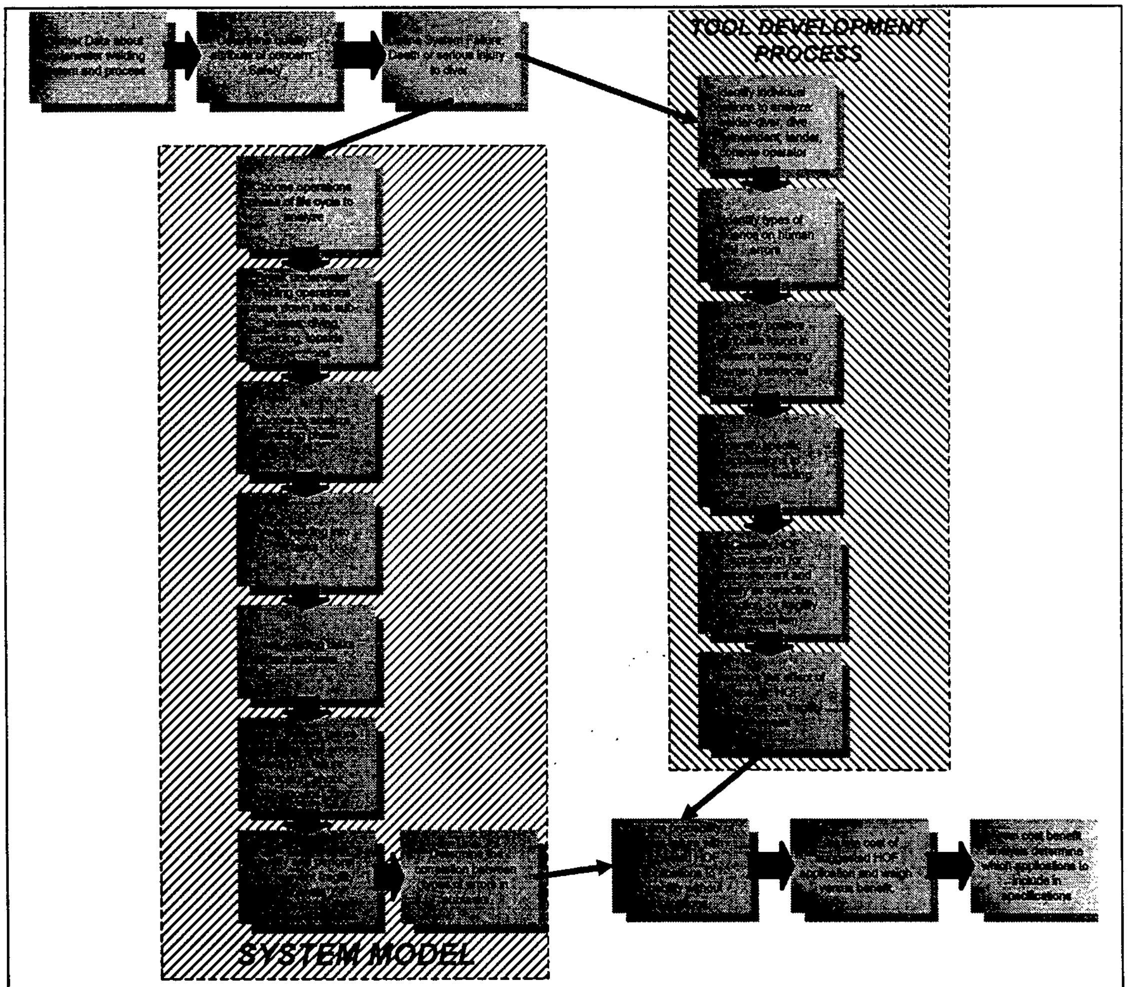

Figure 4- Process Flow Diagram of HOF Analytical Model

resulting from an injury to or the death of a welder-diver.

Based on estimates from diving insurance underwriters, the average jury awards for diving industry accidents on behalf of one diver is approximately $1.2 Million.[1] Such high costs were the indirect result of court rulings which determined that welder-divers may collect awards as "seamen" based the Jones Act of 1970. This Act had included seamen under the Federal Employees Liability Act.

### 3.3.2 System Life Cycle Model Development

Traditional approaches to safety management have been concentrated on identifying and correcting intrinsic safety defects. Applying these traditional approaches to underwater welding incorrectly implies that all underwater welding accidents result from hardware or software problems within the underwater welding systems, e. g. the diver's life support system (DLSS), the welding system, or the platform's lock out/tag out systems. Often these approaches are reactive. In other words, when a failure in safety occurs in a system component, effort is concentrated on preventing future failure in that component only.

There are two primary flaws to such traditional approaches. First, it is rare that an accident occurs in the same manner twice. Often a whole row of events precede the final event that hurts or kills the diver. Secondly, these approaches often ignore the most common category of cause of safety failures, extrinsic causes - human and organizational factors (HOF).

The earlier review of welding and diving accidents revealed that they were often caused by operator error compounded by management related factors that influenced the operations and emergency preparedness. While every diving or welding accident is different, many of them have the same signature. They occur due to similar issues such as a breakdown in communications, incentives, selection of properly trained and experienced personnel, etc.

Multiple disciplines including human factors engineering, organizational behavior studies, and process safety procedures must be incorporated into the HOF improvement process as required by the scope of the task. Some of the activities which may be necessary include:

- Determining the relevance of prior Safety and HOF studies, reports, and other pertinent documents
- Conducting HOF assessments (i. e probabilistic, narrative, checklist/questionnaire, ranking, or indexing assessments.)
- Investigating current design practices to identify HOF concerns

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[1] The 1977 Diving Insurance Symposium Proceedings cited awards of $700,000. This sum was discounted forward to 1997 based on a relatively conservative annual inflation rate of 3% per year.

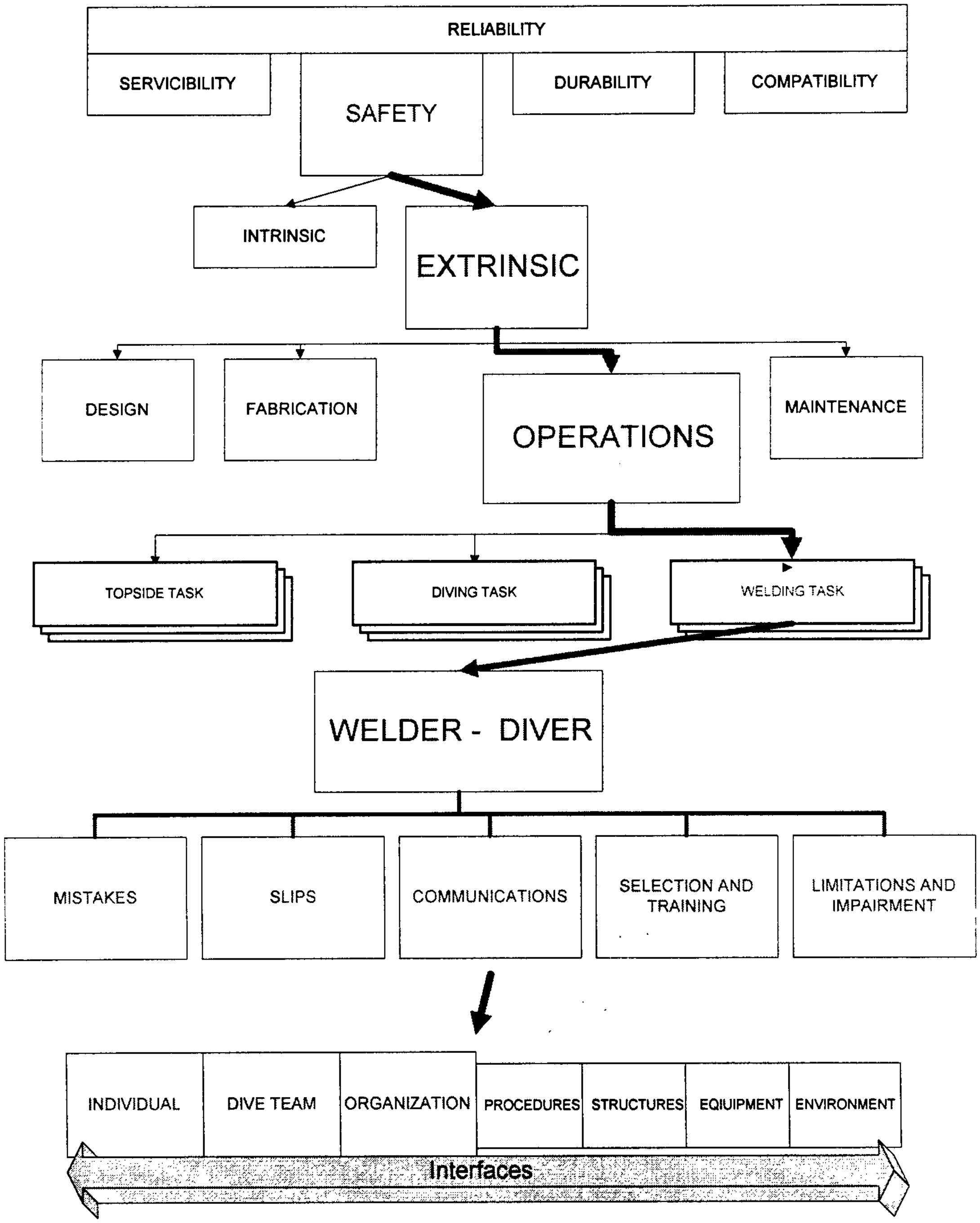
- Establishing trade-offs of HOF considerations with design, operation, testing, or maintenance considerations.

The study and improvement of HOF should be considered an ongoing activity with respect to any future design, modification to existing designs, or evaluation of existing designs.

Due to their substantial impact, human and organizational factors (HOF) considerations should be an integrated in all phases of the underwater welding life cycle including design, construction, operations, testing, and maintenance.

### 3.3.3 Underwater Welding HOF Assessments

**Figure 5 - Safety HOF in Underwater Welding**



A full schema, life cycle model developed by Bea has been modified and applied underwater welding in Figure 5, This model implies the extrinsic causes of failure in safety

are rooted in malfunctions developed in one of the four phases found in every engineered system life cycle: design, construction, operation, or maintenance. Consistent with the operations focus of these AWS D3b Specifications for Underwater Welding, the implementation of HOF considerations into the system will begin with the operations phase It is important, however, for the reader to recognize the inherent interactions between the operations and the other three phases of the underwater welding systems, design, construction, and maintenance. In fact, the extension of HOF applications into the design, fabrication, and maintenance of underwater welding systems is highly encouraged and the operator's role in feeding back to these three phases is included in the specification.

Within the operations phase of the life cycle, the underwater welding system can be broken down into three components, a diving component, a welding component, and a topside operations component as shown in Figure 5. Though these three components combined constitute the underwater welding system, typically each component is designed, constructed, operated, and maintained separately based primarily on constraints from other functions of these subsystems. For example, many underwater welding systems are adaptations of surface systems which were not originally designed for use in the water. Thus, safety features added to protect against the hazards found underwater are often awkward modifications added to a surface welding system, not features of well integrated underwater welding system designs. Similarly, many mechanisms used for lock out or tag out were designed to protect the moving equipment during maintenance and, therefore, may not be ideally suited to ensure the welder-diver's safety.

During operations it is the responsibility of the welder-diver, the dive team, and the supporting organizations to bring together all three components in a safe, coherent underwater welding system. As is any system with many complex man-machine interfaces, there is a high susceptibility to errors occurring in its most valuable component, the human component, or, specifically, the welder-diver. In underwater welding such errors can generally be classified as individual errors such as mistakes, slips, and limitations or organizational errors such as communication malfunctions and selection and training malfunctions.

Mistakes are cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis and action. Slips occur when the outcome of an action was not what was intended; therefore, slips are normally easily recognized and corrected. Limitations are malfunctions which occur as the result of excessive fatigue, stress, or diminished senses. Communications malfunctions are simply the ineffective transmission or receipt of information. Selection or training malfunctions occur when personnel are not suited, educated, or practiced for the activities. (Bea, 1997)

HOF that occur during the operations phase can be related first to the individuals that operate the system. The actions or inactions of these operators are influenced to a very significant degree to the organizations that they work for and with. In the case of the welder-diver, these organizations include the weld-dive team and the corporate administrative organizations that control the dive team. Also the individuals are influenced by the interfaces between the system operators and the procedures, structures, equipment, and environment.

The probability of the system failure due to extrinsic causes from operations was calculated using a life cycle, reliability based formulation modified from Bea. (Bea, 1997) Using this approach the probabilities of each influence factor causing a human error was determined based on Table 5. This data was collected by the nuclear safety industry.

| | |
|---|---|
| 1 | |
| | new or rarely performed task, extreme stress, very little time, severe distractions and impairments |
| 1.00E+00 | |
| | highly complex task, considerable stress, little time, moderate distractions and impairments |
| 1.00E-01 | |
| | complex or unfamiliar task, moderate stress, moderated time little distractions and impairments |
| 1.00E-03 | |
| | difficult but familiar task, little stress, sufficient time, very little distractions or impairments |
| 1.00E-04 | |
| | simple, frequently, skilled task, no stress, no time limits, no distractions or impairments |
| 1.00E-05 | |

**Table 5 - Mean Rates of Human Error**

The probabilities of human errors for given influence factors were assumed to be lognormally distributed. These probabilities were then summed using the Algebra of Normal Functions (AONF) in order to determine the overall probability of human error for a given underwater welding subtask. Likewise the probabilities of human error for given subtasks were similarly combined to determine the probability of human error in underwater welding.

Welding was divided into subtasks based on the subtasks relationships with the most likely system failures: electrocution, explosion, impact injury, and asphyxiation. See Figure 6 - Welding subtask breakdown

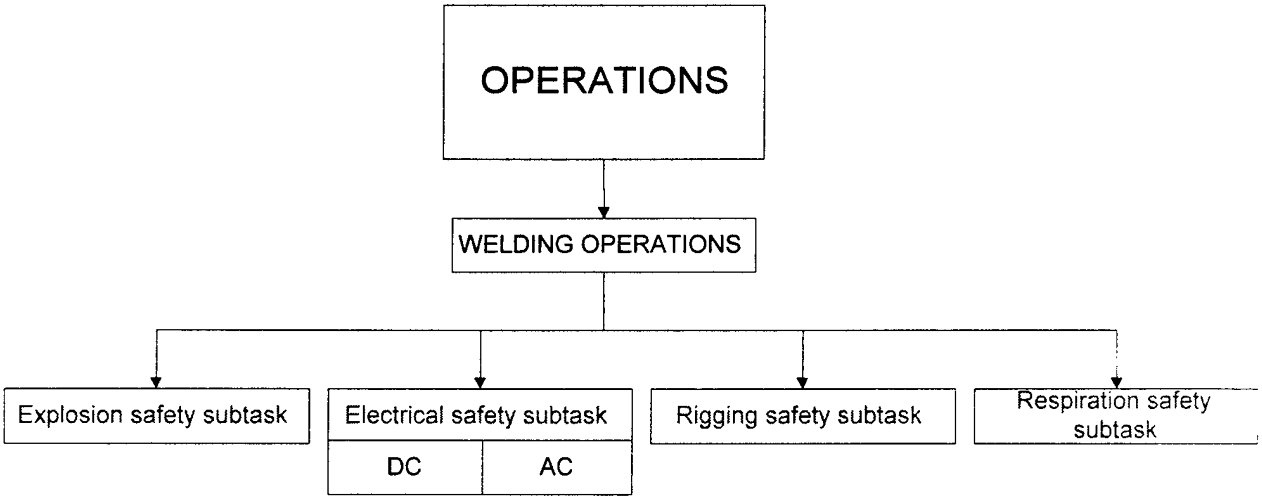


**Figure 6 - Welding subtask breakdown**

### 3.3.4 Underwater Welding System Error Tolerance

The deterministic framework already discussed identifies the effect of organizations and interfaces with system components on an individual's propensity for human error, but it does not explore the underwater welding system's error tolerance to such human error. Error tolerance reflects the system's fragility, its ability to detect, and/or its ability to correct the human error prior to system failure.

A comprehensive review of the error tolerance of the underwater welding system includes the error tolerance of the system given an error in the electrical safety , explosive safety, respiration safety, or rigging safety subtasks. A mathematical representation of the systems error tolerance can be developed as a fragility analysis. A output of the fragility analysis is the probability of a system failure given a human error. The input into the fragility analysis is the probability of occurrence of the human error.

#### 3.3.4.1 Electrical Shock Fragility Analysis

As shown in Table 6 effects of electrical charges on the human body vary with the amount of current going through the body. Approximately 500 milliamperes of DC current results in possible ventricular fibrillation. IN accordance with __ resistance of the human body to electric current is Current varies as a function of resistance through the body. Resistance is low for soft wet skin (1000ohms) compared to dry skin (100,000-200,000 ohms. (Marshall)

| | Current in milliamperes | | | |
|---|---|---|---|---|
| | DC | | AC | |
| Effect | Men | Women | Men | Women |
| Sligth sensation to hand | 1 | 0.6 | 0.4 | 0.3 |
| Perception threshold | 5.2 | 3.5 | 1.1 | 0.7 |
| Shock - not painful, no loss muscular control | 9 | 6 | 1.8 | 1.2 |
| Shock- painful, loss of muscular control | 62 | 41 | 9 | 6 |
| Shock - painful, let go threshold | 76 | 51 | 16 | 10.5 |
| Shock - painful, and severe | 90 | 60 | 23 | 15 |
| Shock - possible ventricular fibrillation effect from 3-second shock | 500 | 500 | 100 | 100 |

**Table 6 - Current at which people experience various effects from electricity.**

| Path through | Resistance in ohms |
|---|---|
| Hard, dry calloused skin on hand | 500,000 to 600,000 |
| Soft, dry skin on hand | 100,000 to 200,000 |
| Soft, wet skin | 1000 |
| Internal body from hand to foot | 400 to 600 |
| Ear to ear | About 100 |

**Table 7 - Resistance of human body to electric current**

Calculations of the probability of failure given that the human error results in a shock of the mean current value of .334 amps DC are provided in Appendix H. By performing similar calculations over the range of currents encountered in the process, a probabilistic data fragility curve could be developed relating probability of error to the likelihood of death or serious injury.

### 3.3.4.2 Explosion Fragility Analysis

The release of energy which occurs during an explosion in a pipeline is a function of the specific heat of the product, the pressure inside the pipe, the volume of pipe, and the ambient pressure. The high heat of electrical sparks is equal to thousands of degrees centigrade and, generally, sufficient to ignite all gases and vapors.

In most cases involving underwater welding, an explosion would need only to penetrate the welder-diver's helmet in order to cause death by drowning. The force needed to penetrate the welder-diver's helmet is a function of the strength of the glass of the face shield and the distance between the explosion and the diver's helmet. Since welder-divers perform welding with their head only centimeters from the weld arc, it is reasonable to make a qualitative judgment that most explosions during underwater welding would result in death. A conservative estimate of a 90% probability of death or serious injury given an underwater explosion caused by underwater welding was used in the model.

### 3.3.4.3 Toxic Inhalation Fragility Analysis

A determination of the system fragility given an accidental inhalation of toxic gases requires specific knowledge of the toxic gases involved. Additionally, death or serious injury from inhalation of toxic gases found in an underwater welding habitat is a function of pressure, length of exposure, concentration, etc.

Due to the complexity of respiratory injuries, a reasonable fragility determination is beyond the scope of this paper.

### 3.3.4.4 Rigging Error Fragility Analysis

Diver injury due to impact is a function of the force of the impact, the location of the injury, and the time necessary to stop the bleeding resulting from the injury. Determining a suitable fragility curve for rigging errors is again very difficult because no empirical safety data was readily available. It is however possible to make a very rough estimate of underwater impact injuries from an analysis of incidence rates for fatal accidents resulting from falls. According to a study by Griffiths and Fryer 250 fatal accidents occur per million workers each year as a result of falls. It seems reasonable that the risk of being seriously injured during underwater rigging operations would be close to the risk of a deadly fall on the surface. (Kinchin, 1982)

### 3.3.5 Effect of HOF Applications

Once the relevant fragility analyses were conducted, it was possible to determine the overall extrinsic probability of system failure assuming none of the HOF applications suggested had been applied. This probability of failure could then be compared to the probability of system failure given a specific HOF application.

In order to determine the probability of failure given a specific HOF application, the mechanism for improvement of the given application was determined. In general there are four mechanisms by which HOF can be used to improve system reliability: (1) mitigation of error (2) improvement in detection, (3) improvement in correction, and (4) improvement in system fragility.

An HOF application which improves detection provides for quicker or more accurate detection of a human error which could cause system failure. Likewise an improvement in correction increases the probability that the system will not fail because the human error will be corrected in time. Lastly the improvement in fragility increases the systems human error tolerance.

Another important statistical relationship which must be carefully considered is the correlation between the likelihood's of different human or organizational errors (HOE). If HOE are not correlated ($\rho=0$), then they are independent. The occurrence of one type of HOE has no effect on the occurrence of another type. If HOE are perfectly correlated ($\rho=1$), then the likelihood of one HOE can exactly predict the likelihood of another HOE.

The baseline case assumes likelihood's of HOE are not correlated. Many HOF applications do act to correlate the likelihood of HOE; therefore, correlation is a variable which may change according to the HOF applications utilized.

### 3.3.6 Failure Consequences

Once the probability of failure has been determine, it can be multiplied by the consequences of failure to determine the overall risk to the system. Based on the definition of system failure chosen, death or serious injury to the welder-diver, the consequence of failure is the consequence resulting from the loss of the welder-diver. It is difficult to quantify such a consequence, since it is impossible to accurately quantify the value of a human life.

One attempt to quantify the consequence of death or serious injury is to determine the average value of insurance claims which were successfully brought against diving companies in the past. However, this valuation technique requires a determination of party responsible for the human error. A conservative assumption can be used that regardless of the human error, it is the fault of the diving company. By using this assumption the diving company can calculate the financial risk of failure as "the probability of system failure times the cost of an a serious injury or death to employee (s)."

### 3.3.7 Cost Benefit Analysis

In order to accurately determine which HOF applications should be included requires a determination of the costs of each application and a comparison of these costs with the benefits of utilizing a particular HOF application. This benefit is equal to overall risk of to the system if the HOF application is not applied.

## *3.4 Probabilistic Phase*

The final phase of development of a viable HOF Annex is a probabilistic phase. This phase would incorporate an accident and near miss reporting system to gather statistical data regarding the role of human error in underwater welding. Such a reporting system should collect fragility data for each potential underwater welding accident. Also human and organizational data should be collected and the probability of HOE per task should be calculated.

# 4. HOF Tool Development Analysis

This section provides recommended HOF applications to be included in the HOF annex and detailed justification for each HOF application. These applications were devised based on qualitative data from the literature and personal interviews.

## *4.1 Individual Operators - Welder/Divers*

According to diving contractors asked by a NIOSH committee about their primary problem in diving safety, all agreed it was the qualifications of the individual. According to these contractors, it was estimated that approximately 80-85% of all diving accidents involve the individual on an individual basis.

### 4.1.1 Selection

Underwater welding is a highly specialized task requiring welder-divers to possess special mental, physiological and behavioral characteristics. As a result underwater welding firms have a responsibility to both prospective welder-divers and those who will dive with them to select those most fit for diving. Recommended selection practices are provided below to help firms chose welder-divers and to ensure safer and more efficient workers.

#### 4.1.1.1 Physiological

**Extreme care should be taken to select welder-divers who are physiologically fit to dive.** There are numerous stresses placed on the body during diving which primarily include static and dynamic load on the lungs, inert gas supersaturations during decompression, inert gas narcosis, high pressure neurological syndrome, oxygen toxicity, and temperature stress. Also underwater welding tasks are typically physically demanding and require above average levels of strength and stamina.

#### 4.1.1.2 Medical Examination Standards

**Medical examinations should be conducted in accordance with the recommendations set forth in the ADC Consensus Standards. In addition to excluding major disqualifying medical conditions, the examining physician should identify and give careful consideration to minor, chronic, recurring or temporary mental or physical illnesses which may distract or cause the welder-diver to ignore factors concerned with safety.**

In accordance with the ADC standards, the examining physicians must have a list of the essential job functions (Job Description) to review with each commercial diving physical examinations.

**The following job functions are provided as guidance for determining medical examination standards for welder-divers:**

1. **Welder-divers shall perform duties including weld setup and weld preparation work including rigging, materials alignment and materials preparation including beveling, stripping of concrete, and fitting steel patches or repair plate.**
2. **Welder-divers shall perform certified welds in wet and/or dry environments. In dry hyperbaric welding, welder-divers shall be exposed to numerous pressurized gases including welding fumes, welding gases, soot, and carbon monoxide.**
3. **Welder-divers shall be required to perform welding inspections of various types.**

### 4.1.1.3 Physical Fitness

**While maintaining adequate physical fitness is the personal responsibility of the individual welder-diver, baseline physical fitness evaluations are recommended prior to acceptance of students into welder-diver training. Furthermore, periodic physical fitness evaluations are recommended to ensure maintenance of welder-diver fitness.** The importance of physical fitness in underwater welding can not be overstated. Some underwater welding tasks require considerable strength and stamina as well as a reserve of physical strength sufficient to cope with unexpected situations.

### 4.1.1.4 Pressure and Oxygen Tolerance Screening

**Each welder-diver candidate should complete a hyperbaric pressure test conducted in a hyperbaric recompression chamber prior to beginning underwater welding instruction. Only candidates who are known to tolerate decompression well should be selected.** The test is designed to determine if the applicant can successfully adapt to increased atmospheric pressure without adverse physiological reaction.

### 4.1.1.5 Dexterity

A welder-diver's dexterity is directly related to his or her success underwater. Several dexterity tests are commercially available which could be used to measure a welder-diver's manual capabilities. Typically, the most successful welder-diver's are those who are ambidextrous.

### 4.1.1.6 Age limits

**The diving profile and task structure should be carefully considered when assigning underwater welding tasks to welder-divers over 40 years old.** While the ADC Consensus Standards do not mandate an age limit provided the diver meets minimum medical requirements, diving medical research demonstrates a substantial increase in risk to diver's over 40 years old.

### 4.1.1.7 Gender

**Gender specific procedures for the selection and medical certification of welder-divers should be developed. These procedures should include consideration of a history of hypothermia, strength measurements, and diver's attitude.**

As the result of differing physiology between men and women, selection and medical certification should involve slightly different emphases. The following parameters are worthy of note:

- It has been suggested that women are more susceptible to hypothermia due to their lower body weight.
- Strength of men and women should be evaluated on a task-specific basis and should be adequate for foreseen circumstances.
- Culturally, there is evidence to suggest that men are more likely to be cavalier about diving safety, more apt to abuse alcohol, dive when fatigued, or not be up to standard physically.

### 4.1.1.8 Diet

**A balanced diet is recommended. Diving should be avoided for 2 hours following a heavy meal. Light meals should be taken during the day's diving operations. Liquid intake must always be maintained at normal or above normal levels.** Dehydration is particularly dangerous prior to dives requiring decompression. In most circumstances diet is left to individual discretion.

**Alcohol use is discouraged prior to diving operations. Excessive use of alcohol the evening before underwater welding operations is also discouraged.** Alcohol may increase the susceptibility to decompression sickness, and may enhance heat loss in cold water exposure.

### 4.1.1.9 Psychological Screening

#### 4.1.1.9.1 Panic and stress

**Several precautions are recommended to minimize occurrences of panic in underwater welding. These precautions include recognition of welder-divers who exhibit high levels of anxiety, counseling of individuals who are predisposed to panic, and training welder-divers to avoid potential panic situations.**

**Instructors must be trained to recognize welder-divers who exhibit high levels of anxiety, recommend further stress training, or, when necessary, deny certification to these welder-divers. On an individual level, welder-divers must be proactively informed of the risks associated with diving and be able to make an honest assessment of their personal anxiety level and how it might change in the case of a high-stress situation underwater. Individuals believed to have a history of high anxiety and panic episodes should be counseled during initial welder-diver training classes about the potential risks.**

There are some underwater situations that would cause any welder-diver to panic, but there are ways to minimize the risk a panicked response. **Throughout training and operations the welder-diver should be reminded:**

- ***Not to attempt work clearly beyond their capabilities.*** **They should make sure that they are experienced enough to conduct the operation being planned. A welder-diver's training does not replace the need for his buddy's own training.**
- ***To avoid situations requiring unavailable resources.*** **Welder-divers should not try to squeeze in that last dive at dusk, unless the entire team is prepared to finish it as a night dive. And if you don't have the proper equipment to make a certain dive, it's better to pass on the dive and do it another day.**
- ***To stay current with their training.*** **It's important that they stay current with skills, and to practice skills that are appropriate to the type of welding operations being performed.**
- ***Not to dive if it doesn't feel right.*** **They may be eminently qualified to make the planned dive and may have done it before, but if something doesn't feel right when it's time to get into the water, they shouldn't. One's ego should never get in the way of safety.**
- ***To preplan, anticipate, and rehearse actions taken under stress.***

Episodes of panic or near-panic may explain many diving accidents and deaths. Recent research indicates that more than half of all recreational divers reported experiencing at least one panic or near-panic behavior. Though the levels of panic experienced by the professional welder-diver are assuredly less frequent, panic, at some level, contributes to many underwater welding emergencies.

Panic can be broken down into two basic classes of anxiety, *trait anxiety*, a stable or enduring feature of personality, and *state anxiety*, a reaction to a situation. Typically individuals who possess high trait anxiety are more likely to have increased state anxiety. Consequently, such individuals are more susceptible to panic during welding or diving activities.

Though some forms of interventions (e. g. biofeedback, hypnosis, imagery, and relaxation) are shown to reduce anxiety responses in divers exposed to various stressors, these efforts are not considered effective due to their undesirable side effects. For example, hypnosis has shown to increase heat loss in divers. In some "high anxious" individuals, relaxation can even lead to increased anxiety and panic attacks known as relaxation-induced-anxiety (RIA).

#### *4.1.1.9.1.1 Panic Screening Methods*

**Speilberger's *State-Trait Anxiety Inventory* is one recommended method of screening prospective diver-welder's who could be considered as anxiety risks. In research conducted on recreational welder-divers, it was proven 88% effective in predicting panic.**

### 4.1.1.10 Mental

#### 4.1.1.10.1 Capacity Measurement

**While there is no prescribed minimum IQ requirement for underwater welding, the complex welding and diving systems involved suggests that welder-divers require at least a basic capacity for understanding system relationships.**

#### 4.1.1.10.2 Mechanical Aptitude

Several aptitude tests are commercially available which measure a person's analytical ability as applied to mechanical tasks. Though no specific test is currently recommended, any such measure of a welder-diver's mental aptitude should be weighed in the welder-diver selection process.

#### 4.1.1.10.3 Education

**Prior to entrance into underwater welding training, candidates should earn a high school diploma or a General Educational Development (CED) Certificate. When hiring new underwater welders, it is recommended that first hand knowledge be obtained on their qualifications. It is recommended that welder-divers have, at a minimum, completed the curriculum at an accredited commercial diving school.**

## 4.1.2 Training

**To prevent unnecessary accidents, HOF principles should be introduced during the earliest stages of training and incorporated by the instructors and students throughout the entire training phase.** Empirical evidence suggests that diving accidents occur more frequently during training than during operations.

### 4.1.2.1 Entry Level Diving Training

**At a minimum, all welder-diver candidates should fulfill Association of Diving Contractors entry level qualifications prior to acceptance into a specialized underwater welding curriculum.**

### 4.1.2.2 Entry Level Welding Training

**In addition to entry level diving qualifications, it is recommended that entry level welder-diver candidates specializing in underwater wet or dry welding complete a program consisting of topside and underwater burning and welding training, and advanced courses in the technology of wet shielded arc welding. This training should include recognition and correction of safety hazards and the use of safe practices**

**In addition to necessary diving requirements, it is recommended that diver-welders entering the field of hyperbaric wet or dry welding should receive training in all applicable topside certifications, prior to commencing attempts to earn corresponding certifications underwater.**

### 4.1.2.3 Team Preparation Training

**Formalized training should be incorporated into underwater welding curriculum to identify and train welder-divers in the importance of their roles as a dive team members.** Welder-divers participate in operations requiring them to give and take directions from others, in both a peer relationship and a supervisor/employee relationship. Individuals must be taught basic responsibilities of being a member of a team. It can not be assumed that effective attitudes toward teamwork will develop naturally once an individual becomes part of a team.

### 4.1.2.4 Panic Training

**Welder-divers should be provided with instruction in coping with stress in the underwater working environment. Emphasis should be placed on in-water skills and comfort, reaction to potential panic situations, effects of stress and fatigue on performance, fatigue prevention, and the recognition of individual limitations.**

**Emphasis should be placed on the importance of in-water skills and comfort during underwater operations. All levels of training should include the reinforcement of basic in-water skills and individual emergency procedures (i.e. loss of air, loss of communications, diver recall).**

In emergency situations, welder-divers should be taught to "stop, breathe, think, and act." In other words, the assigned task should be stopped until the welder-diver restores normal breathing, thinks about a proper course of action to correct the emergency, and acts accordingly.

**Welder-divers should be trained in procedures to increase comfort under normal conditions.** For example, they should receive instruction in maintaining effective welding position, management of umbilicals, and choosing appropriate thermal protection.

**Welder-divers should be trained on the effects of stress and fatigue on performance**. It is important to recognize that individual performance is a function of the perceived stress level. If stressors are completely absent, people may be careless and commit careless errors resulting in poor performance. Conversely, intense stressors can overwhelm capacity, causing other errors and associated poor performance.**Performance can be improved through training by increasing an individual's performance level for a given stress level and by developing response rules or templates. Ultimately, training should attempt to increase an individual's ability to cope when presented with never before seen circumstances; therefore, it should emphasize continuous information processing and decision making.**

**Welder-divers should be trained to recognize and respond to indicators or mental and physical fatigue.** Fatigue and stress are closely related. Underwater welding operations can be highly stressful to the individuals involved. The long term effects of this stress can lead to both physical and mental fatigue which can impair coping capabilities. **Welder-divers should be taught to communicate honestly their fatigue to their supervisor.**

### 4.1.2.5 High stress Training

**In addition to theoretical studies of stress and its effect on underwater welding operations, welder-divers should receive practical, in-water high stress training. The training should be conducted in a safe, controlled environment such as a pool or wet pot and all efforts should be made to simulate realistic at sea conditions. Care should be taken to encourage questions at all stages of the training, where practical, and to debrief all training evolutions.**

### 4.1.2.6 Leadership

**All welder-divers should receive leadership training at an appropriate level.** The critical nature of working at pressure increases the need for every team member to be prepared to assume a leadership role in a time of crises underwater.

One approach to assigning responsibility suggests the use of designated diver levels of responsibility, ranging from the lowest level of diver trainee up to the highest level of corporate authority over diving operations. By being assigned differing levels of responsibility, all diving personnel would know the "pecking order" of the team, and, hopefully, team members would be more likely to assume leadership roles as necessary.

**At the most basic level, all welder-divers should be encouraged to develop safety judgment, to trust that judgment, and, in a time of perceived danger, to take early, decisive, and effective action to correct the situation.**

**Structured leadership training should be formally or informally provided at every level. As welder-divers advance into supervisory roles, they should receive instruction in project planning, project implementation, progress monitoring, personnel management, and motivation in addition to technical competencies.**

### 4.1.2.7 Decision Making/Crisis Management

The importance of decision making during underwater crises cannot be overstated. Consequently, it is recommended that welder-divers recognize the problems and master the skills of an evolving crisis. Specifically, **each welder-diver should be taught to perceive and recognize an underwater crisis, identify problems and causes, identify alternatives and consequences, implement appropriate alternatives, and observe results. Through formal training in these areas and incorporation of prescribed procedures**

**during drills, welder-divers will develop instinctive patterns of corrective actions during a rapidly developing crisis.**

### 4.1.2.8 Conflict Resolution

There is no room for personal or professional conflict during dangerous, high stress underwater welding operations; therefore, **welder-divers should be trained in conflict resolution. Communications, empathetic listening, seeking mutual gain, and emotional control skills training is recommended.**

### 4.1.2.9 Individual Limitations Training

**Welder-divers should be trained that individuals possess strengths and weaknesses which could affect the safety of the individual or the team. Furthermore, welder-divers should be taught to recognize their individual limitations and to notify appropriate team members or supervisors when such limitations may hinder the safety of the operation. It should be stressed that knowing one's own physical and psychological abilities to cope with applied stressors and to recognize when one's performance is degrading due to the excessive stress is the personal responsibility of the individual welder/diver.**

The competitiveness of many diving programs, the "no whining" mentality of many welder-divers, and the internal locus of control often found in divers (Morgan, 1995) combine to produce a dangerous side effect. Often the intense training environment and the competitive nature of young welder-divers leads to attitudes of invincibility and arrogance. Both of which can be extremely dangerous in the underwater environment. Many welder-divers are unable to recognize or reluctant to admit individual limitations for fear of social scrutiny or due to a desire to maximize their diving time. Such behavior can degrade the efficiency of the team and lead to dangerous consequences including danger to the diver.

One method of training welder-divers to recognize their limits under conditions commonly found in the underwater environment involves a one day program consisting of an annual medical examinations for divers, followed by CO2 rebreathing, hypoxia exposure, narcosis exposure, and cold water exposure. A welder-diver who has been through such a program would have a better chance of recognizing when something has gone wrong during diving. Furthermore the welder-diver would have a better knowledge of personal "limits" and be more careful.

### In-House Training Program

**Since underwater welding companies use different procedures and instructions, all welder-divers should, when hired, go through an in-house training program which gives the new employee an introduction to manuals, procedures, and equipment which is used in the actual company. Comparison should be made between procedures learned at dive school and those utilized by diving companies. Areas of special importance for their safety should be pointed out.**

### Communications Training

**Prior to the performance of initial underwater welding, all welder-divers should realize the importance of communications between the welder-divers and the tender, and they should be taught correct communications procedures. Communications procedures must include an emphasis on standardization of phrases and the effective use of "repeat backs." Welder-divers should also be practiced in redundant communications techniques such as line pull signals and hand signals.**

Communications training is crucial to underwater welding safety. Most welding operations require the diver/welder to have two-way phone communications with the surface at all times when the circuit is energized. This two-way phone is the primary means of communicating when the welder-diver needs the welding circuit energized and, more importantly, secured. In the event that the topside phones operator hears any sound other than the predesignated signal for energizing the circuit, the circuit is to be opened immediately. A simple block diagram demonstrating the topside operators role in communications with the diver is provided in Figure 7.

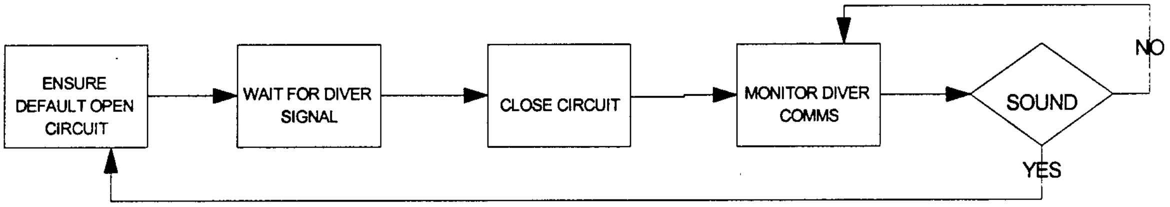


**Figure 7 - Topside Communications with Diver During U/W Welding Operations**

### 4.1.3 Experience

**The experience of the welder-diver should always be weighed when assigning personnel to specific projects. Likewise, more experienced welder-divers should be assigned with less experienced welder-divers whenever possible.**

There is no substitute for quality field experience. Underwater welding is by nature skill-based. The expertise developed by individual welder-divers over years of wet and/or hyperbaric welding is one of the most valuable resources which the relatively young industry possesses. It is difficult to acquire the skills needed to be a successful underwater welder in the classroom or a simulator. While detailed welder qualification procedures are provided throughout this specification, these procedures do not address the value of proven success in actual underwater conditions .

Most industry experts agree that the risk of diving casualties associated with underwater welding operations is significantly lower than risks of diving casualties during general diving operations due to the high experience level of welder-divers.

### 4.1.4 Incentives

**During underwater welding operations, careful consideration should be given to individual incentives provided to the welder-diver to ensure safe operations. The welder-diver should receive incentives promoting reliability and safety over production, schedule, or cost. Directing a welder-diver to perform a task is not the same as providing the welder-diver the incentive to perform a task correctly, efficiently, and safely. Positive incentives are recommended. Such incentives may be monetary or otherwise. Choosing and implementing incentives should be based on the proven motivational value of the particular incentives not on a theoretical or perceived value. Incentive programs should include feedback and monitoring systems.**

**Welder-divers are professionals who command a high scale of pay and incentives should be put in place to ensure they maintain a corresponding high level of professionalism and personal responsibility. They should be held to high standards at all times. Welder-diver personal accountability must be emphasized at all levels, by diving supervisors, company executives, and government regulators alike.**

**Traditionally incentives have been based on the depth of dive. This may not be the best choice of a metric for an incentive system. When developing incentive systems, the variable which represents the most risk should be measured and incentivized. For example, under a depth pay system, the most qualified, experienced diver or superintendent may chose a deeper diver with a simple task over a more risky, shallow dive. As a result a less experienced diver may be placed at the greater risk.**

### 4.1.5 HOF Attributes of Supporting Individuals

**Commercial underwater welding operations involve numerous individuals within organizations which may have a direct or indirect effect on underwater welding operations. While this section specifically discusses the human factors affecting individual welder-divers, a similar level of effort should be applied to the consideration of human factors for each supporting individual involved in any capacity with the underwater welding operations.**

Supporting individuals could include a diving ship Master and crew members, topside contractor personnel, and offshore platform personnel. While an in-depth analysis of HOF for all supporting personnel is beyond the scope of these specifications, the results of studies of HOF in the marine industry overall are available for review. One such study summarizes the causes of severe offshore accidents from 1970-1984 and identifies corresponding initiating events as the catastrophic compounding of human factors. (Bea and Moore, 1991)

## 4.2 Operating Teams

Though the task of welding a bead underwater is normally performed by a welder-diver acting alone, the preparations for that weld require teamwork by a large number of people in many organizations. The complex nature of welding and diving systems, combined with the extensive coordination efforts required in managing marine construction or repair projects, forces all team members to work together to ensure the safety of the welder-diver and the success of the project.

For the purposes of this specification the underwater welding organization has been divided into two subsets, the operating welding team and the administrative organization. The role of the administrative organization will be discussed in the following section.

The operating team, commonly referred to as the dive team, consists of all the field personnel responsible for the day to day operations of diving and underwater welding. The nature of the organization and the dangerous operations which it performs require the dive team members to possess characteristics distinctly different than the other members of the supporting administrative organization.

Emergencies at depth require prompt, instinctive responses by all members of the diving team. Often during an underwater welding accident, there is little or no time to refer to written procedures or geographically distant experts. The consequence of incorrect decision making or even mere hesitation can include serious material damage, injury to the welder-diver, or even the death of the welder-diver.

In general the dive team is made up of one or more welder-divers, one or more diving supervisors, the standby diver, the diver tender, the life support technicians, and other supporting technicians. Details of the duties assigned to each member of the team are provided in the *ADC Consensus Standards*.

The significance of individual preparation was stressed in the previous sections. It is important that each team member has the necessary skills, knowledge, and motivation to perform his or her assignment, but even with the best individual training available, there is still no guarantee that the team will be successful. Certain team attributes are therefore recommended to promote safe underwater welding operations.

### 4.2.1 Process Auditing

**Process auditing is defined as actions taking place to monitor processes and, when necessary, taking actions to correct deviations which lie outside of the established norms. The objectives of process auditing are to ensure that rules and regulations (designed to mitigate risk) are followed and to identify potential sources of risk.**

In other words, any organization attempting to maintain a high competency level must have a method in place for objectively monitoring and improving its processes, a self evaluation. The degree of formality of such a program is dependent upon the size of the group, the complexity of the task at hand, and the resources available to perform the process auditing function.

**At the dive team level, process auditing involves a series of ongoing checks to spot expected as well as unexpected safety problems. Process auditing steps should be included in pre-project preparations, pre-dive preparations, and post project debriefings at a minimum. Recommended sources of information used in process auditing include diving and treatment records, individual dive logs, safe practices/operations manuals, Job Hazard Analyses (JHA), and comments from dive team members.**

## 4.2.2 Culture

**Ideally, the dive team possesses a well planned safety culture developed by the senior level management of the diving contractor's organization. Often, however, the parent diving organization's culture may not strongly influence an operating dive team which is deployed offshore. In this case the dive team's culture is developed within the team itself and may often influenced by the culture of the working environment around it, i. e. the offshore rig's culture.**

**Three characteristics which are normally found in the cultures of effective organizations include focus on reliability, focus on teamwork, and effective crew resource management.**

### 4.2.2.1 Focus on Reliability

By focusing on organizational reliability of the underwater welding team, overall personnel safety and project quality can be improved. **All team members should understand their importance in ensuring the safety of the operations. The culture of the operating dive team should include the realization that mistakes will occur, and such mistakes should not be punished in a misguided attempt to promote safety. Rather upon recognizing mistakes, members of the dive team should work with the person(s) making the error by first trying to identify the source of the error and then determining corrective actions.**

**A key element in the dive team's focus on reliability is the concept of safety problem ownership by each individual team member. It is critical that all involved recognize their duty to identify and report potentially hazardous conditions to the level where corrective action can occur.** Without establishing a willingness to accept unavoidable mistakes mentioned above, individuals will be reluctant to report the hazardous condition. The individual welder-diver will be more likely to hide the condition in an attempt to protect himself or his teammate from reprimand.

### 4.2.2.2 Focus On Teamwork

**Every effort should be made to emphasize the importance of teamwork in the success of the dive team. Team members should possess mutual trust, compatibility, the willingness to work together, and an appreciation for the value of cooperation.**

Where underwater welding projects involve the use of specialized equipment or work in extreme or potentially hazardous conditions, an important factor of safety is the degree of team work. In these circumstances **the known or recorded qualifications of team members are not in themselves a guarantee of safety, and the divers should be trained together frequently until the required degree of cohesion and mutual trust is developed.**

If the underwater welding operation is to be carried out in pairs the diving supervisor may establish fixed pairing for the work as it becomes clear which divers work best together. If a more general degree of team unity is required, diving pairs may be switched around, but it becomes important to drop from the team any individual who turns out to be incompatible with more than one or two of the other divers.

**Dive team members should recognize an individual's inability to complete complicated underwater welding tasks alone. Since efficiency in underwater work depends on making the most effective use of the limited number of underwater man-hours per day, cooperation and synergy must be stressed at every opportunity. Additionally, cooperation among team members in recognizing safety hazards or near misses provides redundancy which protects against unsafe operations.**

The same elements of team work which ensure success in welding operations under normal conditions become even more crucial in emergency situations. A growing body of evidence suggests that, **when teams face sudden transitions from routine procedures to a medical emergency, coordinations can break down and conflicts can occur Thus, by establishing team compatibility, cooperation, and trust during daily welding operations, the operating team mitigates the risk of a diving casualty. There are numerous references for developing a teamwork culture. A few basic principles which can be readily applied to underwater welding teams are provided as follows:**

- **Emphasize team basics such as appropriate size, purpose, goals, skills, approach, and accountability.**
- **Set clear rules of behavior for all team members.**
- **Establish urgency and direction to enhance what the expectations of the team are and promote the team's purpose as worthwhile.**
- **Promote demanding performance challenges and challenge the group regularly with fresh facts and information. High performance standards seem to spawn real teams.**
- **Use positive feedback and reward.**

- **Emphasize team accountability not just individual accountability.**

#### 4.2.2.3 Effective Crew Resource Management (CRM)

CRM is a tool to develop an effective culture. CRM, a specific training methodology which has been used extensively by the commercial airline industry, is based on two overarching principles, a focus on admitting infallibility, and the realization of stress effects.

**The goal of CRM is to reduce the frequency and mitigate the consequences of human errors. This goal is accomplished through a three stage process of (1) avoiding as many human errors as possible, (2) containing the effects of unavoidable errors, and (3) attempting to mitigate the consequences of accidents which result from errors.**

**CRM accomplishes these lofty goals through training. CRM requires strong organizational support for concepts taught and recurrent training accompanied by continuing feedback and reinforcement for the practice of effective teamwork.**

### 4.2.3 Risk Perception

Risk perception involves two key elements: (1) Whether or not there is any knowledge that risks exist at all, and (2) if there is knowledge that risk exists, the extent to which it is acknowledged appropriately and minimized.

The second element, the appropriateness of acknowledgment is situation dependent and is greatly influenced by the team's reliability focus. Proper training regarding the potential risks of underwater welding and cures for such risks provides the answer to the first element, knowledge of the existence of risk. A rough framework for such training is provided below.

#### 4.2.3.1 Underwater Welding Risks

**Since underwater welding involves the combination of two highly specialized skills, diving and welding, the associated risks are typically complex. By considering underwater welding as a subtask of diving and diving as a subtask of marine industrial operations a relatively simple taxonomy of underwater accidents can be developed.** One such breakdown of underwater welding accidents estimates that approximately 75% of all underwater welding operations accidents which occur are basic industrial safety accidents, injuries common to all industrial and construction environments (i. e. tripping, falling objects, etc.) Furthermore, it is estimated that approximately 15% of the underwater welding accidents involve diving casualties such as barotrauma, arterial gas embolism (AGE), and decompression sickness. It is estimated that the remaining 10% of underwater welding accidents are the result of conditions unique to underwater welding such as injuries caused by the welding electrode or the ignition of flammable gases caused by the intense heat.

### 4.2.3.2 General Industrial Risks

**Recognition of the general risks associated with industrial work is a key element in ensuring the safety of welder-divers. Often underwater welding safety concentrates on hazards below the waterline: hazards above water must be considered as well. All operating team members must be aware of the risks of performing topside work, particularly when tasks place the welder-diver at risk. For example, care must be taken to avoid actions which may result in falling objects in the area in which the welder-diver is working, entering, or leaving the water.**

Though beyond the scope of this specification, numerous references are available which provide guidance for protecting against general industrial accidents.

### 4.2.3.3 Diving Risk

**The ADC Consensus Standards for Commercial Diving Operations provides guidance regarding general diving risks. Underwater welding teams must be aware of all pertinent hazards which may lead to death or injury from traditional diving disorders, i. e. arterial gas embolism, decompression sickness, barotrauma.. All team members must be trained to recognize and communicate those hazards which are sufficiently risky to cause immediate termination of diving. In accordance with ADC Standards, a system must be in place to communicate the emergency termination of diving.**

### 4.2.3.4 Risks Of Welding In An Aqueous Environment

**Specific recommended safety guidelines are provided in Annex D of these specifications.**

**There are several acknowledged risks common to all underwater welding procedures and other risks which are unique to specific procedures. Complete perception of applicable underwater welding risks should only be evaluated based on the specific welding procedure in use.**

**The general safety risks involved in underwater welding are electric shock, fire or explosion, asphyxiation, and toxic or narcotic effects resulting from presence of certain welding byproducts.**

**Though the use of low level, DC current welding mitigates the risk of death by electrocution, the high electrical conductivity of water does provide the potential for a significant electric shock from an arc welding rig.**

**Due to the increased pressures at depths at which underwater welding is performed, there is an increase in the flammability of materials and explosiveness of gases.**

**In the case of wet welding, there is a risk of the arc creating chemical reaction in water breaking the water down into an explosive combination of hydrogen and oxygen. During repair or salvage of vessels with voids which may contain contaminated material, there is a heightened risk of explosion.**

**The intense glare of a welding arc could cause damage to sight as a result of welding operations**

#### 4.2.3.5 Job Hazard Analysis (JHA)

**One useful tool in identifying and prioritizing risks is the Job Hazard Analysis. A job hazard analysis must be performed in accordance with the ADC Consensus Standards.**

### 4.2.4 Emergency Preparedness

**Operating teams must be prepared for all emergencies. Contingency plans for each likely emergency should be prepared in advance. Emergency response training and practice drills closely simulating actual emergencies should be conducted frequently.**

### 4.2.5 Command and Control

#### 4.2.5.1 Structure

**In order to achieve success, an underwater welding operating team must maintain an effective command and control structure. Though the specific organizational structure and control mechanisms may vary between organizations, it is recommended that the command and control features include an adaptive organizational structure, decision making authority which has been delegated to the lowest possible level, mechanisms by which emergency problem solving and decision-making management can be practiced, and techniques by which fault diagnosis can be taught in complex systems.**

The importance of an adaptive organizational structure can not be overemphasized. A team's structure defines the extent to which the team has a clear chain of command or authority gradient. An adaptive organizational structure is particularly important in underwater welding because of the potential for reliability oriented safety processes to compete with production oriented processes. Specifically, the mission of safely deploying the underwater welder often conflicts with the costly mission of performing the underwater weld.

It is easy to imagine many possible scenarios where the two competing missions could become mutually exclusive. For example, an attempt by an inflexible command structure to prevent a failed evolution during a critical operation could result in an injured welder-diver. In this example the mission of completing an operation on time conflicts with the mission of completing a safe mission. The organization must be flexible enough to maintain production while still knowing when to end the operation due to a risk to the welder-diver.

An adaptive organizational structure also ensures critical redundancy within the organization. A simple example of an adaptive underwater welding organizational structure would be a team which contains two qualified diving supervisors, with both available topside. In the case of a welder-diver emergency, the acting diving supervisor could manage the solution of the welder-diver emergency, but transfer control of the remainder of the operation to the second qualified diving supervisor. If the organization had not been able to adapt in this way all of the welder-divers would be at a greater risk due single diving supervisors required focus on the troubled diver-welder.

**The operating team's command and control should be structured to maintain decision making authority at the lowest possible level. This is often termed "Command by Negation." In other words, more senior level managers monitor the performance of subordinates. Subordinates are allowed to make decisions and act unless the more senior managers say "no" to specific decisions. Not only should the operating team itself be given organizational autonomy, but the welder-divers themselves should be allowed to make decisions at their level in cases where their vantage point affords them the best understanding of the situation.** Put simply underwater welding operational safety decisions should not be made at corporate headquarters and the choice of underwater tools should not be made topside.

### 4.2.5.2 Robustness

Back up systems should exist involving people, procedures, and hardware.

### 4.2.5.3 Use of Drills

**In any system of command and control, emergency problem solving and decision-making management need to be practiced in advance. This can be done through simulator training or by on site training simulations. Drills should be imposed on operating teams. Team members at all levels should be encouraged to develop contingency plans for all possible emergencies and to practice solving welding and diving problems.**

**Similarly, efforts should be made to completely understand all components of the welding and diving systems and sub systems. Symptoms of systems malfunctions should be studied and troubleshooting techniques should be practiced.**

## 4.2.6 Training

**Operating team members should not only train individually but also together as a group to promote team integrity.** Team integrity, the extent to which crew members continue to work together over time or continue to belong to the same unit is necessary to maintain the capability of the operating team.

### 4.2.6.1 Frequency of Training

**Team training should be conducted when a new team is formed, after prolonged non-operational periods, and periodically, as necessary to maintain team operational proficiency.**

### 4.2.6.2 Team training principles

**The following team training principles should be applied to welding team training:**

- **Participant feedback should be encouraged throughout all parts of the training process.**
- **After all simulations, near misses, or actual emergencies, a follow-up analysis of the team's performance should be conducted. Normally this should occur in the form of an informal debrief. Similarly, briefings should be conducted prior to simulated drills, and contingency briefings should be conducted prior to the commencement of operations.**
- **Training focus should be on accident root causes rather than technical proficiency.**
- **Training should place an emphasis on repetition and task variety.**
- **Team members should be trained to cross check one another's performance of critical tasks and non critical tasks when time permits.**
- **All training should include "repeat backs."**
- **Training simulations and exercises should contain sufficient flexibility to allow people some creativity in problem solving.**

## 4.2.7 Communications

**Effective communications must be maintained during operations.** Communications between welder-divers and the surface results in increased flexibility of operation, economy of diving effort, and much greater safety Communication between topside personnel is also critical to the success of the dive team. **The two key methods of communication within the operating team are the dive team briefing and voice communications between topside and the welder-divers.**

### 4.2.7.1 Dive Team Briefing

**Dive team members shall be briefed on**

- **Welding tasks to be undertaken.**
- **Safety procedures for the diving mode and the welding mode.**
- **Hazards and environmental conditions resulting from welding operations which may affect the safety of the operations.**
- **Modifications to the operating procedures necessitated by the specific welding operations.**

**Pre-dive and pre-project discussions should also include promulgation of the project plan, designation of individual responsibilities, and the review of contingency plans in case of emergency**

#### 4.2.7.2 Two-Way Voice Communications During Welding Operations

Three key problems of underwater voice are (1) poor auditory quality of the signal, (2) lack of face-to-face communications, eliminating important non verbal cues, and (3) the stressful environment of the welder-diver. While this combination leads to degraded communications, it can be methodically improved through the use of restricted standardized vocabulary and redundancy through repeat backs.

**When the diver is at the underwater work site, the responsibility for protection against electrical shocks is shared by the diver and the tender. Heightened awareness by the tender is crucial to the safety of the operations. Standardized terminology (e. g. "Make it hot", "make it cold") between all tenders and welder-divers should be determined and utilized. The use of "repeat backs," repeating the sender's signal to verify the comprehension of the receiver, is recommended. Furthermore, the tender must be careful to communicate a response only after the required action has been taken. For example, the tender should first open the knife switch and then indicate to the welder-diver that the knife switch is open.**

### 4.2.8 Team Requisite Variety

**Effective teams should maintain optimum requisite variety. In other words the team should contain a group of members with all the individual knowledge and experience required to assist in making decisions and effecting action Required members of the operating team are discussed below.**

#### 4.2.8.1 Welder-Diver Support

**An adequate number of personnel shall be provided topside to support the welder diver with optimum safety and efficiency. While this number shall vary depending on the particular welding operation, it shall be at least two.**

**One person (the tender) must maintain communications with the welder-diver, transmit his instruction to others, and operate the welding or cutting current knife switch.**

**A second person shall control the amperage and respond to the instructions of the tender. In some instances he may need to be dedicated to tending the diver umbilical and maintaining proper tension or slack.**

#### 4.2.8.2 Life Support Technician

**Each dive team should have a fully qualified diver with extra specialty training enabling him to handle front-line diver emergencies and stabilize them. Such duties should not detract from his diving duties. During underwater welding operations the life support technician, in addition to**

**fulfilling the requirements of the ADC Consensus Standards, should be aware of the potential medical emergencies associated with underwater welding.**

**The Life Support Technician should be keenly aware of the hazardous effects of welding gases on the welder-diver's atmosphere.**

### Senior Diving Supervisor

**A Senior Diving Supervisor is responsible for a number of Diving Supervisors or for a major diving operations where diving is being carried out on a shift basis and where it is necessary to have more than one Diving Supervisor.**

**While it is not the role of the senior diving supervisor to override the actions of another diving supervisor in charge of a specific dive, he should advise the acting supervisor in the interests of safety and efficiency. He should also act as the liaison between the dive team and the customer.**

### 4.2.8.4 Diving Supervisor

The diving supervisor for underwater welding operations is responsible for the safety and health of the underwater welding team. He is required to carry out his responsibilities in accordance with the ADC Consensus Standards for Commercial Diving Operations.

**In addition to the general requirements outlined for diving operations in the *ADC Standard* the Diving Supervisor for underwater welding operations must modify procedures to ensure safe welding operations. Specifically the Diving Supervisor should:**

- **provide necessary modifications to the Safe Practices/Operations Manual**
- **provide necessary modifications to the pre and post dive check lists to include underwater welding operations**
- **perform a Job Hazard Analysis for underwater welding**
- **ensure the appropriate and sufficient breathing mixtures, supplies, and proper equipment for underwater welding**
- **ensure that the detailed briefing of the dive team and support personnel includes unusual hazards associated with underwater welding.**

### 4.2.8.5 Welder/Diver

In addition to the general requirements outlined for diving operations in the ADC standard the Welder/Diver for underwater welding operations must be qualified in accordance with this specification and follow safe underwater welding practices at all times during the underwater welding operations whether on deck or underwater.

### 4.2.9 Incentives

**Team incentives should be implemented to supplement individual welder-diver incentives.** Providing team incentives is often the best way to promote team work the organization. Peer pressure often proves to be more effective at motivating those team members who do not carry their load than does pressure by superiors. For example operating teams should in some cases receive grades or bonuses based on the entire groups accomplishment of group goals, not on the accomplishment of individual goals.

### 4.2.10 Shiftwork and Rest

**A duty schedule, with special attention to the cycle time, is essential to good crew performance.**

**Sleep schedules should be mandated and enforced, especially for operators who perform low-level vigilance monitoring tasks or complex cognitive tasks**

## *4.3 Corporate Administrative Organization*

**There is a myriad of possible corporate organizational designs under which the underwater welding function can be performed. There is no perfect organization for every situation, however, there are key corporate organizational features which are of importance to the safety of underwater welding operations.**

### 4.3.1 Organizational Structure

#### 4.3.1.1 High Reliability Organization

**The organizational structure of an underwater welding organization should be designed to ensure high safety reliability.** Typically, companies are organized by product (project), by function, or by some combination in between. No matter how the parent organization is structured, everyone employed in the component responsible for the underwater welding function is a participant in a high reliability organization (HRO). HRO's are characterized by both advanced technology (requiring specialist understanding) and high degrees of interdependence (requiring generalist understanding) **Adaptive Organizational Structure**

Organizational complexity must be carefully considered in an HRO, such as the underwater welding function of the corporate structure. Steps should be taken to diminish negative consequences of complexity when it is perceived that the organization is becoming dysfunctional.

More specifically **a hierarchy should be developed in case of a mishap. People should be given specific roles in such situations. In order to ensure optimal emergency preparedness, the corporate organization should assume a crisis is going to happen and address the role of the organization in damage control This emergency hierarchy may not be consistent with the routine hierarchy in place in the corporation.**

### 4.3.2 Command and Control

#### 4.3.2.1 Levels Of Authority

**Levels of authority should be defined for normal and emergency operations. Particularly in the event of an emergency, there should be no question of who is in charge of resolving the emergency. While a definite hierarchy should exist, it should not be bureaucratic.**

### 4.3.2.2 Accurate decision making

**Key decision makers in organizations should see the "big picture." Information about risks should flow to those decision makers who can put together warning signals from various areas of the organization, thus forming a picture of a risky or hazardous situation in its early stages of development.**

### 4.3.2.3 Flexibility within formal rules

Flexible decision making is essential in organizations that have potential to create catastrophic consequences but manage to avoid them. **Flexible decision making must span the organization. It should be monitored from the top. Critical decisions are not only pushed down to the lower levels of the organization, but they are made by the individuals most qualified to make them. Low-level managers must draw on the experience of their higher level colleagues.**

**Formalized rules are often a source of risk mitigation, although such rules must be followed and enforced in order to be effective.**

### 4.3.2.4 Communication

**Lines of communication between corporate level and field level operating personnel must be clearly defined and utilized. Corporate level managers must seek feedback from field personnel and trust field expertise in operations.**

### 4.3.2.5 Appropriate Checks and Balances

Organizations in which errors can propagate into catastrophes require checks and balances across activities. **Redundancy in personnel is required so that appropriateness of activities is constantly monitored.** Organizations are more susceptible to risk when they rely on outsiders to set operating or safety standards; therefore organizations should be "self - policing."

### 4.3.2.6 Level of Interdependence

**It is the role of corporate management to manage the level of interdependence among organizational units. Corporate level managers must take responsibility to coordinate resources across all field units and resolve any conflicts.**

## 4.3.3 Organizational Culture

**Organizational culture is the set of important assumptions that members of an organization share in common. Every organization has a culture. It is similar to an individual's personality - an intangible yet ever-present theme that provides meaning, direction, and the basis for action.**

**The internal culture is tutored from the highest level of management. The head of organization should perceive himself to be constantly in a training mode in terms of developing a culture**

### 4.3.3.1 Emphasis On Safety And Reliability.

**Every person is responsible for every safety problem he or she discovers, at least until he or she can find the individual with skills appropriate to the problem's solution.**

The corporate culture is internal, but it often has external consequences. An HRO's culture should include specific characteristics to promote safety in all operations. Failure to develop a strong safety culture in a commercial diving organization could lead to the consequence of severe injury or death to the welder-diver. The practice of safety is not simply a set of protocols using the latest in technology or in the art of human relations. It is a state of mind, of individuals having their hands on the hardware, and of corporate executives isolated on the top floors.

The development of a safety culture begins at the top of an organization and filters down to the front line operations. There is no prescriptive formula on how to develop and maintain a safety culture.

### Support of Training Goals

**Training should not only be done for its own sake but also for the purpose of creating climates of reliability and enhancement. The corporate culture should include support for operations safety training. Classroom training, drills, and exercises must be supported from the top levels of management. Resources should be allocated to ensure the adequacy of training. Safety training programs should be developed which meet the needs of field personnel and are consistent with operational risks**

### 4.3.3.3 Linking of Accountability with Control Systems

**Organizational culture must support the linking of authority and accountability systems with appropriately placed reward and control systems.** For example if an underwater welding company has a true safety culture, then employees should be accountable for safety violations, supervisors should have the authority to enforce safety rules, and incentives should be denied to personnel for violating or not enforcing these safety rules.

### 4.3.4 Process Auditing

**Process auditing refers to regular inspection of operations or processes within the organization. It is intended to ensure that rules and regulations designed to mitigate risk are followed and to identify potential sources or risk.** In order for process auditing to be truly effective an organization must not perform it in a way that yields few results or simply ignores the audit committee's reports.

**Corporate management must determine appropriate auditing techniques necessary to control the safety of underwater welding operations. The following sources may be useful in providing data for audits:**

<u>Management rules and regulations</u>

<u>Work schedules</u>

<u>Operating Procedures (OP's)</u>

<u>Emergency Procedures (EP's)</u>

<u>Diver's Personal Log Book</u> - The use of a welder-diver's personal log book is recommended. Such a log book should be comprehensive as maintained by the welder-diver and periodically audited by the employer.

<u>Diving Company Log Book</u> - The diving company must maintain a detailed diving log covering all aspects of every diving operation that it has conducted.

<u>Chamber Log Book</u> - The diving company should maintain a detailed chamber log covering all aspects of recompression chamber operations that it has conducted.

### 4.3.5 Appropriate Risk Perception

**Managers should understand and contemplate the inherent risks of operations. Underwater welding organizations are capable of contributing great harm to welder-divers and platform inhabitants, yet their managers are often unwilling or unable to recognize this possibility.** As ever more complex systems handle ever more complex tasks, we inevitably build more systems that can fail. Maintenance of corporate memory

Corporate managers must recognize similarities, implement lessons learned, and encouraged synergy across projects. Systems should be implemented to compile lessons learned and retain them over time.

## 4.3.7 Incentives

### 4.3.7.1 Contract Types

Contracts should not be implemented which provide excessive incentives to violate safe diving and underwater welding procedures. For example, contracts should be written which limit the percentage of the operating team which may be allowed to make repetitive dives, not which encourage too many to make repetitive dives, thus leaving no one available to man the chamber in the case of an emergency.

### 4.3.7.2 Employee Reward and Control Systems

Avoiding risk and enhancing reliability requires appropriately designed reward and control systems.

Conflicting goals and poor alignments between rewards and desired outcomes should be recognized and eliminated.

## *4.4 Interfaces*

There are many areas of man-machine or organization-system interfaces in the underwater welding system. The relationships between the individual or organization and the system influences are represented in Appendix G.

### 4.4.1 Operating Procedure/ Welder-Diver Interface

**Operating procedures should be developed and implemented with the limitations of individual welder-divers in mind. General knowledge of the capabilities of typical welder-divers should be combined with judgment about specific welder-divers. In other words, the design of a procedure should consider the capabilities and constraints of the average or representative welder-diver, and the assignment of a specific individual to perform a procedure should include a consideration of that specific individual's capabilities relative to average welder-diver for which the procedure was designed.**

Perhaps the most useful tool for tracking an individual welder-diver's capabilities is the diver's personal log book. The ADC Consensus Standards requires that the log book details all dives. Many in the industry believe that such a document should be comprehensive. It is recommended that in the case of underwater welding that such detail include specific details of welding procedures which were performed. Such documentation allows the log book to later be used as a tool for assignment of individual welder-divers.

#### 4.4.1.1 Task Considerations

On-line emergency procedures which are developed should be brief and succinct so that persons carrying out the emergency procedures understand them clearly and do not waste time interpreting the action(s) to be taken.

Procedures should be phrased as actions to be taken, not as prohibited actions or system state descriptions. At the procedural level there is no need to include theory or explanation which may confuse the operator. Also processing what should not be done uses up valuable time in which the necessary action could be taken.

#### 4.4.1.2 Function Allocation

Function allocation refers to the conscious design decisions which determine the extent to which a given job, task, function , or responsibility is to be automated or assigned to human performance. Such decisions should be based upon aspects of task loading and precision requirements.

Automating some tasks can obviously be effectively used to reduce the number of tasks performed by a welder-diver, but automation should not be considered the best action in all circumstances. Precision requirements must be analyzed. Often those tasks which require a large amount of task feedback aren't well suited for automation. On the contrary, tasks which do not require task feedback and have a low error tolerance are well suited.

#### 4.4.1.3 Stress Loading

Due to the numerous stressful environmental conditions which are inherent in underwater work, procedures should be designed to minimize the stress imposed on the underwater welder. Such stresses can categorized as two general types, speed stress and load stress.

Speed stress is a function of the rate at which signals from the environment (i. e. voice communications, visual observations of the welding arc, line pull signals ) impinge upon the welder-diver's senses. Procedures must be developed in an effort to ensure that the welder-diver is provided with adequate time to perform tasks and assure that safety shall not be compromised for the sake of speed.

Load stress is related to the number of independent streams of signals or information sources which the diver/welder is required to monitor. To minimize load stress on the welder-diver, it is recommended that an emphasis be placed on the performance of tasks topside or by other supporting divers.

Since work under pressure places a tremendous strain on the welder-diver and fatigue increases stress on the diver, procedures should be designed which limit the amount of time an individual welder-diver is deployed.

Put simply, maximizing work performed topside, scheduling adequate time to complete underwater tasks, minimizing welder-diver deployment time, and providing sufficient diver support are the best defenses against welder-diver stress overload.

Interestingly, a lack of sufficient stress can also have a negative effect, manifesting itself as stress underload. Research demonstrates that not having enough stimulation can dull a worker's perception of stimulus. Once the welder-diver is in position, welding the tender is often subject to this phenomenon. Diver tenders often experience stress underload in the form of failure in vigilance performance. For example, in monotonous and boring surroundings, the ability to detect infrequent, irregular, and often indistinct signals is often diminished.

### 4.4.2 Procedure/Operating Team Interface

The design and implementation of operational procedures must include consideration of numerous organizational factors of the underwater welding team. It is important that the operating team be allowed to provide input to planners of the construction process. It is equally important for the operating team members to be allowed to provide feedback to all procedures which affect the safety of operations.

### 4.4.2.1 Effective Development of Procedures

Three major areas have to be dealt with in the development of procedures: (1) technical content, (2) presentation, and (3) the potential errors and their consequences. Procedures should be correct, accurate, complete, well organized, well documented, and not especially complex. (Bea, 1997)

Exercises should be implemented to test the coherence and adequacy of the specified actions.

Particularly where actions cannot be reversed once performed, specific means should be proved to confirm that the chosen procedure is the correct one for the particular situation at that time.

The presentation should be adapted to the level of education or training required and to that which is consistent with the operators educational background.

Procedures should show different actions which are taking place in parallel.

### 4.4.2.2 Construction Planning Procedures

The diving supervisor should be included in formulating construction plans and procedures. In most cases he should be included in the planning process well before the arrival of the operational team on the underwater construction site. In many cases the diving supervisor is management's only expert in the capabilities of welder-divers and in recognizing conditions which are hazards to underwater welding operations.

#### 4.4.2.2.1 Explosive and Hazardous Materials

During welding operations in areas potentially containing explosive or hazardous materials as built drawings should be studied to identify all areas in close proximity to the work area which could contain or might entrap explosive gases. Cargo manifests should be reviewed to identify explosive material and the location of such material. Procedures to vent areas containing such hazardous materials should be designed.

If wet welding is to be performed in a confined space or under structural members of shapes that would hold rising gas bubbles, vent holes should be made to preclude gas entrapment, particularly, at depths below 66 fsw.

#### 4.4.2.2.2 Dry Hyperbaric Welding

Dry hyperbaric safety precautions shall include all of those required for welding in wet, constrictive space above water. "Blow-down" procedures for removing water from habitats must be determined prior to commencing operations.

#### 4.4.2.2.3 Hot Tap Procedures

The operating team must be included in determination of procedures which are to be used for hot tapping of any existing pipelines.

#### 4.4.2.3 Operating team feedback

Procedures which are most affected by their interface with the operating team include not only welding and diving procedures but also inspection and lock-out/tagout procedures. The welding operating team should be involved in providing feedback to the development and maintenance of these procedures.

### 4.4.3 Operational Procedure/Corporate Administration Interface

Corporate level management ultimately has the responsibility of ensuring that operational procedures are updated to reflect the most current information available.

In addition to having the responsibility for quality assurance of operational procedures, the corporate organization is also responsible for maintaining numerous administrative procedures important to welding and diving. These procedures include but are not limited to the following:

- medical staff procedures
- accident reporting procedures
- contractor/subcontractor selection procedures
- systems inspection maintenance and repair procedures
- internal audits and management review procedures

#### 4.4.3.1 Emergency Response And Control

Corporate office personnel must take responsibility to proactively maintain up-to-date instructions and procedures for safe operations of underwater welding teams in the field. Contingency procedures and emergency response procedures should also be maintained for those most likely emergency situations.

Accident reporting procedures should be enforced from the corporate level. The value of accident reporting is in providing lessons learned and in establishing databases for better management of resources to prevent serious accidents. Accident reporting procedures should emphasize the use of accident reporting as a safety performance improvement tool not as career ending device.

### 4.4.4 Delivery Structures/Welder-Diver

For the purposes of this specification, delivery structures are defined as those items used for delivery of welder divers to the work area and structures which physically support the welder-diver during operations.

This includes stages, habitats, and rigging. Parameters of concern for these structures include structural design and, in the case of habitats, ventilation and background gas constitution.

#### 4.4.4.1 Load Design

External forces exerted on the weld habitat by wave loading must be considered in the design of the habitat.

The weld habitat is designed and custom-built to accommodate braces and other structural members whose centerlines may intersect at or near the area that is to be welded.

Size and configuration of the habitat is determined by dimensions and geometry of the area that must be encompassed and the number of welders that will be working in the habitat at the same time.

#### 4.4.4.2 Rigging Systems

The numerous methods of rigging prohibit providing specific directives for rigging. All rigging components should be properly weight tested, inspected, and maintained. Rigging systems which are required to maintain the safety of the welder-diver should include adequate redundancy. All lock out/tag out rigging should be monitored regularly to ensure proper maintenance.

#### 4.4.4.3 Welding Habitat Ergonomic Considerations

Care must be taken to ensure welder-diver comfort and that utility is designed into a habitat prior to fabrication. This can be done through the field of Ergonomics. Ergonomics should be applied in the early phases of the design, that is in the concept, planning, and initial design steps of [habitat systems]. In other words, ergonomics needs to be proactive instead of reactive

Applicable data from ergonomic handbooks should be utilized when possible in the design of welding habitats. This data includes:

- anthropometric data such as human body dimensions, reach capabilities, and muscular strength
- human sensing capabilities such as sight, hearing, touch, etc.
- human motor activities
- human reactions to the physical environment such as heat, humidity, vibration, noise, and pressure.

Due the numerous variations of structural configurations being prepared, hyperbaric welding habitats are often unique in design. It is typical for specific habitats to be designed and built from scratch to meet a specific need. Consequently, the re-use of such habitats may be limited so the improvement of that specific habitat is not likely. Likewise, it is difficult to improve ergonomics of a given habitat prior to performing a repair project because the already high cost of constructing a unique habitat prohibits the construction and testing of a prototype. Also, the urgency of repairs places time constraints on completion.

Welding habitats meet the established definition of confined spaces. (1) They are large enough and so configured that an employee can bodily enter and perform assigned work. (2) They have limited or restricted means for entry or exit. (3) They are not designed for continuous human occupancy and have a known potential to contain a hazardous atmosphere. Welding habitats should therefore be designed to incorporate principles of confined space entry.

In addition to design consideration for surface confined spaces, designers and fabricators should consider the pressure effects imposed on welding habitat systems. For example, the use of Argon in welding gas is known to multiply the narcotic effect on a welder-diver at depth. Argon has narcotic effect of approximately twice that of nitrogen.

A welder-diver may often be required to dive into a maze of complex instruments, projecting arms, piping, lines, and hoses and perform multiple tasks. Prior to navigating such structures, welder-divers should familiarize themselves with the layout of the structure using drawings on the surface.

### 4.4.4.3.1 Dry Hyperbaric Welding

when air is used as the background gas, the weld chamber can be continuously or intermittently vented to avoid accumulation of fumes and smoke. The high cost of mixed gas precludes venting, so smoke and fume scrubbers must be used in the chamber. If high $PPO_2$ of the background gas exists the welder's exhaust gas must be discharged outside the chamber by means of an overboard dump system.

In many circumstances breathing gas composition must be monitored for levels of $O_2$, $N_2$ and He. A welding gas absorber may be required to remove the welding gas and to dissipate heat. There are many impurities which tend to accumulate in the breathing gas including $CO_2$, CO, methane, dust, etc...(Lubitzsch et al, 1986)

According to ADC, each diving contractor should have an appointed safety director designated in writing by an officer of the company whose specific tasks include dictating the background gas mixture to be used in dry hyperbaric welding and determining the need for equipping the dry hyperbaric chamber with a high-pressure water spray system. Ergonomics of the habitat also include consideration of the size, geometry, and layout of the welder-diver's workplace.

## 4.4.5 Delivery Structures/Operating Team Interface

The operating team is responsible for the safe installation and operations of the all welder diver delivery structures including welding habitats.

### 4.4.6 Delivery Structures/Corporate Administration Interface

The corporate administration is responsible for assuring proper design, inspection and repair of all delivery structures.

### 4.4.7 Equipment/Welder-Diver Interface

Ergonomics of diver/welder equipment should be considered in order to minimize the demands placed on the welder-diver. Design of the hardware and software with which the welder-diver is given to work must be consistent with the behavioral and physical capabilities and limitations of that employee as an operator. General ergonomic design solutions which should be applied to underwater welding equipment include the following:

- Use of familiar elements and elimination non-essential elements.
- Display of information that is directly necessary.
- Highlighting of important information.
- Integration of displays.
- Work up training on new equipment

#### 4.4.7.1 Awareness of System Causes Of Accidents

Operators must be aware of subsystems serving multiple and incompatible functions. When systems are supposed to act independently of one another but are in close proximity there is the greater possibility they will interact, leading to disaster. Tightly coupled systems are prone to accidents. Such systems involve more time dependent processes, invariant sequences, little slack, and overall designs that allow only one way to reach a goal. Color coding is often a useful tool in preventing erroneous subsystem interactions.

#### 4.4.7.2 Redundancy

Redundancy in equipment is required so that appropriateness of activities is constantly monitored.

##### 4.4.7.2.1 Thermal Protection

Care should be taken to maintain the proper temperature or the welder-diver through the use of passive or active insulation. Passive insulation (i. e. wet or dry suits) protects the welder-diver from the cold through a layer of insulation. Active insulation uses an outside heat source, hot water or an electrically heated garment, to warm the diver-welder. When using hot water suits care should be taken not to scald the welder-diver. Often this can be accomplished by adjusting the water temperature at the beginning of the dive only.

A significant major thermal encountered by working welder-divers is that of progressive hypothermia. It starts with the limbs and body regions most poorly perfused or distant from the core. The principle avenues of heat loss for immersed divers are convection, which is relatively constant in magnitude for all depths, and respiration heat loss, which increases with depth of the diver and becomes the major avenue of heat loss for depths greater than 600 feet (Kuehn and Acklesn 1978).

Mental function becomes quickly impaired with hypothermia. When this occurs, the individual may become semiconscious, confused, disorientated, introverted, and upon recovery have amnesia. In potentially hypothermic conditions, coldness of the skin to the point of pain, and intense uncontrollable shivering are indicators of rapid heat loss. If either sign is not apparent to monitors due to diver unawareness or unwillingness to inform, then confusion and irrationality in the diver's verbal communication may review his condition. It is important to realize that most divers expect to be cold and may have a tendency not to complain about it. They should be encouraged to complain

A diver's evaluation of their thermal balance may vary greatly. When heat loss takes place over a prolonged period or time, the diver is more likely to misjudge his/her thermal state than one who cool rapidly A small loss in core temperature may result in loss in mental capacity, memory, muscle strength, and dexterity. These effects can be furthered magnified by nitrogen narcosis.

### 4.4.8 Equipment/Operating Team Interface

The proper interaction between the operating team and the equipment is crucial to safety of underwater welding systems. The operating team's interface with the equipment manifest itself in all phases of the system's life cycle. Though this document is primarily concerned with system operations, it is recommended that the operating team play a crucial role in equipment design, and the inspection, maintenance and repair (IMR) for underwater welding systems.

#### 4.4.8.1 The Operation of Systems

As earlier described, operators must be aware of the systems causes of accidents. Each equipment operator within the team should understand the role of the specific piece of equipment within the system in order to recognize potential system failures which could result. It is important for equipment operators to recognize equipment malfunctions immediately and provide sufficient feedback to allow the diving supervisor to take corrective action.

#### 4.4.8.2 Operations Feedback To Design

Members of the underwater operations team also have a duty to provide feedback for equipment design improvements to equipment designers. It is recommended that each operating team provide a process for such feedback.

#### 4.4.8.3 Inspection, Maintenance, and Repair (IMR)

While it is recognized that in many organizations operating teams do not perform maintenance and repair of their equipment, operating teams also have a duty to provide feedback inspection maintenance and repair of underwater welding equipment to appropriate maintenance personnel. It is recommended that each operating team provide a process for such feedback.

### 4.4.9 Equipment/ Corporate Administration Interface

The corporate organization has responsibilities to ensure that operators have access to the equipment they need to properly perform the tasks assigned. Meeting this responsibility requires design of special tools for special jobs, research and development of new tools and techniques, and appropriate allocation of resources including tools and job aids. Job aids (e. g. operational or maintenance manuals and hazard warnings) should be prepared to enhance their use by a welder-diver to assist in performing the required job.

# 5. Analysis and Evaluation of HOF Applications

Once the HOF applications were developed, an attempt was made to determine the usefulness of each one by applying each to the analytical model. In order to provide a baseline for comparison, the probability of system failure was determined assuming no HOF applications have been applied to the system. (See Appendix I.) This baseline was based on the fragility analyses described in the analytical model section. No provisions for detection or correction were included. The welding safety subtasks were selected based on information from the literature, expert interviews, and the author's personal experience. The results indicated an extrinsic probability of system failure in the welding component as 3.48%. It is important to note that while this is high system failure rate, it is based the application of no HOF measures, no mechanical correction or detection measures, and it is primarily calculated as a relative risk used for comparison with systems with the HOF applications applied.

The mechanism for system improvement of each application has been classified as either error mitigation, detection, correction, or fragility improvement. (See Appendix J.) Each of the HOF applications were placed in the model based on these classifications. If an HOF application improves the probability of detection of a human or organizational error, a determination of the new probability of detection given that application was applied to the model. For example, if implementation of training program to teach welder-divers to properly perceive the risk of explosions in welding habitats could double the probability of the detection of explosion risks, the P(D) would double in the explosive safety subtask.

Just as an HOF application can improve the probability of detection, it can also improve the probability of correction. An improvement in the probability of correction increases the probability that the system will not fail due to a human error because it will be corrected prior to the occurrence of system failure. For example, conducting drills can greatly increase the probability that a welder-diver would correct an unsafe condition.

The probability of system failure can also be decreased using an improvement in the system's fragility, thus increasing the system's human error tolerance. For example, medical examination of welder-divers can screen out candidates who are prone to heart failure or respiratory illnesses.

Perhaps one of the most difficult yet important judgements that must be made in employing this model is determining the correlation between probabilities of human errors. By default the model assumes that the occurrence of HOE is statistically independent, and therefore uncorrelated ($\rho=1$). Some organizational factors can increase the correlation between human and organizational errors in subtasks. For example a strong organizational safety culture has a tendency to correlate the risks of human error between subtasks. In these cases, the probabilities of human error should be assumed to be perfectly correlated, ($\rho=0$).

All HOF applications were considered for testing. Several such as diet were considered to have an insignificant effect on human organizational error and were therefore not tested. Some HOF applications, such as selection based on education, were considered to be to difficult to estimate their effects and as a result were not tested. Additionally, the direct effects of corporate administrative recommendations were determined too difficult to quantify and were therefore not tested.

Twenty-nine of the recommended HOF applications were tested using the process. The results were ranked based on ascending probabilities of system failure given the HOF applications. These results are provided in Appendix K. Two example model calculation spreadsheets are provided in Appendix L. The choice of these two HOF applications was based on concerns expressed by two underwater welding industry experts.

One expert suggested that most accidents he has seen in over twenty years of underwater welding operations could have been prevented if superintendents did not intimidate welder-divers and prevent them from expressing confusion or fear about an operation. Training welder-divers to recognize there limits and to communicate their concerns to the diving supervisor is one way to respond to this problem. Implementation of such a training program was tested using the model. It was assumed that such a training program would reduce the probability of human error in all subtasks by fifty percent. It is also true that instilling an attitude that it is okay for an operator to know his limits and to speak up about any such concerns would correlate the probabilities of human error. Perfect correlation was assumed. Based on these assumptions the probability of the welding system failure in safety was determined to be 1.12%. This represents a 68% decrease in the probability of system failure.

Another industry expert suggested that welder-divers cannot be electrocuted from the underwater wet welding. In an attempt to verify this, standard detection and correction measures for DC welding equipment electrical safety were tested using the model. It was assumed that there was no correlation between the probabilities of human error. As shown in Figure 8 there is a .012 probability that the welder-diver will commit an error.

It was assumed that there is a 90% probability that the buddy diver would observe that the welder is between being shocked. Once the error is detected by the buddy diver or welder, proper corrective action may or may not be taken.

If the buddy diver does notice and takes proper action, he will tell topside to de-energize the welding generator by merely saying "power off." Topside personnel should respond by immediately backing away from the power switch if it is open or opening the knife switch if the system had been energized. Again the action of the topside switch operator is a function of his training and experience, stress, and alertness. It was assumed that there is a 75% probability that the topside personnel will correct the situation within the three seconds recognized as the amount of time needed to stop the heart. Using the model the probability of death through electrical shock was determined to be .12%. This is a significant improvement, but it still represents a risk of electrocution to the welder-diver. As shown in Figure 8, underwater welding circuits are required to have an installed ground fault indicator which acts to provides a redundant system for opening the circuit. It is important to note that this device was not included in the calculations, but it is shown in Figure 8.

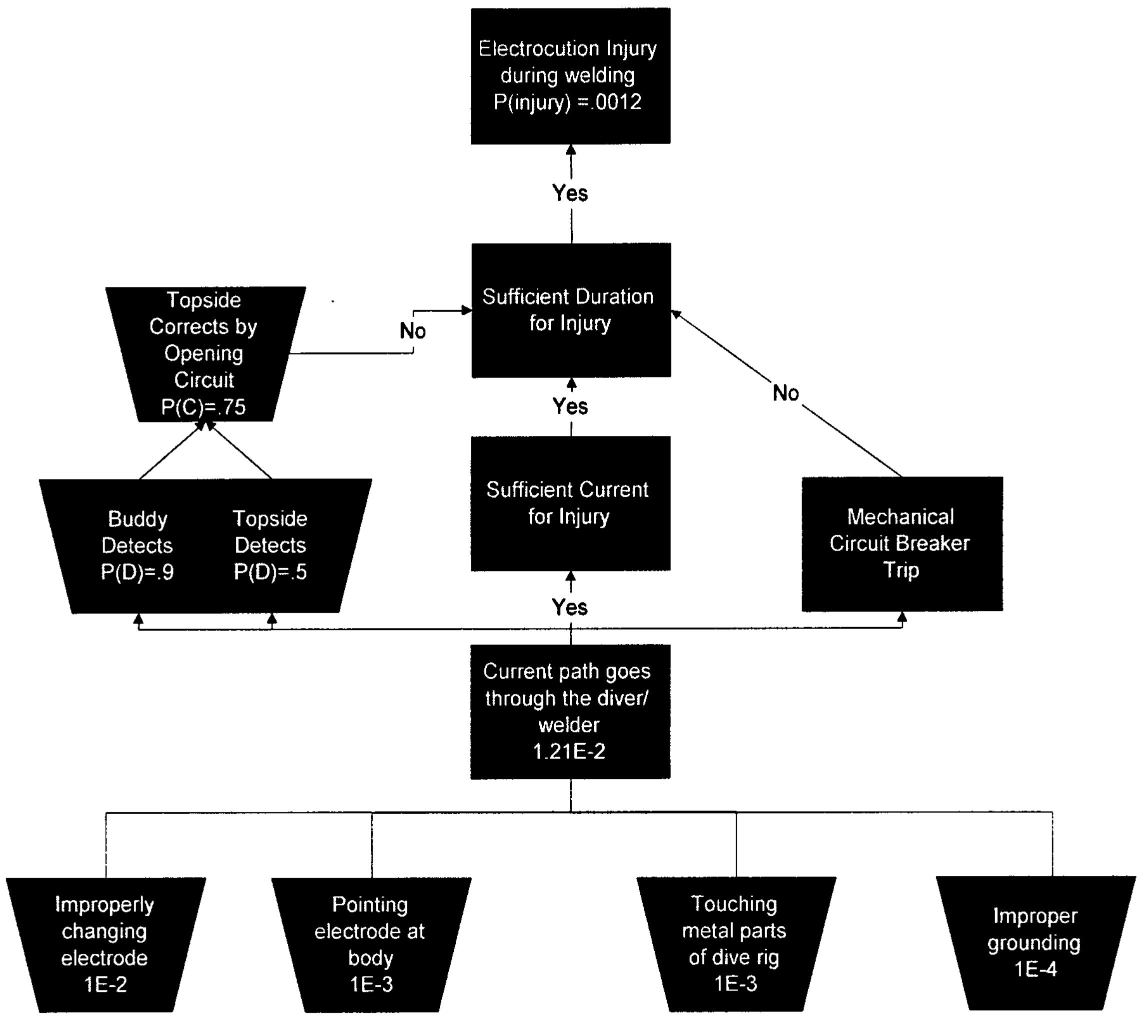


**Figure 8 - Fault Tree for Diver Electrocution**

# 6. Conclusions

1. No comprehensive database exists which includes accurate accident data for underwater welding or the broader category of commercial diving. Neither commercial diving organizations nor insurance companies maintain such an industry-wide database. While several diving companies claim to maintain accurate records of their companies diving accidents and near misses, few or none were willing to make this information available for this study. In general diving companies appear reluctant to release accident data to the public.
2. The reluctance to maintain an accurate accident database has led to a dangerous industry-wide misconception that commercial diving is relatively safe, and there is little or no need to devote substantial resources to improvement of commercial diving safety. When questioned privately, "off the record," most individuals involved in commercial diving were able to cite several specific diving accidents with which they had first hand knowledge.
3. One study conducted on the causes of diver fatalities concluded that only 18% were caused by intrinsic causes (equipment) while the remaining 82% of the causes were related to human and organizational factors. Similarly a study of offshore welding accidents in the GOM found over 90% of the accidents to be caused by HOF. Based on these statistics the development of HOF techniques is critical to the underwater welding industry.
4. Currently, no industry specific HOF standards or specifications exists. Those HOF specifications which do exist are generally broad in nature and are not reflect an operational focus.
5. Accidents in underwater welding should be classified as industrial accidents, accidents associated with diving, and accidents unique to welding underwater. Most industry experts believe that topside accidents, those resulting from general occupational hazards, account for the majority of the accidents which occur in underwater welding. While general industrial accidents may occur at the highest rate of any of the three types of accidents mentioned, typically the consequences of these accidents are not as severe as those occurring as a result of the diving process or the underwater welding process.
6. The sources of potential failure for underwater welding, defined as major injury or loss of life to the diver/welder, were classified as diving accidents, explosions, electrocution, and rigging accidents.
7. Based on personal interviews with several underwater welding professionals, the accident rate for underwater welding operations is considerably lower than the accident rate for general commercial diving operations. This lower rate is attributable to the significantly higher amounts of experience underwater possessed by welder-divers in comparison to general divers.
8. A deterministic model was utilized to calculate the probability of death or serious injury as the result of human or organizational error in the welding task of underwater welding as 3.48%. This result is

intended to represent a worst case scenario where no consideration is given to extrinsic causes of underwater welding accidents. Though common sense dictates that this probability of failure is too high, it does provide an effective measure of relative risk for comparison of the effectiveness of prescribed HOF applications. When tested using this model the HOF applications of panic and stress screening, frequent team training, entry level welding training, dexterity screening, and communications training were determined to be the five most effective HOF applications which should be incorporated into an underwater welding system.

9. Several hypothesis were developed primarily as the result of qualitative information collected from this study. These hypothesis are included below:

- While electric shock in underwater welding is normally the result of error by the welder-diver, the severity of the injuries resulting from this shock depend greatly on the proper function of the welding team.
- Impact injuries occurring during rigging operations are generally the result of organizational errors.
- Explosions also tend to be affected more by organizational errors than individual diver-welder errors.

# 7. Recommendations

1. Efforts should be made to better diagram the underwater welding safety processes incorporating more first-hand knowledge by underwater welding experts.
2. More research should be conducted to more accurately determine the explosion, respiration, and impact fragility analyses.
3. The current draft of the HOF annex should provide more specific HOF tools, and its language should be simplified to promote ease in understanding and use in the field.
4. All of the recommended HOF applications should be tested, and the outcome of these tests should be used to prescribe applications to be included in the HOF Annex. The output of the model should be used as a first attempt to determine the HOF applications which are the highest priority for underwater welding operations.
5. A questionnaire should be developed for distribution to underwater welding experts asking them to provide specific applications which they have used successfully to prevent human and organizational errors.
6. A similar full schema, life cycle analysis should be made of the underwater welding process in which weld quality and durability are defined as the quality attributes of interest.
7. According to members of the AWS D3b subcommittee, the analyses of wet welding and dry welding should be conducted separately. Preferably, dry welding should be studied first because less safety information is currently available for dry welding than for wet welding.

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# IEEE Guide for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations

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# Foreword

(This Foreword is not a part of IEEE Std 1023-1988, IEEE Guide for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations.)

The need for the application of human factors engineering (HFE) in the design, operation, testing, and maintenance of nuclear power generating stations has been demonstrated by plant operating histories and regulatory and industry reviews. Prior to the incident at Three Mile Island-Unit 2 (TMI-2), little guidance for the application of HFE in nuclear power plants existed, even though well established HFE principles were available and routinely applied to aerospace, defense, and other industries. Studies of operational nuclear power plants prior to 1980 found that many did not reflect the application of HFE in the design. The evaluation of the TMI-2 incident revealed that proper application of HFE in nuclear power plant design could contribute to reducing human errors and could improve accident prevention and mitigation. Based on this potential for improving nuclear plant safety, the Nuclear Regulatory Commission (NRC) began instituting guidance for the incorporation of HFE principles in the design of nuclear power plants. In 1981 the NRC published NUREG-0700, Guidelines for Control Room Design Reviews,[1] which provided HFE criteria for evaluating existing nuclear plant control rooms and those under construction. During this same time industry groups such as the Electric Power Research Institute (EPRI), the Institute of Nuclear Power Operations (INPO), and others also provided research, studies, and methodologies to support the application of HFE to further the safe operation of nuclear power plants.

The intent of this guide is to provide guidance to management and engineers to develop an integrated program for the application of HFE in the design, operation, and maintenance of nuclear power generating stations. In both the design and construction of new nuclear power plants and operation and maintenance of existing nuclear power plants, the design or modification of man-machine systems is being undertaken. Typically, many diverse activities are being conducted independently, for example, design, construction, and development of operating, maintenance, and testing procedures.

The above mentioned activities should be integrated to obtain an acceptable level of man-machine performance. An ongoing program is needed to ensure that HFE is an equal design consideration with the traditional engineering disciplines in those activities that have a significant human interface. A significant human interface is defined as an interface between personnel and equipment, facilities, software, or documentation, where the resulting human performance is a determinant in the achievement of system performance. The definition for significant human interface does not include those interfaces covered by Occupational Safety and Health Administration regulations and standards pertaining to the general safety and health of employees.

This guide is intended to provide overall guidance for establishing a program for the application of HFE to systems, equipment, and facilities of nuclear power generating stations. It is applicable to new facilities or modifications to existing facilities. Guidance is provided on the program organization and applicability, the plant design aspects to consider, the HFE methodologies that may be used, and a typical program plan for the application of HFE.

It is intended that this guide will be a top-level guide under which additional IEEE Standards may be written to provide guidance for carrying out various specific aspects of the HFE program plan. It is expected that these IEEE Standards may address such areas as methodologies for evaluating man-machine performance, methodologies for considering human reliability, man-machine interface design criteria, and others.

This standard was prepared by a Working Group of Subcommittee 7, Human Factors and Control Facilities, Nuclear Power Engineering Committee of the IEEE Power Engineering Society.

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# IEEE Guide for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations

## 1. Scope

This document provides guidelines for applying human factors engineering (HFE) to the systems, equipment, and facilities that have significant human interfaces in nuclear power generating stations.

## 2. Definitions

**human factors engineering (HFE).** An interdisciplinary science and technology concerned with the process of designing for human use.

**an-machine interface (MMI).** The devices through which personnel receive information from the system or process and the devices through which personnel exercise their control of the system or process.

**significant human interface.** An interface between personnel and equipment, facilities, software, or documentation, where the resulting human performance is a determinant in the achievement of system performance.

## 3. Planning for Human Factors Engineering

Human factors engineering (HFE) should be considered an integral part of the design, operation, testing, and maintenance process. HFE is best implemented with a coordinated plan. Multiple discipline functions (for example, HFE, instruments and controls, nuclear engineering, operations, testing, and maintenance) may be needed in the process as required by the scope of the task.

Some of the activities which may be necessary are:

(1) Determine the relevance of various HFE studies, reports, and other pertinent documents.

(2) Conduct HFE reviews.

(3) Investigate current design practices to identify HFE concerns.

(4) Establish trade-offs of HFE considerations with design, operation, testing, or maintenance considerations.

HFE should be considered an ongoing activity with respect to any future design, modification to existing designs, or evaluation of existing designs. Since the application of HFE affects all aspects of plant design, operation, testing, and maintenance, HFE should be applied as early as possible. Follow-up reviews should also be established to confirm effectiveness of resulting HFE decisions (see 6.3).

## 4. Fundamental Considerations of Human Factors Engineering

Implementation of an effective HFE process should consider the following aspects which are described separately in 4.1 through 4.6.5.

(1) Tasks
(2) Environment
(3) Equipment
(4) Personnel
(5) Nuclear operations
(6) Documentation

### 4.1 Task Considerations

**4.1.1 Function Allocation.** Function allocation refers to the conscious design decisions which determine the extent to which a given job, task, function, or responsibility is to be automated or assigned to human performance. Such decisions should be based upon aspects such as relative capabilities and limitations of humans versus machines in terms of reliability, speed, accuracy, strength and flexibility of response, cost, and the importance of successful and timely task or function accomplishment to successful and safe operations. A wide variety of allocations is possible, ranging from totally automated functions with personnel merely overseeing and monitoring machine performance, through totally human dominated manual tasks. At the finest level of refinement, function allocation also includes determining specific roles and responsibilities of various personnel operating as a team to accomplish the function.

**4.1.2 Task Loading.** The extent to which the demands of any given task or group of tasks tax the attention, capacities, and capabilities of personnel (individually and as a crew) in the system and thus affect performance should be considered. The human's responsibilities in the whole should be designed to provide adequate loading.

At the extremes, performance will suffer when humans are overloaded or underloaded. Overloading can take the form of requiring personnel to keep track of, and attend to, too many factors at the same time (sometimes referred to as channel stress) or requiring response at a rate beyond the human capability (speed stress). Performance will degrade under nontaxing, nonarousing, nonstimulating, underloading conditions, all of which lead to boredom and inattention.

The format of and rate at which data are presented to the human is a task loading consideration. Also, the physiological limitations of the human body, such as strength, endurance, range of motion, and the capability to apply force or torque can be challenged by the design and requirements of a given task.

**4.1.3 Precision Requirements.** Jobs, tasks, and functions should be designed to be compatible with human capabilities with respect to accuracy and precision. Concepts such as the manipulatory abilities (for example, dexterity) and discriminatory abilities in applicable sensory modes (for example, vision, audition) should be considered. Both absolute one-time precision and permitted variability over repeated or sustained efforts should be considered.

**4.1.3.1 Task Feedback.** The effect of task feedback on accuracy should be considered. Task feedback should be provided by direct variable measurement wherever practical. When precision or accuracy of performance is required, immediate meaningful feedback on the adequacy of performance should be provided. Performance will be affected by such factors as the delay of feedback response and the format and precision of the feedback information.

**4.1.3.2 Error Tolerance.** The consequences of and tolerance to human errors in performance should be considered. The system should be designed to permit recovering from those errors which do occur. Should error consequences be unacceptable, interlocks should be provided, where practical, to reduce the possibility of the errors.

**4.1.4 Training.** Training should be considered to the extent that it affects the implementation and utilization of the equipment and procedures. Design conventions such as color codes, configuration coding, and standardized directions of motion are seldom self evident and will only facilitate operator action if such conventions have been explicitly provided to personnel as part of their training. Hardware and documentation can be effectively utilized and maintained only by properly trained personnel.

### 4.2 Environment Considerations.

**4.2.1 Temperature, Airflow, and Humidity.** There are certain limits in temperature, airflow, and humidity which define a comfort zone preferred by personnel. Exact limits vary with the nature of the activities being performed. When conditions exceed these limits, decrements in human performance may occur, either from a lack of concentration induced by discomfort or, as the limits are greatly exceeded, limitations due to either additional clothing or actual physiological effects. The three factors interact and should not be investigated separately. Trade-off decisions should consider environmental conditions for the plant equipment as well as the comfort requirements of plant personnel.

**4.2.2 Illumination and Acoustics.** As with other aspects of the environment, there are certain ranges to the ambient light and sound which are best suited for a particular human activity. When light levels are inadequate for the task, persons may not be able to perform safely or reliably, especially when they can no longer see the details of what they are doing. Similarly, ambient illumination can be excessive for a given task, literally being too bright for a person to see or recognize detail. Usually, problems are not encountered with overall ambient levels as much as with localized variations resulting in contrast or glare problems. Interactions in the use of colors in the environment can have several effects on performance and should be considered. The overall level and spectral composition of ambient sound can affect human performance, either from direct physiological effect, or through disruption of communications.

**4.2.3 Workplace Size, Geometry, and Layout.** Human performance can be affected by the size, geometry, and layout of the workplace, when considered in relation to the tasks to be performed and the number of personnel performing the tasks. Adequate space is needed to accommodate the number of personnel expected to be in the workspace, allowing for normal movement, (including when special bulky clothing is used). Expected traffic patterns should be accommodated. The workstation should be configured such that personnel can see or reach the displays and controls, and communicate with other personnel if required.

**4.2.4 Nuclear Radiation and Other Environmental Hazards.** There are a number of environmental considerations related to health-threatening agents, toxins, substances, and energies. From the earliest stages of design development, every effort should be made to design the workplace, allocate the functions, and design the personnel tasks to minimize the exposure to such elements. When exposure is probable, consideration should be given to the effects the hazards may have, and the effects of any countermeasures required, such as respirators, protective clothing, and control of exposures.

### 4.3 Equipment Considerations.

**4.3.1 User Operability.** There are certain types of equipment (for example, displays and controls) within the system which require particular attention from the aspect of human factors engineering. The displays should be usable by the personnel who must use and respond to them. This includes concepts such as visibility, readability or legibility, ability to access information, the attention attracting capability of the display, the meaningfulness of the display format (that is, its understandability without interpretation) and the precision to which the output can be read. All controls should be examined, considering aspects such as how much force or torque is required for operation, the precision required, response time, and ease of operability. Inherent to such considerations is the physical location of the control or display with respect to the human operator.

**4.3.2 Application.** Human engineering evaluation of equipment should also include consideration of the actual application. It is entirely possible for a given piece of equipment to have an outstanding design from a human engineering viewpoint in one application yet be unacceptable for another. For some applications, digital readouts are required for high-accuracy readings but may be inappropriate for check-status readings or when rapidly comparing several separate readings, observing trend information or rapidly changing data. The suitability of a given display is determined by the type of information needed from the display (for example, accuracy, quantitative versus qualitative, history or trend, simple status—on/off) and how the operator must use the information. This determines which display formats are suitable to the application. Similar evaluations should be made of controls in terms of expected use, considering aspects such as limb used (hand, foot, or finger operated), continuous versus discrete outputs, required feedback, time, frequency, and strength needed.

**4.3.3 Maintenance.** A human factors evaluation of equipment should consider the interface with personnel engaged in maintenance or repair of the items. Considerations include the ease with which the equipment can be assembled or disassembled, tools required, interchangeability of parts, features necessary to prevent incorrect assembly, and level of training and skill required to maintain the item correctly.

**4.3.4 Accessibility.** Equipment should be designed and located such that it is readily accessible for operation or for maintenance action. Implementation of this concept usually requires some trade-off, and prioritization should be based on task demands (for example, expected frequency of use, special tools, local environmental conditions, time constraints) when access is required. Under some circumstances, it may be prudent to deliberately impair the accessibility of an item. This may be desirable, for example, when inadvertent actuation of a control could produce a major plant transient. Under those circumstances, devices such as guardrails and cover plates, or two-hand or two-step operations should be considered.

**4.3.5 Testability.** Equipment should be testable to the extent feasible, to verify proper operation or need for maintenance. Test results should be unambiguous. The requirements for testing equipment should be considered during the design. Adequate space required for test personnel to perform their tasks should also be provided.

**4.3.6 Dependability.** The dependability of equipment, especially in terms of how it will influence personnel actions, should be considered. The operator interface equipment should be as dependable as possible in order to ensure operator confidence. A universal initial reaction in any transient is to assume that the indicators are malfunctioning. It is therefore necessary to consider two problems when designing equipment: 1) how to determine when a piece of equipment is malfunctioning, and 2) what is the appropriate response(s) when the equipment does malfunction. This may include using redundant, diverse, alternate equipment, or positive indication of equipment malfunction.

**4.3.7 Standardized Conventions and Nomenclature.** To minimize potential for errors and facilitate training and actual operations, man-machine interface equipment should be standardized as much as is practical. Design conventions should be established and should be consistently followed. Some conventions involve the coding or meaning associated with features such as size, shape, color, or orientation. Other conventions may relate to the relative locations of components (for example, "A" above or to left of "B"; display above associated control,). Another convention is the direction of motion of control or display pointers.

In many cases there are preestablished conventions based on historical usage. These may vary from culture to culture or industry to industry. A preestablished convention unique to a given group of people is referred to as a "population stereotype". Where such stereotypes are known to exist, it will be necessary to determine the existing conventions of the expected population of users and ensure that they are consistent with the stereotyped conventions and expectations.

Standardized nomenclature and abbreviations should be used for equipment in all text, labels, and drawings.

### 4.4 Personnel Considerations

**4.4.1 Physiological Limitations.** The limits of the human body, in terms of strength and range of motion of various limbs and joints, tolerance to temperature and other environmental stressors, and other limits in terms of physiological fatigue and impairment should be considered.

**4.4.2 Anthropometry.** The workplace layout should be consistent with the body dimensions of the personnel interfacing with it, in terms of reach distances, seating height, lines of sight, and physical clearances. The relevant population of users and maintainers should be identified, and the appropriate sources of anthropometric data (which vary by age, sex, and ethnic groups) should be used in the HFE design process.

**4.4.3 Sensory Limitations.** The capabilities and limitations of human sensory perception should be considered. Display signals must exceed the minimum threshold levels in order to be perceived, without grossly exceeding tolerance levels and saturating the sensory mode. The minimum levels of difference required to discern signals, discriminate between colors, and thus attract attention or permit detection, should be considered.

**4.4.4 Memory.** The nature and limitations of both short- and long-term human memory should be considered. This becomes important in the design of display formats, preparation of instructions, and the development of procedures The use of memory aids designed into interfaces should be considered to assist humans in the recall and use of knowledge.

**4.4.5 Decision Making.** The capabilities and limitations of humans to make and implement decisions should be considered. Relevant system elements and interfaces should be designed to facilitate the decision-making process. Accuracy in decision performance decreases when people are required to respond too rapidly (speed stress) or are subjected to too many different stimuli (load stress).

In the allocation of functional requirements, the risks of making an incorrect decision should be considered for each alternative being evaluated. Designs should be simplified or enhanced to prevent or minimize situations where human decisions are made under uncertainty.

**4.4.6 Experience and Education Level.** The inherent task requirements should be matched to the capabilities and knowledge level of the applicable personnel. Procedures and other documentation should not exceed the reading and comprehension abilities of the users. The design should reflect the competence, level of technical expertise, and the training of the personnel. There are frequent needs for tradeoffs in these areas. If machine and system elements are designed to put minimal demands on operating personnel, the system may become complex, thus requiring highly trained maintenance personnel.

**4.4.7 Human Adaptability.** Humans have a wide range of adaptability. Even in ill-conceived designs, with time or training, humans are sometimes sufficiently adaptable to offset the design deficiencies. This should be recognized when evaluating existing designs or drawing on past experience and practices to develop a new design. A conscious effort should be made to ensure that there are no underlying design deficiencies which can be masked by adaptable human performance under normal conditions. Under stressed conditions, the human may have exhausted this adaptability and may no longer be able to control the situation or compensate for the inherent design deficiency.

**4.4.8 User Acceptance.** User acceptance of system design can severely affect system performance and should be considered in system design. When users accept a design, they may adapt and compensate for deficiencies. However, if the users find the system unacceptable for any reason, they may not attempt to compensate for design deficiencies, and may therefore not use the system properly. System performance could thus be degraded.

The acceptance factors may be independent of the specific design features but relate to matters such as prestige, economics, perceived safety, or a reluctance to change.

### 4.5 Nuclear Operations Considerations

**4.5.1 Operational Safety.** Operational safety of nuclear power-generating stations involves many major concerns such as maintaining reactor coolant inventory, preventing radioactive releases, and removing decay heat during shutdowns. These unique concerns place major emphasis on error-free operation. Human factors engineering applies structured analysis of operating modes and activities to improve operational safety by implementing man-machine interfaces that improve human performance and reduce human error.

**4.5.2 Long Continuous Operation.** Good work space design, good environmental design, and good man-machine interfaces can reduce stresses often noted with shift operation (stresses which often contribute to errors). For instance, good work space design should consider the need for both, resting and mobility.

**4.5.3 Shift Rotation.** Operating shifts are rotated periodically to alleviate social and physical concerns of personnel. Shift rotation affects human circadian rhythms, posing stress concerns; some of these concerns can be alleviated with good work space design and good environmental design.

**4.5.4 Shift Turnover.** Proper work space design should accommodate two shifts during turnover Proper turnover methods are important in assuring that the next shift has received and understands current operating status of all plant systems and equipment.

**4.5.5 Normal, Startup, Shutdown, and Emergency Operation.** Operation of nuclear power plants involves long periods of normal operation, short periods of startup/shutdown operations, and very short infrequent periods of abnormal and emergency operations. The use of HFE to improve human response should consider the effects of operator practice and experience related to the frequency of performing emergency operations versus normal operations. Also, task loading imposed during design basis events should be considered.

**4.5.6 Total Plant Operation.** Operating staffs generally operate most or all plant equipment. Man-machine interfaces for all plant equipment should be standardized to the extent practical, in order to reduce confusion and possible errors.

**4.5.7 Remote Operation.** Plant equipment and systems are generally operated from man-machine interfaces that are remote from the equipment. Remote operation places greater importance on this interface. Feedback of operational information improves these man-machine interfaces by providing associative cues through techniques such as functional groupings, static mimics, live mimics, video display terminals, and good labels.

**4.6 Documentation Considerations.** The required documents and their content should be determined and prepared during the design of the system and should be maintained to reflect the current status. Special considerations for some specific types of documentation are covered in 4.6.1 through 4.6.5.

**4.6.1 Plant Procedures.** Plant procedures should be both, technically correct, and presented for ease of reading and comprehension. Plant procedures should include an explanation of the purpose of the procedure and the expected plant response. Procedure development should be based on analyzing the task to be performed and determining how it is to be accomplished. Task analysis should include such details as, expected outcome of the task, which person is to perform each step, and that the control and displays required to perform the step are available and suitable to perform the task steps.

Plant procedures should be appropriately presented. This entails determining the most appropriate format (for example, flowchart, diagram) and media for display (for example, written page, video display) as well as specific details of information display such as, selection of language, reading ability of users, typography (font and size of lettering) color, and the consistency of procedures with other available documentation (for example, nomenclature).

**4.6.2 Equipment Manuals.** HFE should be considered in developing documentation (for example, manuals, handbooks, parts lists, and others) which accompanies each piece of equipment. Some considerations include (1) the thoroughness and technical accuracy of the documentation (does it explain in sufficient detail how to use and maintain the equipment?), (2) the format of the documentation (can it be used readily?), and (3) the reading level and technical sophistication required to understand the documentation and its clarity, including quality of illustrations.

**4.6.3 Computer Software.** HFE should be considered in software development, use, and maintenance, wherever people must interface with computers or computer input and output controls and displays.

**4.6.4 Specifications.** The human performance requirements should be included in the functional requirements contained in the system, facilities, and component specifications. All constraints on the use of people in the system should be considered within the conceptual and development specifications so that they may be considered early in the design process.

**4.6.5 Engineering Drawings.** Human factors engineering principles should be used for developing engineering drawings. Engineering drawings should reflect the needs of all users.

## 5. Methodology

The following techniques and methods discussed in EPRI NP-3659, Human Factors Guide for Nuclear Power Plant Control Room Development,[2] should be considered.

**5.1 Non-Observational Methods.** The following non-observational methods are considered acceptable:

(1) Human factors checklist
(2) Historical review
(3) Task analysis (desktop task analysis)
(4) Logic trees

**5.2 Observational Methods.** The following observational methods are considered acceptable:

(1) Walk-through/talk-through (dynamic task analysis)
(2) Time line analysis
(3) Automated performance tracking

**5.3 Expert Opinion Techniques.** The following expert opinion techniques are considered acceptable:

(1) Delphi
(2) Nominal group technique
(3) Paired comparison
(4) Ratio estimation

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[2] EPRI publications may be obtained from the Electric Power Research Institute, Research Reports Center, P.O. Box 50490, Palo Alto, CA 94303.

## 6. Implementation in the Design, Operations, Testing, and Maintenance Process

The application of HFE to systems, equipment, and facilities having significant human interface in nuclear power generating stations should be based on an integrated systems approach to the design, operations, and maintenance process. The initial steps in this process will vary depending on whether a new design or modification to an existing design is being undertaken, but in either case the human should be considered as an integral part of the system being designed. HFE should be applied at the initial stages and throughout the design process to assure that the functions allocated in whole or in part to the human operator(s) and maintainer(s) can be successfully accomplished to meet the integrated system design goals. The organization(s) responsible for HFE should review the fundamental considerations which affect human performance and should develop a program plan for applying appropriate HFE methodologies to address those fundamental considerations that are pertinent to their specific application. The HFE methodologies used and the sequence in which they are applied may vary and should be determined by the organization(s) responsible for HFE to meet their specific applications.

**6.1 Program Plan.** The flowchart shown in Fig 1 illustrates a typical comprehensive plan for the application of HFE in the design, operations, and maintenance process. The flowchart has a defined entry point for new designs and for modifications to existing designs. The intent of developing a program plan is to apply HFE early in the design process. This should reduce the need for design process iterations. An interpretation of the application flowchart of HFE in the process is discussed in 6.1.1 through 6.1.2.5.

**6.1.1 New Designs.** New designs include the design of systems, equipment, or facilities for new nuclear generating stations or the design of new systems, equipment, or facilities to be added to existing nuclear generating stations. The determination of the depth of the HFE evaluation should consider design standardization, system complexity, consequences of human errors, and effect on safety. The application of HFE to the design of new systems should be an integral part of the planning process, which typically may include some or all of the steps covered in 6.1.1.1 through 6.1.1.22.

**6.1.1.1 Define Need.** The top level design goals of the new systems, equipment, or facility should be determined.

**6.1.1.2 System Analysis.** From the top level design goals, specific objectives and measurable performance requirements or criteria, including those for HFE, should be developed, and constraints to be used throughout the subsequent design process should be determined.

**6.1.1.3 Functional Analysis.** Functions required to meet the system design objectives should be determined.

**6.1.1.4 Function Allocation.** Functions should be allocated to the human operator(s) and maintainer(s), to machines, or to a combination of humans and machines.

**6.1.1.5 Task Analysis.** For each function, the task activities that must be performed by the human operator(s) and maintainer(s) to accomplish that function should be analyzed. A task description may be an adequate substitute for task analysis for that portion of the design that already exists.

**6.1.1.6 Equipment Requirements.** Control, display, and communications equipment requirements necessary to perform each task should be determined, based on the task analysis.

**6.1.1.7 Selection, Training, and Job Requirements.** Based on the task analysis, the human performance requirements and tasks should be determined, which in turn determine the personnel selection and training requirements. For existing designs, this may require retraining.

**6.1.1.8 Procedures Requirements.** Based on the task analysis, procedural requirements should be developed to integrate the operator(s), the maintainer(s), and the equipment, to accomplish each function. For existing designs this may require procedure modifications.

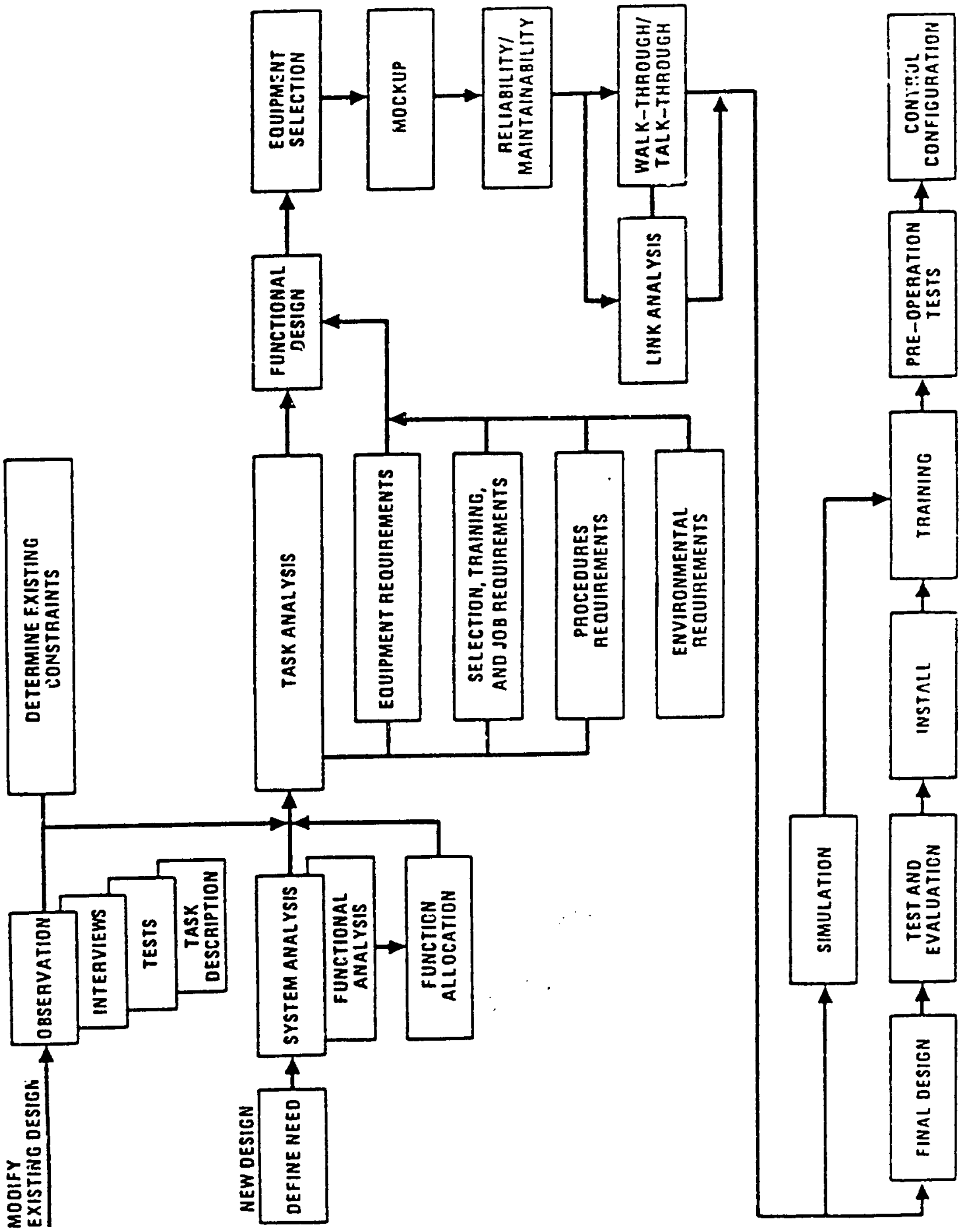

Fig 1
Typical Comprehensive Application of HFE in the Design Process

**6.1.1.9 Environmental Requirements.** The effects of environmental condition [illegible] the human operator(s) and maintainer(s) should be considered and the system, equipment, or facility designed to adequately accommodate the human operator(s) and maintainer(s). For existing designs this may require system, equipment, or facility design changes, where necessary, to accommodate the human operator(s) and maintainer(s) adequately.

**6.1.1.10 Functional Design.** Based on the task analysis and equipment requirements, functional hardware and software design alternatives should be developed that meet the requirements and perform trade-off studies to select a preferred functional design. For modifications to existing designs, this may be limited by current constraints, but wherever possible, alternative functional designs should be developed and the preferred design selected by trade-off analysis.

**6.1.1.11 Equipment Selection.** HFE hardware related considerations should be applied in the selection of specific equipment to implement the functional design.

**6.1.1.12 Mockup.** Based on the equipment selections and functional design, a mockup or model (if not previously developed) of the systems, equipment, or facility, should be used in order to evaluate human interface compatibility. Iterate the design and equipment selection based on the results of these measures. For modifications to existing designs, it may be useful to construct a mockup or model and develop the alternate modifications.

**6.1.1.13 Reliability and Maintainability.** Reliability and maintainability should be evaluated to provide appropriate input prior to completion of final design.

**6.1.1.14 Walk-Through and Talk-Through.** The actions documented in the task analysis should be performed using the mockup(s) or model(s) and the documented sequences to evaluate the human interfaces and capability of function accomplishment.

**6.1.1.15 Link Analysis.** In parallel with walk-through and talk-through, the human operator(s) and maintainer(s) movements, communications, and interactions required to perform the tasks should be analyzed and documented.

**6.1.1.16 Final Design.** The system, equipment, or facility hardware and software design should be finalized.

**6.1.1.17 Final Test and Evaluation.** A final test and evaluation of the integrated system, including the human operator(s) and maintainer(s), should be conducted to verify that all previously determined HFE criteria and requirements are met and that the functional requirements are satisfied. Design deficiencies should be corrected.

**6.1.1.18 Simulation.** A dynamic simulation capability for personnel training should be provided for systems, equipment, or facilities with significant human interfaces that involve complex and interactive processes.

**6.1.1.19 Installation.** Installation at the site should be performed.

**6.1.1.20 Training.** Operator and maintenance training on a simulation facility or the actual system, equipment, or facility should be performed.

**6.1.1.21 Preoperational Tests.** Functional tests on the installed equipment should be performed to verify that functional requirements are satisfied using the as-installed equipment. As-installed deficiencies should be corrected.

**6.1.1.22 Control Configuration.** Documented control of the design configuration and procedures, including an HFE evaluation of all subsequent design modifications throughout the design life cycle should be maintained.

**6.1.2 Modification to Existing Designs.** Modification to existing designs includes the design or modifications to existing systems, equipment, or facilities in nuclear generating stations. The determination of the depth of the HFE evaluation should consider design standardization, system complexity, consequences of human errors, and effect on safety. The application of HFE criteria to the modification of existing designs should be an integral part of a systems engineering process that typically includes an initial series of steps to collect data on the existing design functions, function allocations, and design constraints. These initial steps typically may include some or all of the following steps covered in 6.1.2.1 through 6.1.2.5.

**6.1.2.1 Observation.** Operator(s) and maintainer(s) performance with the existing design should be observed.

**6.1.2.2 Interviews.** Operator(s) and maintainer(s) should be interviewed to determine the tasks they perform and the equipment and procedures they use to perform the tasks.

**6.1.2.3 Tests.** The capability of existing man-machine interfaces to perform operations, testing, and maintenance functions should be tested and quantified where possible.

**6.1.2.4 Task Description.** The task that must be performed by the human operator(s) and maintainer(s) to accomplish each function should be described.

**6.1.2.5 Determine Existing Constraints.** Constraints imposed on the design modification due to the existing design and outside constraints, such as time and budget, should be determined.

At this point, the process of modifying an existing design typically follows the same path as for new designs beginning with task analysis, covered in 6.1.1.5.

**6.2 Documenting HFE in the Design, Operations, Testing, and Maintenance Process.** Appropriate documentation should be produced and maintained current to provide a tracerble record of the use of HFE in the design, operations, testing, and maintenance process (see 6.1.1.22).

**6.3 Operational Experience Review.** The performance of the design, operation, testing, and maintenance of the nuclear power generating station should be monitored for human factors concerns. Such documents as licensee event reports, maintenance, and surveillance experience reports, and reactor trip reports should be reviewed for any human factors aspects requiring design and procedure modifications. If required, resulting modifications to the design, operation, testing, and maintenance should be implemented in the manner described in 6.1.

# *10.* Appendix B - *Standard Practice for F1337-91 HUMAN ENGINEERING Program Requirements for Ships and Marine Systems, Equipment, and Facilities*

**Designation: F 1337 – 91**

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# Standard Practice for Human Engineering Program Requirements for Ships and Marine Systems, Equipment, and Facilities[1]

This standard is issued under the fixed designation F 1337; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This practice establishes and defines the requirements for applying human engineering to the development and acquisition of ships and marine systems, equipment, and facilities. These requirements are applicable to all phases of development, acquisition, and testing and shall be integrated with the total system engineering and development, and test effort. It is not expected nor intended that all of the human engineering activities should be applied to every marine program or program phase. Therefore, these activities shall be tailored to meet the specific needs of each program and the milestone phase of the program within the overall life cycle. This tailoring shall be performed by the procuring activity or by the contractor or subcontractor with the assistance and approval of the procuring activity in order to impose only the essential human engineering requirements on each program. Guidance for selection of only the essential requirements is contained in Appendix X1.

## 2. Referenced Documents

2.1 *ASTM Standard:*

F 1166 Practice for Human Engineering Design for Marine Systems, Equipment and Facilities[2]

2.2 *Other Standard:*

SNAME Sample Model Specification for Human Engineering Purposes—Technical and Research Bulletin 4-22[3]

## 3. Terminology

3.1 *Descriptions of Terms Specific to This Standard:*

3.1.1 *arrangement drawings*—engineering design drawings that provide plan, sectional, and elevation views of: (*1*) the configuration and arrangement of major items of equipment for manned compartments, spaces, or individual work stations, and (*2*) within the work station, such as in a modular rack or on a fiddleboard.

3.1.2 *critical activity*—any human activity that if not accomplished in accordance with system requirements (that is, time limits, specific sequence, necessary accuracy) will have adverse effects on system or equipment cost, reliability, efficiency, effectiveness, or safety.

3.1.3 *cultural expectation*—the cause and effect relationships (for example, red means stop or danger) that humans learn from their culture.

3.1.4 *duty*—a set of operationally-related tasks within a given job (for example, communicating, operator maintenance).

3.1.5 *function*—an activity performed by a system (for example, provide electric power) to meet mission objectives.

3.1.6 *human engineering*—a specialized engineering discipline within the area of human factors that applies scientific knowledge of human physiological and psychological capabilities and limitations to the design of hardware to achieve effective man-machine integration.

3.1.7 *human factors*—the application of scientific knowledge about human characteristics, covering both biomedical and psychosocial considerations, to complete systems, individual equipments, software, and facilities. This application is through such specialized fields as human engineering, manning, personnel selection, training, training devices and simulation, life support, safety, job performance aids, and human performance testing and evaluation.

3.1.8 *human interface*—any direct contact (that is, physical, visual, or auditory) with a piece of hardware or software by a human operator or maintainer.

3.1.9 *job*—the combination of all human performance required for operation and maintenance of one personnel position in a system.

3.1.10 *life support*—that area of human factors that applies scientific knowledge regarding the effects of environmental factors on human behavior and performance to items that require special attention or provisions for health promotion, biomedical aspects of safety, protection, sustenance, escape, survival, and recovery of personnel.

3.1.11 *mission*—a specific performance requirement imposed on one or more systems (for example, unload cargo) within the operational requirements.

3.1.12 *operational requirements*—requirements under which the platform, system, equipment, or software will be expected to operate and be maintained (for example, day/night, all weather operation, sea state, speed, endurance) while completing a specific mission or missions.

3.1.13 *panel layout drawings*—detailed drawings that include such features as: a scale layout of the controls and displays on each panel or an item of equipment such as a shipboard command console; a description of all symbols used; identification of the color coding used for displays and controls; the labeling used on each control or display; and the identification of control type (for example, alternate action or momentary), also screen layouts for software generated displays.

3.1.14 *platform*—the major hardware (for example, ship,

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[1] This practice is under the jurisdiction of ASTM Committee F-25 on Shipbuilding and is the direct responsibility of Subcommittee F25.07 on General Requirements.

Current edition approved April 15, 1991. Published November 1991.

[2] *Annual Book of ASTM Standards*, Vol 01.07.

[3] Available from Society of Naval Architects and Marine Engineers, 601 Pavonia Ave., Jersey City, NJ 07306, Attn: Technical Coordinator.

off-shore rig, barge, submarine) on, or in which, the individual equipment, system, or software will be installed or added.

3.1.15 *spatial relationships*—placement of multiple but separate components of a system together, so it is visually obvious that the components are related and used together, or placement of identical components used on multiple systems to provide the user with a spatial clue as to where the components are located.

3.1.16 *subtask*—activities (perceptions, decisions, and responses) that fulfill a portion of the immediate purpose within a task (for example, remove washers and nuts on the water pump).

3.1.17 *system*—a composite of subsystems, including equipment, communications, software, and personnel that either independently, or in conjunction with other systems, performs functions.

3.1.18 *system analysis*—a basic tool for systematically defining the roles of and interactions between the equipment, personnel, communications, and software of one or more systems. It is an iterative process, requiring updating. Used in the early phases of design, it can be useful in allocating assignment of tasks to personnel, equipment, software, or some combination thereof. Done in later design stages, it can serve as the basis for the arrangement of equipment and work stations.

3.1.19 *task*—a composite of related activities (perceptions, decisions, and responses) performed for an immediate purpose, written in operator/maintainer language (for example, change a water pump).

3.1.20 *task analysis*—a method used to develop a time-oriented description of the interactions between the human operator/maintainer and the equipment or software in accomplishing a unit of work with a system or individual piece of equipment. It shows the sequential and simultaneous manual and intellectual activities of personnel operating, maintaining, or controlling equipment, in addition to sequential operation of the equipment.

3.1.21 *task element*—the smallest logically and reasonably definable unit of behavior required in completing a task or subtask (for example, apply counterclockwise torque to the nuts, on the water pump, with a wrench).

3.1.22 *vendor drawings*—design drawings prepared by the manufacturer of an individual piece of equipment which is purchased for installation aboard a ship or other marine platform.

## 4. Summary of Practice

4.1 *Human Engineering Program Plan*—The human engineering program plan, in accordance with the requirements of this practice and the equipment or ship specification, shall include the tasks to be performed, human engineering milestones, level of effort, methods to be used, design concepts to be used, and the test and evaluation program, in terms of an integrated effort within the total project.

4.2 *Quality Assurance*—Verification of compliance with the requirements of this practice and other human engineering requirements specified by the contract will be the responsibility of the procuring activity. Human engineering performed during the development program by a contractor or subcontractor shall be demonstrated to the satisfaction of the procuring activity at the scheduled design and configuration reviews and inspections, as well as during development test and evaluation inspections, demonstrations, and tests.

4.3 *Nonduplication*—The efforts performed to fulfill the human engineering requirements specified herein shall be coordinated with, but not duplicate, efforts performed in accordance with other requirements. Necessary extensions or transformations of the results of other efforts for use in the human engineering program will not be considered duplication. Instances of duplication or conflict shall be brought to the attention of the procuring activity.

4.4 *Cognizance and Coordination*—The human engineering program shall be coordinated with maintainability, system safety, reliability, survivability/vulnerability, and integrated logistic support, as well as other human factors functions, such as life support and safety, personnel selection, preparation of job aids, and training. Results of human engineering analysis or lessons learned information shall be incorporated into the logistic support analysis as applicable. The human engineering portion of any analysis, design and development, or test and evaluation program shall be conducted by, or under the direct cognizance of, personnel properly trained and experienced in human engineering and assigned the human engineering responsibility by the contractor or subcontractor.

## 5. Significance and Use

5.1 *Intended Use*—Compliance with this practice will provide the procuring activity with assurance that the operator/maintainer will be efficient and effective in the operation and maintenance of systems, equipment and facilities. Specifically, it is intended to ensure that:

5.1.1 System performance requirements are achieved by appropriate use of the human component,

5.1.2 Proper design of equipment, software and environment permits the personnel-equipment/software combination to meet system performance goals,

5.1.3 Design features will not constitute a hazard to personnel,

5.1.4 Trade-offs between automated vs manual operation have been chosen for peak system efficiency within appropriate cost limits,

5.1.5 Application of selected human engineering design standards are technically adequate and appropriate,

5.1.6 Systems and equipments are designed to facilitate required maintenance,

5.1.7 Procedures for operating and maintaining equipment are efficient, reliable and safe,

5.1.8 Potential error-inducing equipment design features are eliminated, or at least, minimized,

5.1.9 Layouts and arrangements of equipment afford efficient communication and use, and

5.1.10 Contractors provide the necessary, technically qualified manpower to accomplish the objectives listed.

5.2 *Scope and Nature of Work*—The human engineering effort shall include, but not necessarily be limited to, active participation in three major interrelated areas of platform, system, and equipment development.

5.2.1 *Analysis*—Starting with a mission analysis developed within baseline operational requirements, the functions that must be performed by the system in achieving its mission objectives shall be identified and described. These functions shall be analyzed to determine the best allocation to personnel, equipment, software, or combinations thereof. Allocated functions shall be further dissected to define the specific tasks that must be performed to accomplish the functions. Each task shall be analyzed to determine the human performance parameters, the system/equipment/software capabilities, and the operational/environmental conditions under which the tasks are conducted. Task performance parameters shall be quantified, where possible, and in a form permitting effectiveness studies of the crew-equipment/software interfaces in relation to the total system operation. Human engineering high risk areas shall be identified as part of the analysis.

5.2.2 *Design and Development*—Design and development of the equipment, software, systems, and total platforms requiring personnel as operators or maintainers, or both, shall include a human engineering effort that will ensure that adequate and appropriate human engineering design standards are incorporated into the overall engineering design. Such standards may be specifically stated in the system equipment, software, or facilities acquisition specifications, or they may be generated from the analysis work completed prior to design and development.

5.2.3 *Test and Evaluation*—Test and evaluation shall be conducted with the newly designed equipment, software, facilities, and environment to verify that they meet human engineering and life support criteria and are compatible with the overall system requirements. This shall include periodic on-site checks of the platform, systems, equipment, software, or facilities during construction to ensure that changes are not made during construction that would degrade earlier human engineering efforts.

## 6. Human Engineering Activities

6.1 *Scope*—The human engineering program shall include the following activities:

6.1.1 *Operational Requirements (OR)*—Operational requirements (ORs) are established first to define the parameters within which the individual equipment, system, or total platform shall be expected to perform. ORs shall be expressed in such terms as the weather conditions under which it must operate (for example, rain, snow, sea state limits); number of days it must operate without being refueled or re-supplied; and maximum number of personnel that will be available to operate and maintain the hardware. Human engineering shall be considered in the development of ORs, especially when the ORs include requirements on the number, type, or training of operators or maintainers, or both.

6.1.2 *Mission Requirements Analysis*—Mission requirements define the performance parameters of the equipment, system, or total platform in greater detail than that provided by the ORs, and in terms of specific activities the hardware/software is supposed to accomplish. Human engineering shall be involved in establishing the mission requirements since the human's capabilities or limitations may well be a controlling factor regarding whether or not the mission requirements can be met.

6.1.3 *System Requirements Analysis*—System requirements analyses define the specific systems that will be needed to successfully complete each of the missions delineated above. Human engineering shall be involved in establishing system requirements, since some systems can require greater numbers of personnel and higher skill levels for operators or maintainers than others. Human engineering data from existing systems similar to those being proposed for the new design may be used as a baseline in defining the new system requirements.

6.1.4 *Function Definition*—The functions that must be performed by each system to achieve the desired mission objectives shall be defined. This definition shall be done without consideration as to whether the function will be performed by a human, by a machine, or by a combination of the two. Functions shall be stated as a required action (for example, monitor, receive, communicate, view, send, calibrate). Functional block diagrams shall be used, as appropriate, as a presentation tool. Functional definitions shall be as detailed as is necessary to permit the successful allocation of the functions. The transfer and processing of information (for example, verbal communications, electronic transmissions, printed material) shall be identified as a function but without reference to specific machine or human involvement. Human engineers shall be involved in identifying functions, since this activity serves as the base for the next step, which includes major participation by human engineering.

6.1.5 *Function Allocation*—Each function identified from the previous step shall be assigned to be machine implemented, performed by software, reserved for the human operator/maintainer, or performed by some combination thereof. Human engineering specialists shall participate in the function allocation process to ensure that each function assigned to the human is within the human's capability. Known human engineering experiences with man-machine functional allocations on existing equipments, systems, or platforms similar to those under evaluation; personal human engineering experience in the function allocation field; and available information on human physical and psychological performance capabilities shall be used when applicable in determining function allocations.

6.1.6 *Equipment Selection*—Hardware and software shall be selected to perform those functions assigned to them from the function allocation activity. Human engineering principles and design standards shall be included, along with other design considerations, in identifying and selecting that hardware/software. Human engineers shall ensure that the equipment provides the human with the opportunity to complete those functions assigned to the operator/maintainer, and that it complies with all of the applicable design criteria contained in Practice F 1166, as well as other human engineering design criteria contained in the contract, or in other human engineering design standards referenced in the contract. Known human engineering problems with equipment now in service (for example, information from equipment casualty reports or personnel injury data associated with equipment failure) that is similar to that being considered, personal experience with applying human engineering design criteria to equipment design, and review of potential supplier engineering data are examples of the human engineering resources that shall be used in assessing the acceptance of the selected equipment from a human engineering viewpoint.

6.1.7 *Human Engineering System Analysis Report (HESAR):*

6.1.7.1 *HESAR (TYPE 1)*—Type 1 HESARs, which are prepared early in the design process (for example, during feasibility design), shall allow for the evaluation of the appropriateness and feasibility, from a human engineering perspective, of the mission, system, and functional requirements, and to serve as one basis for decisions made during the functional allocation effort. The HESAR shall contain the results of the mission, system, and functional requirements analyses and describe the human engineering rationale for, or contribution to, each. In addition, the potential impact, or the proposed use, of these analyses for future human engineering activities (for example, allocation of functions, equipment selection, detail design of equipment, arrangement of spaces or compartments) shall be discussed. The objective of the early HESAR shall be to demonstrate that human engineering considerations have been adequately addressed in the establishment of the mission, system, and functional requirements, and that there exists a sound basis on which to allocate the functions, select the equipment, and perform the detail design of the individual piece of equipment, system, or total platform.

6.1.7.2 *HESAR (TYPE 2)*—A Type 2 system analysis, completed late in the design process (for example, during development of construction drawings or production drawings) shall be done to provide a basis on which to base a particular equipment design, or system or compartment arrangement. In completing a Type 2 system analysis the following factors shall be considered, and shall be discussed in the HESAR: (*1*) description of the equipment, console, compartment, system, or work station on which the analysis was conducted, (*2*) externally imposed design requirements or criteria over which the human engineer had no control (for example, number of operators/maintainers, specific types and numbers of consoles, previously determined man-machine function allocations, predetermined locations of hardware), (*3*) communications requirements (for example, telephone, voice, sound powered phones, electronic), (*4*) work environment, (*5*) mission, system, backup, and functional requirements, and (*6*) human physical and psychological capabilities within the context of the existing design parameters. In conducting the analysis, consideration shall be given to such issues as projected work loads for each manned position; the kind, amount, and criticality of the information that goes into, and out of, each operator/maintainer station; the need for direct voice or visual communication between manned positions; location and suitability of backup equipment in case the primary hardware fails; and the interactions that are required between personnel or equipment, or both. Using the completed analysis, the human engineer shall participate in establishing the final design or arrangement of a piece of equipment, a system, or the total platform.

6.1.8 *Task Analysis:*

6.1.8.1 *Concurrence and Availability*—All task analyses shall be modified as required to remain current with the design effort and shall be available to the procuring activity as requested.

6.1.8.2 *Gross Task Analysis (GTA)*—A GTA consists of defining the major tasks required of the human operator/maintainer to complete each function identified and allocated to the human during the functional allocation activity (see 6.1.5). The GTA shall present these tasks in the sequence in which they must be completed and against an established time line reference. Information flows into, or out from, the human shall be included as a task. The GTA shall include both manual and cognitive tasks, and shall be written in operator/maintainer language (for example, change fuel pump, steer ship on constant heading, calculate fuel consumption rate). Where GTAs are required they shall be performed for both normal and emergency operating conditions. The GTAs shall be used to determine, to the extent practicable, whether the system performance requirements (see 6.1.3) can be met with the function allocations, backup facilities, and equipment selections that have been previously made. These analyses shall also be used as basic information for developing preliminary manning levels; equipment procedures; personnel skill, training, and communication requirements; and as logistic support analysis inputs. Personal experience of the human engineering analyst in the preparation of GTAs, information from equipment vendor operation and maintenance manuals, inputs from the design engineers (either at the procuring activity or the contractor) of the system(s) or equipment under evaluation, and established tasks on equipment similar to that under investigation are all resources that shall be used as appropriate in the creation of GTAs. GTAs shall be presented in diagrammatic form (for example, operational sequence diagrams) unless otherwise approved by the procuring activity.

6.1.8.3 *Critical Task Analysis (CTA)*—Those gross tasks identified in the GTA that require critical human performance (for example, no deviation from a fixed sequence; task completion within a fixed, and limited, time frame; accurate setting or reading of an important control or display), reflect possible unsafe practices, or that are subject to promising improvements in operating efficiency shall be identified and further analyzed upon approval of the procuring activity. CTAs require detail to the subtask (for example, remove hose clamp from hose on the discharge side of water pump), or even task element level (for example, turn screw on the hose clamp on discharge side of water pump counterclockwise with Phillips head screwdriver). Other inputs which shall be made to a CTA include: (*1*) information required by the operator/maintainer for task initiation, (*2*) all information available to the operator/maintainer, (*3*) cognitive functions required of the operator/maintainer to process or act on the information, (*4*) actions required by the human based on the cognitive processes, (*5*) workspace envelope required by the actions, (*6*) workspace available, (*7*) frequency and accuracy required of the actions, (*8*) feedback required to the operator/maintainer regarding the adequacy of his/her actions, (*9*) tools or equipment, or both, required by the human, (*10*) job aids or references required, (*11*) number of personnel required or provided, as well as their specialty and experience, (*12*) communications required, and the types of communications, (*13*) safety hazards involved, (*14*) operational requirements of the human (for example, hours on duty, number of repetitive motions), (*15*) backup facilities available, and (*16*) operator interaction where more than one person is involved. The format shall

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include a time line base for presenting the information listed herein. Task analysis may be produced by automated programs after review and approval of the programs by the procuring activity.

6.1.9 *Human Engineering Design*—Human engineering principles and design standards shall be applied to the design of all compartments, spaces, systems, individual equipment, work stations, and facilities in which there is a human interface. Drawings, specifications, analyses, or other documentation shall reflect incorporation of these human engineering principles and standards. Where specific design criteria are required, they shall conform to Practice F 1166 or other human engineering criteria required by the contract. Design of the compartments, spaces, equipments, systems, work stations, and facilities shall provide for both normal and emergency conditions, and shall consider at least the following where applicable:

6.1.9.1 Environmental conditions, such as temperature, humidity, air flow, noise and illumination levels, and atmospheric contaminants,

6.1.9.2 Weather and climate, such as rain, snow, and ice,

6.1.9.3 Platform motion (for example, ship roll and pitch),

6.1.9.4 Space (that is, access) requirements for personnel to perform operations and maintenance, keeping in mind the special clothing or protective gear they may be wearing and the tools they may be carrying,

6.1.9.5 Safe and efficient walkways, ladders, work platforms, and inclines,

6.1.9.6 Adequate physical, visual, and auditory links between personnel, and between personnel and their equipment so that reach and visual envelopes are within standard limitations,

6.1.9.7 Provisions to minimize physical or emotional fatigue,

6.1.9.8 The effects on physiological and psychological performance due to special clothing, or chemical, biological, and radiological (CBR) protective suits,

6.1.9.9 Provisions to maximize cultural expectations and spatial relationships in the design,

6.1.9.10 Equipment removal and stores handling provisions,

6.1.9.11 Crew safety requirements, and

6.1.9.12 The range in physical size (for example, 5th to 95th percentile dimensions) and mental capabilities of the anticipated users of the equipment.

6.1.9.13 The adequacy of including human engineering principles and design standards into the overall design effort shall be evaluated during design reviews. Where such reviews involve a contractor or subcontractor, the individuals assigned the human engineering responsibilities by these organizations shall participate in the reviews. At quarterly design reviews these individuals shall provide the same type of presentation as is made by the other engineering disciplines.

6.1.10 *Application of Lessons Learned Information*—Information on known or suspected human engineering problems from past or existing equipments, systems, or total platforms similar to that under design shall be obtained and used in the design of the new equipment, system, or platform. This information shall be acquired from such sources as: personal inspection of current hardware, system, or platform (for example, conduct a ship check or ship survey), interviews with past or current operators or maintainers, or both, a review of sea trial deficiency cards, discussions with past or current designers of similar equipments, systems, or platforms, and investigation of personnel injury or equipment casualty reports, or both. Any summation reports prepared from the acquisition of this data shall provide the information by equipment, system, or ship compartment and shall include the ship work breakdown structure (SWBS) number or other corresponding specification section for each identified human engineering problem.

6.1.11 *Engineering Design Drawings*—Human engineering principles and design standards shall be reflected in the engineering design drawings produced for marine systems and equipment. These principles and standards shall be incorporated in all engineering drawings that involve a human interface and are developed during the various design phases. Specific types of drawings to which the human engineering principles and design standards shall be applied include: overall platform (for example, ship, off-shore rig, barge) arrangement drawings, individual compartment or space arrangement drawings, zone arrangement drawings, console or work station panel layout drawings, individual equipment design drawings, piping arrangement drawings, and other drawings depicting the design or arrangement, or both, of equipment requiring operation or maintenance, or both, by humans. The drawings shall comply with the applicable criteria contained in Practice F 1166 or other human engineering design standards, or a combination thereof, as specified in the contract.

6.1.11.1 Where the drawings are produced by a contractor, a specific list of the engineering drawings or a description of the types of drawings that will receive human engineering input shall be included in the contractor's human engineering program plan (HEPP). Personnel assigned human engineering responsibility by the contractor shall approve all drawings included in the HEPP list before the drawings are released for production.

6.1.12 *Human Engineering in Vendor Hardware/Software*—Human engineering principles and design criteria from Practice F 1166 (or other approved design standards) shall be incorporated into hardware and software purchased by the contractor for inclusion on a marine platform or major system. The human engineering program plan shall include a list of the hardware/software items on which human engineering principles and design criteria will be imposed. The contractor shall also ensure that the vendor hardware/software complies with the design standards of Practice F 1166 after installation in or on the platform or system.

6.1.13 *Studies, Experiments, and Laboratory Tests*—The contractor shall conduct experiments, tests (including dynamic simulation per 6.1.14), and studies required to resolve human engineering and life support problems specific to the system. Human engineering and life support problem areas shall be brought to the attention of the procuring activity, and shall include the estimated effect on the system if the problem is not studied and resolved. These experiments, tests, and studies shall be accomplished in a timely manner, that is, such that the results may be incorporated into the design. The performance of any major study effort shall require approval by the procuring activity.

6.1.14 *Dynamic Simulation Studies*—Dynamic simulation studies shall be used as a human engineering design tool when necessary for the detail design of equipment requiring critical human activity (for example, precise ship maneuvering or handling tasks). If such studies are completed, the simulation hardware/software should be evaluated as a training tool as well, and shall be addressed in the dynamic simulation plan. No dynamic simulation studies shall be performed without prior approval of the simulation plan by the procuring activity.

6.1.15 *Mockups and Models*—Models and mockups built to resolve access, workspace design, equipment arrangements, or other human engineering problems shall be constructed at the earliest practical point and well before fabrication of the compartment, system, or equipment. The proposed human engineering program plan shall specify which models and mockups the contractor proposes to use for human engineering purposes. Mockups shall be full scale and models shall be built to SNAME Sample Model Specification for Human Engineering Purposes—Technical and Research Bulletin 4-22. For models and mockups specified primarily for human engineering use, the workmanship shall be no more elaborate than is necessary to determine the adequacy of size, shape, arrangement, access, or panel content of the equipment for human use. Models and mockups shall be constructed as simply and inexpensively as is compatible with the objective and use. They shall be updated regularly to reflect the latest designs. Upon approval by the procuring activity, scale models may be substituted for mockups. The models and mockups shall be available for inspection as determined by the procuring activity. Mockups and models may be disposed of only with the approval of the procuring activity.

6.1.16 *Human Engineering in Performance and Design Specifications*—Where the contractor prepares a specification for the design, development, construction, or acquisition of a marine platform, system, piece of equipment, facility or software, it shall conform to applicable human engineering criteria of Practice F 1166 and other human engineering criteria specified by the procuring agency.

6.1.17 *Equipment Procedure Plates and Manuals*—The contractor shall apply human engineering principles and criteria to the development of procedures and manuals for operating, maintaining, or otherwise using the system and equipment. For individual procedure plates (for example, lubrication charts, hazard warnings, operating instructions, schematics), mounted at the equipment, they shall comply with the design requirements in Practice F 1166. For computer systems, human engineering shall be applied throughout software program planning and development. This effort shall be accomplished to ensure that the procedures are concise, unambiguous, and easy to read and follow with a consistent presentation format, especially for the hazard identification statements. The results of this effort shall be reflected in the preparation of user-oriented operational, training, and technical plates, manuals, and other publications.

6.1.18 *Human Engineering Design Approach Document (HEDAD)*—Two types of HEDADs shall be prepared: the HEDAD-operator (HEDAD-O) and the HEDAD-maintainer (HEDAD-M).

6.1.18.1 *HEDAD-O*—The HEDAD-O shall describe the as-built system or equipment (for example, console, specific work station, compartment arrangement, lube oil system) from an operator's perspective. The system or equipment shall be described in detail (for example, each display or control on a console; each pump, controller, and meter in the lube oil system) explaining the design, layout, and location of each component from a human engineering perspective. The HEDAD-O shall describe where each component is located, why it was designed the way that it appears in the finished product, and why the as-built arrangement was selected (that is, the human engineering rationale). The HEDAD-O shall provide the procuring activity with sufficient detail to evaluate the as-built system or equipment to ensure that it is operable and complies with the human engineering requirements contained in the system or equipment design and acquisition contract.

6.1.18.2 *HEDAD-M*—The HEDAD-M shall be prepared in the same manner and detail as the HEDAD-O but shall describe the system or equipment from a maintenance perspective. In addition to a description of each component, such items as access openings, test or calibration points, lubrication fittings, and other maintenance specific design features shall be identified and discussed. The HEDAD-M shall be in sufficient detail to allow the procuring activity to determine that the system or equipment is maintainable and complies with the human engineering requirements contained in the design and acquisition contract.

6.1.18.3 *General Requirements*—The systems or equipments that will receive a HEDAD during design and development shall be listed in the contractor's human engineering program plan along with a brief rationale as to why the particular HEDADs were selected (the explanation is required only if the contractor was allowed to select the HEDADs). A brief discussion of the contractor's proposed methodology for completing the HEDADs shall also be included in his plan. The contractor shall include drawings (for example, console panel layouts; system arrangement; plan, section, and elevations for work stations), photos, or other visual aids as necessary to assist in describing the system or equipment.

6.1.19 *Human Engineering Progress Report (HEPR)*—HEPRs shall be prepared by the contractor and submitted on a regular basis to the procuring activity. The reports shall be concise, but in sufficient detail to allow the procuring activity to assess the adequacy of the contractor's human engineering program. Information on work accomplished, human engineering problems encountered and solutions generated, as well as projected activity for the next reporting period shall be included.

## 7. Test and Evaluation

7.1 *Human Engineering in Test and Evaluation*—The contractor shall establish and conduct a test and evaluation program to:

7.1.1 Demonstrate conformance of marine system, equipment and facility design to human engineering design criteria,

7.1.2 Confirm compliance with overall system performance requirements where personnel could be a performance determinant,

7.1.3 Secure quantitative measures of system performance which are a function of the human interaction with equipment, and

7.1.4 Determine whether undesirable design or procedural features have been introduced, but went undetected, during design and development. The test and evaluation effort may be required at various stages in system, subsystem, or equipment development but these shall not preclude final human engineering verification of the complete system. The human engineering test and evaluation program shall include both operator and maintenance tasks as described in a test plan approved by the procuring activity.

7.2 *Planning*—Human engineering testing shall be incorporated into the total platform, or individual system, hardware, or software test and evaluation program. The test requirements shall be satisfied through integration with the equipment engineering acceptance tests, contractor demonstrations, ship trials, research and development acceptance tests, or dedicated human engineering tests using actual hardware or mockups. Compliance with human engineering requirements shall be tested as early as possible. Human engineering findings from design reviews, mockup inspections, demonstrations, and other early engineering tests shall be used in planning and conducting later tests.

7.3 *Human Engineering Test Plan*—A human engineering test plan (HETP) shall be prepared describing when, how, and who will complete the human engineering test and evaluation program. For smaller or less complex systems, the HETP may be submitted as part of the HEPP. If the plan is prepared by a contractor, it shall be approved by the procuring activity before the start of testing. The plan shall describe the proposed test and evaluation program in sufficient detail to permit the procuring activity to determine if the test program will meet the objectives listed in 7.1. The plan shall be prepared so that the human engineering tests will involve individuals representative of the intended user population, performing actual (or simulated) operational and maintenance tasks, under actual or realistic operating environments, and using garments and equipment appropriate to the tasks involved in the tests. The plan shall require that all failures occurring during test and evaluation shall be subjected to a human engineering review to differentiate between failures due to equipment alone, personnel-equipment incompatibilities and those caused by personnel alone. The contractor shall identify and notify the procuring activity of suspected design conditions which contributed substantially to or induced human error and shall propose appropriate solutions to these conditions.

7.4 *Human Engineering Test Reports (HETR)*—An HETR shall be prepared for each human engineering test conducted. It shall describe the equipment tested, the test conditions, test subjects, test procedures, results, and design recommendations coming from the test results. For small or less complex systems, the HETR may be submitted as part of the HEPR.

## 8. Documentation

8.1 *Data Requirements*—Human engineering data requirements shall be as specified by the contract. See Appendix X2.

8.1.1 *Traceability*—The contractor shall document his human engineering efforts to provide traceability from the initial identification of human engineering requirements during analysis or system engineering, or both, through design and development to the verification of these requirements during test and evaluation of approved design, software, and procedures. Each human engineering input made during design, construction, and test shall be recorded to indicate that the input was included in the finished product or rationale for exclusion.

8.1.2 *Access*—All data, such as plans, analyses, design review results, drawings, checklists, design and test notes, and other supporting background documents reflecting human engineering actions and decision rationale, shall be maintained and made available at the contractor's facilities to the procuring activity for meetings, reviews, audits, demonstrations, test and evaluation, and related functions.

## 9. Keywords

9.1 drawings; equipment; human engineering; human engineering program; human factors; program; ships; system

## APPENDIXES

### (Nonmandatory Information)

## X1. TAILORING GUIDE FOR PRACTICE F 1337

### X1.1 Scope

X1.1.1 It is not expected nor desired that every human engineering activity contained in this practice should be completed on every marine contract. Therefore, this practice is deliberately constructed to allow the procuring activity, (or the contractor, if directed to do so), to choose only those activities that will directly benefit each contract. This appendix provides guidance and selection criteria to assist in picking from all the human engineering activities described in this practice only those that are necessary for each contract.

### X1.2 Tailoring

X1.2.1 *General*—The underlying purpose for any human engineering program on an equipment, system, or platform design and development contract is to influence the design of the hardware/software, not to produce paper. Lengthy studies, unnecessary analyses, wordy progress reports, simulation studies that make no direct contribution to design, unproductive human engineering test programs, and system analysis studies done after design is frozen are wasteful and undesirable. Thus, every human engineering activity included in a contract must be directly oriented to maximizing the human's contribution to the overall successful operation of the hardware/software under design. That is why decisions to include human engineering and which activities, must be done by human engineering specialists, either at the procuring activity, or within the contractor's organization.

X1.2.2 *Selection Guide:*

X1.2.2.1 *General*—The decision as to whether or not to invoke this practice as a mandatory provision on design and development contracts for marine equipments, systems, or platforms is dependent on several factors including: (*1*) the type of hardware/software (in terms of operation and maintenance requirements), (*2*) the degree to which the human is involved in the operation or maintenance of the hardware/software, and (*3*) the point in the design process when human engineering becomes involved. Use of any, or all, of the requirements in this practice should not normally depend on hardware size (that is, big ship versus little ship), system complexity, hardware duty cycles, number of human operators/maintainers involved, or, within practical limits, the contract type, cost, duration, or size of production lots. These factors may influence the kind, or number, of human engineering activities selected for the contract, but not the decision to include or exclude a human engineering program in the contract.

X1.2.2.2 *Specification Requirement*—For most contracts, but particularly fixed price contracts, the specification, circular of requirements (COR), or statement of work (SOW) shall clearly define which of the human engineering activities from this practice shall be performed by the contractor. The responsibility for selecting these activities must rest with the human engineering specialists within the procuring activity. For cost plus contracts, the contractor is sometimes given the responsibility to define the human engineering program, with procuring activity approval. Therefore, this tailoring guide should be used by whomever shapes the human engineering program.

X1.2.2.3 *Selection Guidelines (General)*—Generally, human engineering activities from this practice should not be included in a contract that covers parts, subassemblies, or other small components (for example, bearings, transformers, wheels). Likewise, the practice should normally not be considered for use in hardware/software development contracts where human involvement or interface is obviously insignificant. In contrast, if the request for proposals (RFP) specification, or other contract documentation states performance requirements or goals (for example, accuracy, time limits, maximum error rates, mean time to repair) to which the human operator/maintainer can reasonably be considered to contribute, then this practice should be employed.

X1.2.2.4 *Phases of the Acquisition Process*—There are distinct phases in the acquisition of a new platform (ship), system, or equipment. For a system or equipment these are normally concept exploration, demonstration and validation, full scale development, and production and deployment. For a ship these four phases are feasibility studies, preliminary design, contract design, and detail design and construction.

X1.2.2.5 *Selection Guidelines (Particular)*—A more specific guideline for selecting particular activities from the practice is included in Table X1.1. The table shows the human engineering activities and requirements, identified by paragraph number and title. It also shows the four stages of the design process commonly found in the marine design and development world. For each intersection of design phase and human engineering activity a letter indicates whether the activity is normally required (*R*), possibly completed (*P*), or normally not completed (*N*) for that design phase. A (—) implies that the activity discussed in the practice is given for informational purposes only and not as a contract requirement. Table X1.1, therefore, provides some guidance as to where along the design and development process each of the human engineering activities should be applied.

X1.2.2.6 *Evolutionary Design and Development*—The use of Table X1.1 is directed at the design and development of new equipments, systems, or platforms. However, much of the design effort in the marine world is devoted to improving one particular piece of equipment, or upgrading one, or a few, compartments on a platform (for example, overhaul of a ship engine room or conversion of a propulsion plant). It is also common to take an existing system (for example, lube oil, water purification, sanitary treatment) or platform (that is, ship) and design and build a new one while using much of

TABLE X1.1 Human Engineering Application Matrix

NOTE—*R* = Normally required
*P* = Possibly completed
*N* = Normally not completed
— = Information purposes only

| Section in F 1337 | Title of Section | Concept/ Feasibility | Validation/ Preliminary | Development/ Contract | Production/ Design/ Construction |
|---|---|---|---|---|---|
| 1 | Scope | *R* | *R* | *R* | *R* |
| 2 | Referenced Documents | *N* | *R* | *R* | *R* |
| 3 | Terminology | — | — | — | — |
| 4 | Summary of Practice | — | — | — | — |
| 4.1 | Human Engineering Program Plan | *R* | *R* | *R* | *R* |
| 4.2 | Quality Assurance | *R* | *R* | *R* | *R* |
| 4.3 | Nonduplication | *R* | *R* | *R* | *R* |
| 4.4 | Cognizance and Coordination | *R* | *R* | *R* | *R* |
| 5.1 | Intended Use of Practice | — | — | — | — |
| 5.2 | Scope and Nature of Work | — | — | — | — |
| 5.2.2 | Design and Development | *R* | *R* | *R* | *R* |
| 5.2.3 | Test and Evaluation | *N* | *N* | *N* | *R* |
| 6 | Human Engineering Activities | — | — | — | — |
| 6.1.1 | Operational Requirements | *R* | *N* | *N* | *N* |
| 6.1.2 | Mission Requirements Analysis | *R* | *P* | *N* | *N* |
| 6.1.3 | System Requirements Analysis | *R* | *P* | *N* | *N* |
| 6.1.4 | Function Definition | *R* | *P* | *N* | *N* |
| 6.1.5 | Function Allocation | *R* | *P* | *N* | *N* |
| 6.1.6 | Equipment Selection | *R* | *P* | *P* | *N* |
| 6.1.7.1 | Human Engineering System Analysis Report (TYPE 1) | *P* | *P* | *N* | *N* |
| 6.1.7.2 | Human Engineering System Analysis Report (TYPE 2) | *N* | *N* | *P* | *P* |
| 6.1.8.2 | Gross Task Analysis | *N* | *P* | *P* | *P* |
| 6.1.8.3 | Critical Task Analysis | *N* | *N* | *N* | *P* |
| 6.1.9 | Human Engineering Design | *N* | *P* | *R* | *R* |
| 6.1.10 | Application of Lessons Learned | *P* | *P* | *P* | *P* |
| 6.1.11 | Engineering Design Drawings | *N* | *R* | *R* | *R* |
| 6.1.12 | Human Engineering in Vendor Hardware/Software | *N* | *N* | *P* | *R* |
| 6.1.13 | Studies, Experiments, and Laboratory Tests | *N* | *P* | *P* | *N* |
| 6.1.14 | Dynamic Simulation Studies | *N* | *P* | *P* | *P* |
| 6.1.15 | Mockups and Models | *N* | *P* | *P* | *R* |
| 6.1.16 | Human Engineering in Performance and Design Specifications | *P* | *P* | *R* | *P* |
| 6.1.17 | Equipment Procedure Plates and Manuals | *N* | *N* | *N* | *R* |
| 6.1.18.1 | Human Engineering Design Approach Document–O | *N* | *N* | *N* | *P* |
| 6.1.18.2 | Human Engineering Design Approach Document–M | *N* | *N* | *N* | *P* |
| 6.1.19 | Human Engineering Progress Reports | *P* | *R* | *R* | *R* |
| 7.1 | Human Engineering in Test and Evaluation | *N* | *N* | *N* | *R* |
| 7.3 | Human Engineering Test Plan | *N* | *N* | *N* | *P* |
| 8 | Documentation | — | — | — | — |
| 8.1 | Data Requirements | *P* | *R* | *R* | *R* |
| 8.1.1 | Traceability | *R* | *R* | *R* | *R* |
| 8.2 | Access to Data | *R* | *R* | *R* | *R* |

the old one as a baseline design. Under these circumstances it is normal procedure to apply the human engineering activities listed in the practice to only those equipments, systems, or platform alterations which are being changed from the baseline. As for the specific activities to be included, those listed for detail design and construction are the most likely to be appropriate.

X1.2.2.7 *Summary*—Although the general and particular guidelines provided above can be helpful in tailoring the human engineering requirements contained in this practice to a specific design and development contract, they are not foolproof. That is why it is so important to have the tailoring done by a human engineering specialist with experience in the marine design and construction business. No tailoring guide can be as effective in defining a good human engineering program as the academic and experiential background possessed by a human engineering specialist in the marine world.

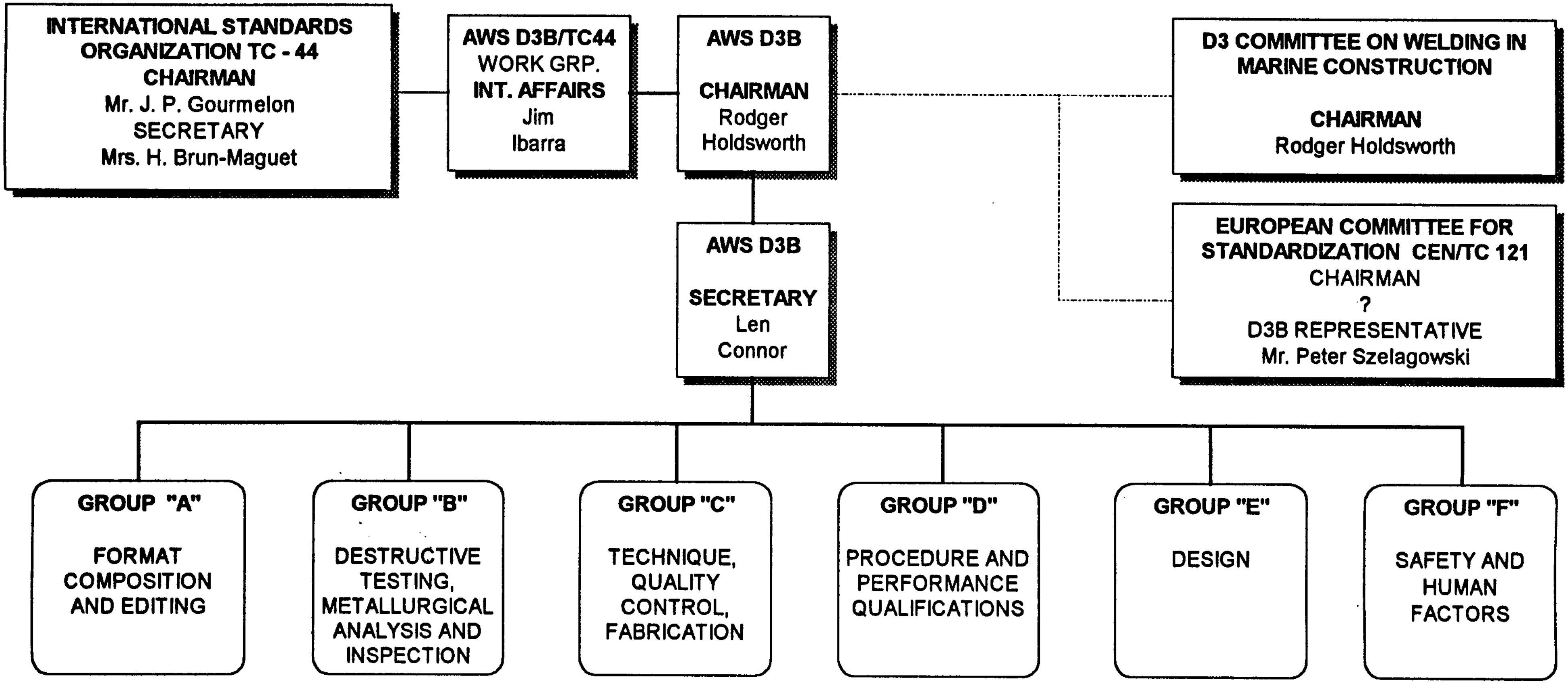
## X2. DATA REQUIREMENTS

X2.1 *Government Data Requirements*—For government procurements, in which the use of a Contract Data Requirements List (DD 1423) is a requirement, the Data Item Descriptions (DID) should be used when applicable.

X2.2 *Commercial Data Requirements*—For commercial procurements, the data requirements should be included in the contract in the manner commonly used for other data requirements.

APPENDIX C

# AMERICAN WELDING SOCIETY D3B SUBCOMMITTEE ON UNDERWATER WELDING



| GROUP "A" | GROUP "B" | GROUP "C" | GROUP "D" | GROUP "E" | GROUP "F" |
|---|---|---|---|---|---|
| **GROUP CHAIRMAN** | **GROUP CHAIRMAN** | **GROUP CHAIRMAN** | **GROUP CHAIRMAN** | **GROUP CHAIRMAN** | **GROUP CHAIRMAN** |
| Jim O'Sullivan | Jack Couch | Rob Murray | Tom Reynolds | Anthony Harjo | Shawn T. Cullen |
| **GROUP MEMBERS** | **GROUP MEMBERS** | **GROUP MEMBERS** | **GROUP MEMBERS** | **GROUP MEMBERS** | **GROUP MEMBERS** |
| Tiny Von Rosenberg | Cliff Anderson | Whitey Grubbs | Greg Cain | Buddy Delaune Jr. | Mike Blumenberg |
| Jessie Grantham | Mike Sammons | Duke Ogden | Tom Payne | Shelton Fortenberry | |
| Bill St. Cyr, II | K. Berard | Ron Rowland | Tom West | Prof. K. Masubuchi | |
| Peter Szelagowski | E. Klein | David Reznik | D. Noble | John Steinmetz | |
| Iwan Pachniuk | Doug McKay | Victor Kononenko | S. W. Scot (AWS Q&C) | J. M. Sturrock | |
| Jim Ibarra | Fon Stonum | | P. D. Watson | | |
| Felix Dyhrkopp | Graham Rand | | | | |

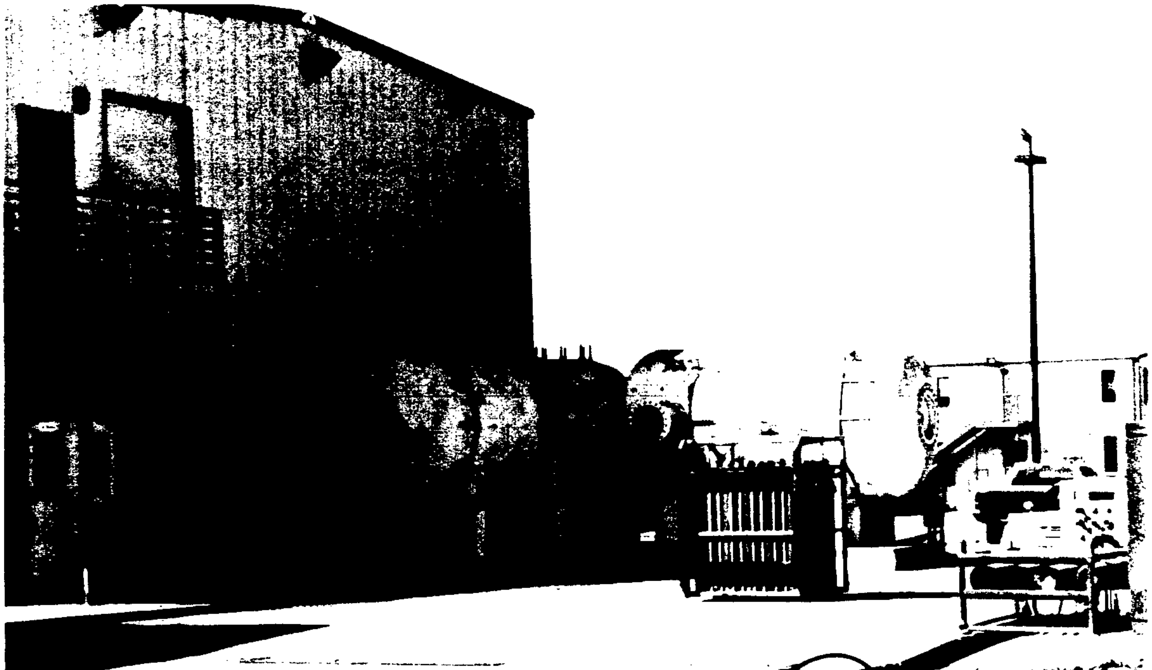
# Appendix D

# Trip Report for College of Oceaneering

## Site Visit

Los Angeles Harbor

September 3, 1997



## Background On College Of Oceaneering

The College of Oceaneering was established in 1969 to train commercial "hard hat" divers. From an initial class of six students, the College of Oceaneering has grown to graduate upwards of 450 qualified, entry level professional divers each year. Over the years, the College has successfully trained more than 7,000 divers to work in the high profile offshore oil industry, as well as in the world's harbors, lakes, rivers, dams and other inland diving jobsites. (College of Oceaneering Website, http://diveco.com/history.html)

The curriculum includes training in the fundamentals of surface supplied diving and specialized training in one of three programs, MedTech©, SpecTech©, or WeldTech.©

The MedTech© program provides training in hyperbaric medicine. The SpecTech© program provides training in underwater inspection procedures. The WeldTech© program consists of topside and underwater burning and welding training and advanced courses in the technology of wet shielded arc welding. This program, designed for the candidate who wants to specialize in the technology of underwater wet welding, was the primary area of interest for the site visit.

### *Personnel*

Mr. Duke Odgen, Head of Wet Welding Training, sponsored the visit. Several College of Oceaneering employees and students were observed on the training site, and four staff members were interviewed. The employees interviewed were Mr. Duke Odgen, Underwater Welding Instructor, Mr. Ernest Barton, Director of Training, Mr. Eric Hexdall, Diving Physics Instructor, and Mr. Tom Mix, Lead Pier Diving Instructor. All personnel interviewed had at least five or more years of experience in the commercial or military diving industries prior to assuming their positions at the College. Qualitative information from discussions with the staff members is summarized throughout this report.

### *Objective*

The primary objectives of the visit included familiarization with the commercial diving industry, on site evaluation of the industry standard commercial diver selection and training processes, evaluation of the school's role in placement of the new diver within the commercial diving industry, and the discussion and observation of the role of Human and Organizational Factors (HOF) into underwater welding training and selection.

### *The Commercial Diving and Welding Industry*

The typical career path for divers and underwater welders, according to the Oceaneering staff members includes working for three to four different companies for five to seven years each. Later in their career, more experienced divers often transition into freelancing, working as an independent contractor where the diver is hired on a project basis.

According to Mr. Mix in most cases the industry pay scale is based on an hourly wage with depth pay, equipment rental, and other specialty pays such as underwater welding pay or certified inspector pay. For example, a certified underwater welder may receive an hourly wage, depth pay of $1.25 per foot of sea water (FSW) provided the depth is greater than 50 FSW, a per diem equipment rental allowance, and a separate fee based on his qualification in welding procedures.

The typical qualified welder - diver shift on an offshore platform may involve only four hours of actual labor. For example, when performing underwater welding at depths requiring surface decompression, the diver would perform one radio watch for another diver's dive for twenty minutes, one dive for twenty minutes with up to 1.5 hours of decompression, and one twenty minute rotation dressed out as the standby diver. It is important to remember that the role as an underwater welder in the rotation is normally earned through several years of increased competency in diving and welding and intense topside labor as a tender. According to Mr. Odgen, graduates from an accredited diving school typically have at least one year as tender, breakout as a lead tender in one to one and one half years, and then assume the role a diver in the rotation.

Within the commercial industry, divers do not perform work on deck such as rigging and maintenance of the topside diving station. These tasks are reserved for the inexperienced tenders. The relationship between the tender and diver often uses the buddy system with each tender assigned to a specific diver. As a result a mentor - protégé relationship has evolved where the experienced divers rotate the task of being assigned the newest tender. The experienced diver informally assumes the responsibility of training this new or "green" diver in all the tasks which much be mastered before the tender enters the rotation as a working diver. A shortage of qualified divers in the industry leads to an increased sense of urgency in training of the tenders to become divers.

During the site visit several observations where made regarding the difference between diving within the military, the author's primary area of expertise, and the commercial diving industry. The primary differences can be found in dive team redundancy, the emphasis on personal responsibility and accountability, the amount of formality in diving system re-entry control procedures, and the emphasis on timely production.

It was noted that far fewer team members were utilized by the commercial industry in comparison to military diving. During the training phase on the welding pier, four diver - tender pairs were typically in the water at one time under the supervision of the welding instructor. For a military dive, the same four divers would require two tenders each, four separate communications personnel, a console operator, and a diving supervisor for a total of at least eighteen.

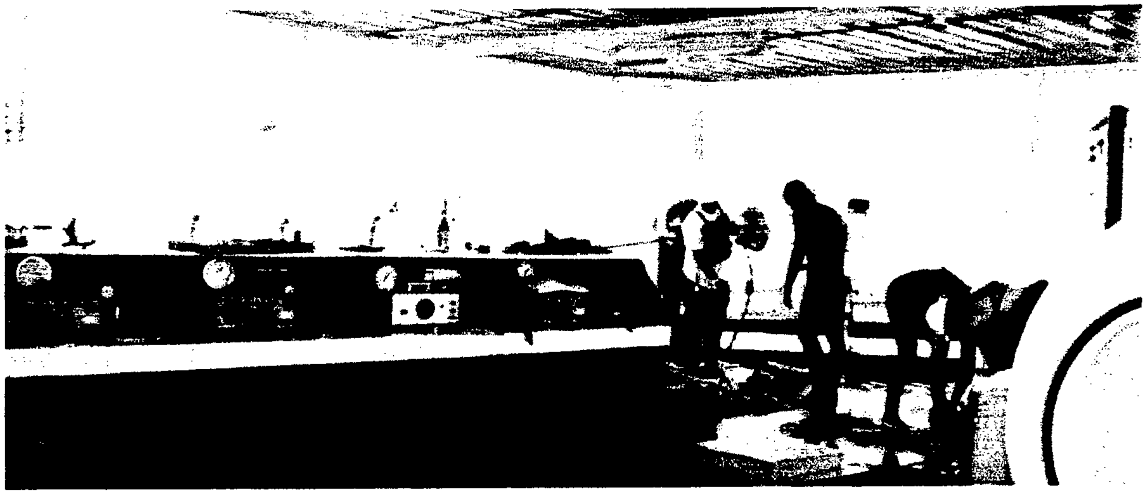


**Figure 1 - Pierside surface supplied dive station. Diver trainees conduct their first open water dives at this location where they are first exposed to cold water, low visibility conditions.**

According to discussions with Mr. Hexdall, an ex-Navy Diving Officer, the commercial diving industry places a greater emphasis on personal responsibility of the diver than the Navy. For example, more effort is taken by authorities to find the person causing the unsafe act and penalize or dismiss that individual responsible. Conversely, the Navy's approach to accident investigation and correction, tends to rely more on identifying the procedural errors and incorporating new procedural requirements intended to make diving "diver proof" without placing blame on an individual.

Another fundamental difference between commercial and Navy diving is the Navy's use of intensive, documentable Diving System Re-Entry Control Procedures (REC's) compared to the commercial industry's less structured approach. Under the Navy system, maintenance or repair of any life support system involving disconnecting system components requires detailed documentation, prior approval from the Naval Sea Systems Command (NAVSEA) in Washington, and NAVSEA system completion certification. In the commercial industry there is no overall requirement for such an exhaustive documentation and approval chain.

## General Structure Of Commercial Diver Training

The overall College of Oceaneering curriculum consists of a year of training two days per week, either Monday-Wednesday or Tuesday-Thursday. The overall tuition costs approximately $14,000 and is covered by government sponsored financial aid.

The program is accredited by the Western Association of Schools and Colleges. It is designed to provide divers for all areas of commercial diving, but most staff members appear to gear their training to for work in the offshore oil industry, more specifically work in the Gulf of Mexico.

When asked characterize life in the industry and the inherent stressors found there, most staff members cited the distant location, the oil company politics, the large amount of money involved, competition among employees, the long hours, confined living spaces, and the time away from normal life.

## Steel Barge Project

The steel barge project makes up the final part of the general diving program. Prior to the steel barge phase students learned all of the skills and procedures necessary for surface supplied diving. Students receive intensive classroom training in diving physics and diving procedures, dive rig familiarization and emergency procedure training in the dive tanks, and practical diver tool and rigging experience through a series of pier dives. Once students have completed all of the practical exercises in operating diving rigs and equipment, they proceed with the steel barge project. The project is performed by a team comprised of the Monday-Wednesday class and the Tuesday-Thursday class. The team is directed to an empty steel barge docked at the pier. Students are required to properly set up the empty barge for diving and complete a prescribed project without the aid of instructors.

This phase of the training is designed to teach through trial and error and to encourage team work. Each of the two shifts is organized into a team structure consisting of several assignments: student supervisor, lead tender, diver safety officer, and project manager.

**Figure 2 College of Oceaneering Steel Barge**

The project consists of assembling a large manifold underwater. The manifold piping, approximately twelve inches in diameter, is assembled using bolted flanges. All of the large piping components for the project are left unassembled on the floor of the harbor by the previous class.

The project team must complete several steps in order to successfully complete this phase of training. First, the team completes a detailed bottom survey to locate and identify all of the components. Next the team devises a plan for recovery of the piping and fabrication of the manifold. Once the plan is approved by the instructor, divers begin retrieving the components and then assemble the manifold on the harbor floor. After the vessel is built to the team's satisfaction, a mandatory final survey is conducted and a formal report is submitted to the instructor. Lastly, the instructor conducts a pressure test on the system. Should the system pass the pressure test on the first try, all members of the team receive an "A," otherwise, students rework the system until it passes.

Two unique aspects of this portion of the diver training are the team grading and the pass down of project status between shifts. Prior to the steel barge project, all grades are awarded on an individual basis. In order to emphasize the importance of working together to complete a large project, a team grade is employed for this phase. According to the instructors interviewed, the use of this team grade results in peer pressure motivating the less productive divers. It also polarizes the organization into leaders and followers. The lessons learned by the students from the shift pass down are equally interesting. Since both classes work for the same grade, cooperation is in everyone's best interest. Communication skills are honed as the result of the information passing down responsibilities. Shift project managers are given no procedural directions for passing down of the project status. They are free to use any communications they desire, e. g. telephone call or written report. To verify the status the first dive of the day is always an inspection dive.

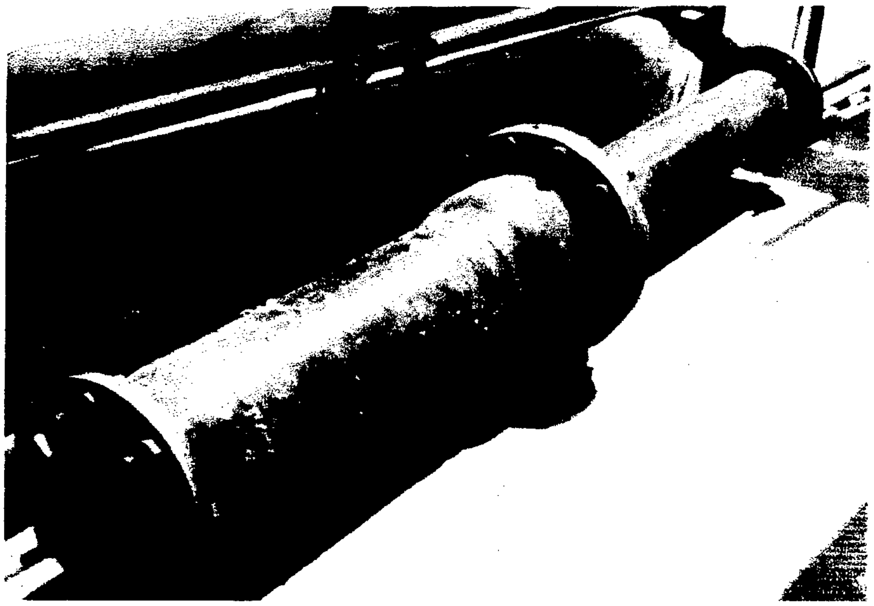


**Figure 3 - Typical piping section found on the bottom, used in team manifold assembly project.**

## Dive System Maintenance

Diver trainees are not expected to perform maintenance on diving helmets or diver life support system equipment. Instead, maintenance of all diving equipment is performed by the maintenance shop. Maintenance is performed by the shop in order to minimize liability problems which could possibly result from students performing maintenance and to closely mimic the commercial diving industry where maintenance is not normally performed by the highly paid divers.

Unlike in the industry, student divers do not own their own hats and rigs; therefore, they are not responsible for performing maintenance on their equipment. Normally, divers purchase there own rig when they have "broken out" from lead tender to diver. The school does offer a separate Divers Supply Inc. (DSI) sponsored program for maintenance training.

## Selection Requirements

Entry into the College of Oceaneering training course requires a high school diploma or equivalent. Students are also required to take a T.A.P. test, which is a standardized test that measures math computational skills, language skills, , spelling, and reading. If a student scores below the seventh grade level, he or she must receive mandatory peer tutoring during the class room phase of instruction. Applicants are required to take a physical exam in accordance with the ADC Consensus Standards. No pressure or oxygen testing is required for entry. However, students are pressed down to 165 FSW during training to demonstrate the narcotic effects of pressure on the diver's dexterity and mental capacity.

The curriculum of the underwater welding program consists of twenty weeks of class with classes meeting two days per week. Students must first complete two basic requirements for entry into program: (1) be a qualified diver who has completed Oceaneering surface supplied dive program and (2) be surface welder qualified on at least one shielded metal arc welding procedure, usually horizontal.

A review of the underwater welding curriculum and discussions with the Mr. Odgen revealed a teaching strategy which emphasizes not only key underwater welding skills but also a broad range of personal work habits and team oriented behaviors which are necessary for success in any job. The lack of substantial prior work experience of many of the students combined with the intense focus necessary for success in the often highly stressful offshore oil industry necessitate the "whole person" approach taken by the underwater welding program. According to Mr. Odgen the average students entering the welding portion of the program are 21 or 22 years old with little "passion" for anything in life.

The curriculum, designed to train the whole person, rewards hard work, quality, consistency, honesty, and professionalism. Laziness is not tolerated at any time in the twelve hours of instruction per day. Students are relentlessly pushed throughout the curriculum. Students are reminded from the beginning of their training that success as an underwater welder is achieved by mastering the art of delivering a quality weld consistently over time. The highest levels of honesty and integrity are expected by all members of the group. There is a formal chain of command among students and the instructor, and everyone is addressed by last names.

Many of the students are accomplished surface welders prior to entry in the underwater welding program. Those prior surface welders often have a hard time switching to underwater techniques due to the difference between the touch required on the surface and the touch required underwater. A small minority of the students, approximately 10 to 15%, are ex-military welders from the Navy's Shore Intermediate Maintenance Authority (SIMA) welding program or from the Army's Metal Workers School. According to the instructor the Metal Workers School students tend to be some of the best students.

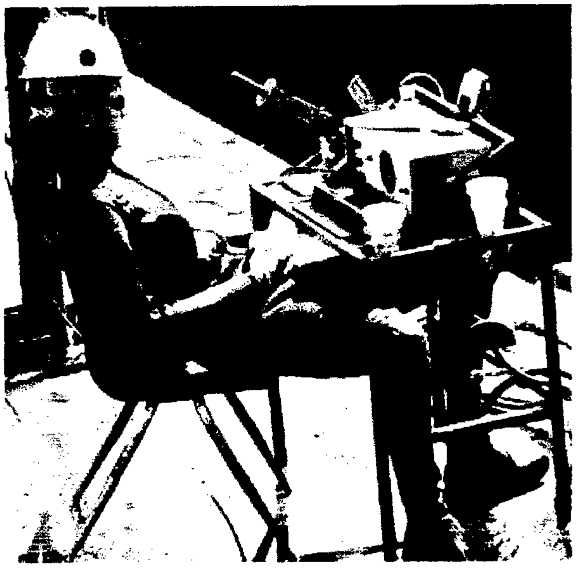


**Figure 4 - Tender monitoring communications with underwater welding student.**

All students are required to learn topside arc welding prior to beginning the underwater portion of the class because according to the instructor, "You can't learn to weld underwater, you must learn topside first." For those students with no prior welding training, the school has developed a relationship with a local vocational school to teach the topside portion. Students must qualify in at least one surface procedure, a horizontal procedure, prior to beginning the underwater portion.

Completion of the course includes 75-80 hours actually welding underwater. Much of the remaining instruction time is spent preparing to weld. According to Mr. Odgen, "Underwater welding is 95% preparation, 5% welding."

Most students have qualified several procedures by the time they finish the curriculum. Qualification consists of performing welds underwater which exceed the AWS D3b specifications as well as meet the even tougher constraints imposed by Mr. Odgen. Upon completion of their welds, students bring the coupons to the surface where they are inspected by Mr. Odgen, a certified welding inspector (CWI). To avoid a conflict of interest, those coupons which are deemed acceptable by Mr. Odgen are taken to an unbiased CWI outside of the training organization for final certification.

The underwater welding staff recognizes that the underwater welding portion of the training only produces "coupon welders" who are not prepared to perform the rigorous, highly varied wet welds encountered in the commercial diving industry. To supplement the development of the student's underwater welding skills, the curriculum includes performance of topside metal working projects designed to promote team building, enhance project management skills, and, in general, impose additional demands on the student, thus improving time and stress management. The topside projects involve the fabrication of practical metal working projects needed by the College or other local businesses. The projects usually require several weeks for completion and involve work from many students in both the Monday-Wednesday and Tuesday-Thursday class rotations. As a result, students learn to properly allocate resources, manage time, and most importantly, to properly stage unfinished projects for the subsequent shift to assume the work. The latter skill is particularly valuable in the shift work oriented offshore oil industry.

The work projects ongoing at the time of field visit included fabrication of the following steel structures:

- a submarine lifting device
- an offshore frame for a Hobart Welder
- a mobile dive control shack
- a riser clamp for a portable Deck Decompression Chamber for chamber

Through these types of welding intensive, multiple person, topside projects Mr. Odgen builds cohesive teams and pride in accomplishing useful projects.

In addition to incorporating an emphasis on the importance of teamwork, the underwater welding curriculum also imposes a great deal of stress on students in attempt to simulate the living and working environment encountered within the underwater welding industry.

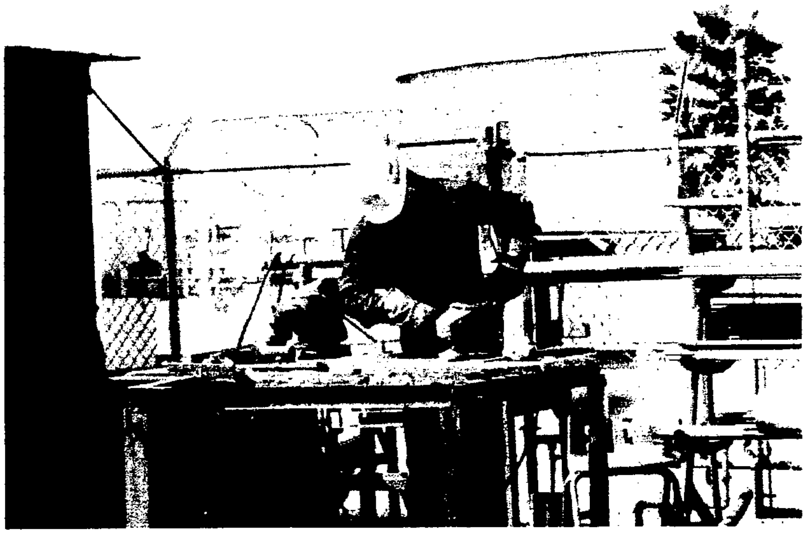


**Figure 5 - Student welder-diver working on topside welding project.**

The students' daily schedule involves a twelve hour work day which typically includes reporting for work promptly at 5:30 A.M., welding-diving station setup until 6:00 A. M., work on topside projects from 6:00 - 8:00 A. M., underwater welding from 8:00 - 2:00 P.M., more topside projects from 2:00 - 4:30 P. M., and station breakdown and clean up until 5:00 P. M. According to discussions with the instructor, this stressful curriculum keeps students busy. The rigorous workday is intended to force multi - tasking and promote an intense focus.

An additional level of stress is placed on the students through the instructor's teaching style. Mr. Odgen admittedly uses fear as a motivator, and from all observations, his approach is effective. Students are expected to perform their assigned tasks and work together as a team or face the consequence of answering to the instructor, a burly ex-Navy Seal and commercial underwater welder of many years.

**Figure 6 - Knifeswitch mounted topside, opened by tender on welder-diver's command or in case of emergency.**

According to the underwater welding staff, the stress level imposed on the students during training keeps graduates from the College in high demand because the long days and hard work prepare them for tremendous stress which they will later encounter in their work offshore. By all accounts, life offshore is much more stressful, too stressful, in fact, to be simulated at the College.

According to instructors, graduates are usually sent off to their first job interview in Louisiana or Texas. For many of them the farthest distance they have ever traveled in their lives. When they arrive at their destination, they are nervous about the interview, and they are alone in a strange new place. Furthermore, managers often assume that "the new guys know a lot more than they really do know" according to Mr. Odgen. After getting the job, the new employees are sent offshore as tenders. They face many new stressors within the industry such as drug testing and the potential consequences of missing the crew boat. According to one estimate all of this stress combined with the inherent stress of underwater welding leads to 70% of all new welder-divers quitting within 90 days.

## Placement of Students in The Offshore Diving Industry

According to school officials approximately 95% of the hundreds of newly trained divers hired annually by diving companies in the Gulf of Mexico (GOM) are from the five Association of Commercial Diving Educators (ACDE) accredited schools. There is, however, a recurring shortage of qualified divers in the GOM.

The College of Oceaneering sends roughly 60 welder-divers to the GOM per year with the majority of them going to work for Caldive or Oceaneering. Of those going to work in the GOM, often as little as ten percent or less stay for more than a few months.

Placement of welder-divers is usually arranged by the welding instructor based on the presumed fit between the company's culture and welder-diver's personality. The international nature of the offshore industry forces employees to work with people of many different cultures. The instructor's prior working knowledge of the companies can ensure a higher probability of a student's success in the industry. For example, a less self-confident welder-diver would not be well suited to work for a large international diving company with a hierarchical structure. By placing this welder-diver in a smaller family run company there would be a better fit.

## Human And Organizational Factors

When asked to elaborate on his vision of the role of HOF in underwater welding selection of team members with skills for job, Mr. Odgen identified the following four key issues:

1. Design engineers rarely consider human factors during the design of procedures for wet weld repairs to structures.

2. Human factors are often more important considerations in wet welding than in hyperbaric welding because of the greater variability in wet weld designs than in hyperbaric weld designs.
3. Quality of welds is the aspect of underwater welding with the greatest potential for improvement through greater consideration of HOF.
4. In the commercial diving industry, productivity is routinely measured in bottom time. Since bottom time is solely a function of human factors, specifically the diver's susceptibility to decompression sickness, diving is one of the few construction specialties in which HOF are directly proportional to productivity.

## Safety In Wet Welding

According to Mr. Barton, the College's Director of Training, an estimated 75% of all underwater welding accidents which occur are basic industrial safety accidents, injuries common to all industrial and construction environments (i. e. tripping, falling objects, etc.) Approximately 15% of the underwater welding accidents involve diving safety issues such as barotrauma, arterial gas embolism (AGE), and decompression sickness. According to Mr. Barton's estimate, the remaining 10% of underwater welding accidents are the result of conditions unique to underwater welding such as injuries caused by the welding electrode and the ignition of flammable gases caused by the intense heat.

According to discussions with Mr. Odgen, a well trained, well supervised group of welder-divers is not at a high risk for serious accidents. Based on his years of experience, electrocution does not occur as a result of contact with the welding electrode. For example, provided that the welder actually touches the electrode to the metal portion of the diving helmet, the shock would provide a stunning jolt to the diver perhaps knocking the welder-diver over, but the force would not kill or cause serious injury. This statement appeared to contradict his earlier reference during student instruction to the "killing zone," the area from the neck to top of head where the electrode is normally positioned during wet welding. It is believed that this reference is used to emphasize potential for a serious, if not life threatening, jolt.

Mr. Odgen also stated that there are few incidents of burns caused by passing the welding arc across a diver's appendage. According to Mr. Odgen the greatest risks occur due to wave surge during welding in the splash zone.

As a result of the observations and informal discussions conducted during the tour of the College of Oceaneering, many insights were made regarding the general training and selection processes involved within the wet welding and commercial diving industry. Specifically, the visit reinforced the author's understanding of the roles that stress, teamwork, and company culture play in wet welding. The intense pressures associated with life in the offshore industry increase the need for the study of stress and performance in diving. The importance of teamwork within the industry is rooted in the preparation phase of underwater welding. Since preparation for wet welding requires such an intense effort by the entire team it makes sense that an understanding of team dynamics is a key to the success of wet welding. Instructors at the College continually identified the corporate culture differences among the various diving companies that make up the industry. Understanding the role of these cultures and the role of the individual diver within them is a key element in ensuring the success of wet welding operations.

# Appendix E

## Trip Report

for

# Global Divers and Contractors, Inc.

## Site Visit

New Iberia, Louisiana

October 10, 1997

## Background On Global Divers and Contractors, Inc.

Global Divers and Contractors, Incorporated is a wholly owned subsidiary of Global Industries, Ltd. which specializes in deepwater diving, saturation diving systems, underwater welding technology, subsea completions, and nuclear power plant diving. Global has over twenty-five years of experience as a diving contractor. Global's accomplishments include their deepest working dive of 1075 fsw in the Gulf of Mexico, underwater wet welding procedures qualified to 325 fsw, and hyperbaric dry welding procedures qualified to 680 fsw.

### *Personnel*

Dr. S. "Jim" Ibarra, a Metallurgy/Weld Consultant for Amoco Corporation's Worldwide Engineering and Construction Division funded the visit, and Mr. C. E. "Whitey" Grubbs, Global's Director of Underwater Welding Research and Development sponsored the visit. Mr. Grubbs provided a tour of the diving and underwater welding facilities and an extensive history of the underwater welding industry, narrative and pictorial histories of his experiences in the application of underwater welding in offshore repairs. He also discussed the current state of the art of underwater welding procedures, and provided unique personal insight into underwater welding operations. While a field excursion to observe underwater welding operations in the Gulf had been tentatively scheduled, Global's operational commitments, and transportation restrictions curtailed the evolution.

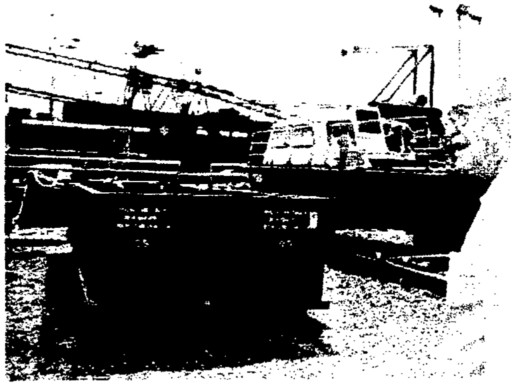


**Figure 7 - Mr. "Whitey" Grubbs, Director of Underwater Welding Research, in Global's diving yard.**

### *Objective*

The primary objectives of the visit included familiarization with the commercial diving and underwater welding industry, on site evaluation of industry standard commercial underwater welding processes, and the collection of information regarding of the role of Human and Organizational Factors (HOF) in underwater welding operations.

### *Design of Underwater Wet Welding Repairs*

Mr. Grubbs has amassed an impressive collection of photographs, drawings, and project completion reports which he utilizes as tools for marketing Global's underwater welding services and promoting underwater welding as a viable method for joining steel structures underwater. A review of Mr. Grubbs' volumes of underwater photographs of underwater welding projects provided a unique perspective of the ingenuity and creativity required in the design and performance of underwater welding of steel structures. The majority of underwater welding operations presented by Mr. Grubbs involved repairs to existing offshore structures.

The projects which were presented included repairs to a wide array of different structural configurations at varying depths. As a result of the variations in depth and configuration parameters every underwater welding repair tends to be unique. Diving system depth constraints and the required bottom times at given depths are considered to determine the most efficient underwater welding method for the given task. The configuration of the structural member must be considered due to the spatial restraints placed on the welder and the requirements to construct a weld chamber in the case of dry welding. decision to remove and do work topside vs. at depth

The underwater welding repair process involves sending trained inspectors down to assess damage to platforms. Repair procedures are then designed based on the inspector's detailed report and drawings.


**Figure 8 - Global pipe barge.**

Based on conversations with Mr. Grubbs a slight majority of the work done by Global is in support of Global's Pipeline Services; therefore, they perform many habitat welds on pipelines. Though habitat design for pipelines is not as complex as habitat design for complicated structural nodes, pipeline connections which involve vertical risers can be quite tricky. Mr. Grubbs pointed out several habitats configured for pipeline connections which are currently being stored in Global's yard. Early models of such habitats were very noisy due to flow noise from the ventilation system. Now, specially designed air diffusers are used to decrease the noise and, consequently, decrease the stress on the welder-diver. There are numerous load calculations required during the design of repair procedures to different structural members. During Global Divers' repair of the trunkline gas T-23 structure, the decision to remove and replace an entire node using wet welding required extensive load calculations.[1]

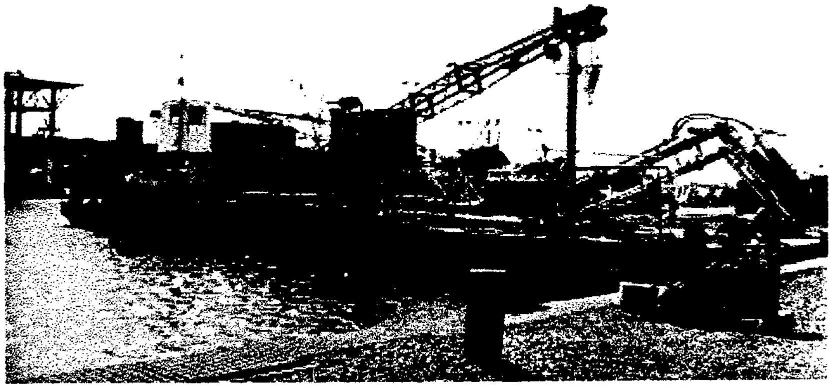


**Figure 9 -** ***Mac II, one of Global's many pipelay barges.***

One of the most interesting design elements presented by Mr. Grubbs was the use of a single scallop welding connection design in lieu of a double scallop in an effort to minimize overhead welding. The single scallop design provides the same weld connection length but eliminates the risk of a weakened connections resulting from the use of the physically complicated overhead welding procedure.

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[1] Maghes, J. M., Thomas Reynolds, and Ronnie Smith, "Hurricane-damaged platform repaired by wet welding, *Offshore, October 1995*

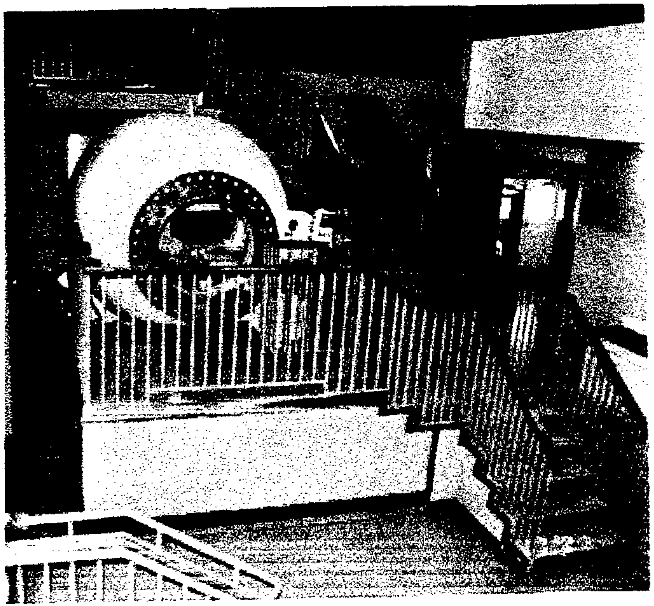

**Figure 10 - Test chamber in Global's underwater welding testing facility**

## *Welding research*

Global divers has an extensive concentration in underwater welding research. The company claims to operate the only commercial hyperbaric welding facility dedicated to research and development of underwater welding. Mr. Grubbs acts as the director of underwater welding research. His experience in the industry includes membership on the AWS committee since its inception and co-authorship of the Welding Handbook's section on Underwater Welding.[2] Additionally, Mr. Grubbs holds three patents on underwater welding procedures.

Currently Global is involved with a joint industry project to develop welding electrodes with Mobile Oil, and the Colorado School of Mines.

Much of Global's research work involves testing welding rods and qualifying of underwater welding procedures to conform with the D3B specifications. The design, fabrication, and transportation of welding rods are key elements in the success of wet welding. Global owns the rights to several welding rod designs. Rod testing is one of the key functions performed at Global's research facility. Prior to testing welding rod performance, the rods are pressure tested using a small hyperbaric chamber specifically designed for the purpose of testing pressure effects on the rod. Another innovation utilized by Global is a specially designed pressure lock used to pressurize the rod in a dry environment in order to compress voids in the rod coatings which could absorb water if pressurized in a wet environment.

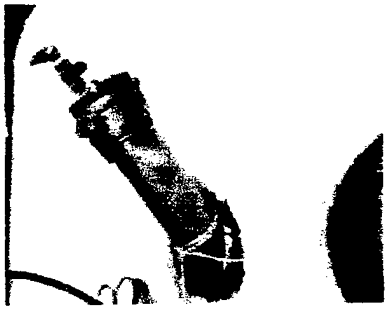

**Figure 11 - Pressure lock for compressing welding rod for use in wet pot.**

## Human And Organizational Factors

When asked to elaborate on his vision of the role of HOF in underwater welding selection of team with skills for job, Mr. Grubbs identified the following key issues:

### *Individuals - selection and training*

One of Mr. Grubbs' most intriguing anecdotes involved his successful deployment of non-divers, construction welders, as underwater welders performing hyperbaric welding procedures. Surprisingly, these welders who were specialized surface tank welders had little or no trouble adjusting to welding underwater. They did however have difficulty re-adjusting to surface welding following the completion of their underwater welding.

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[2] American Welding Society, Welding Handbook, Volume 3 - Materials and Applications, Eighth Edition, edited by William Oates, 1996 Miami

## *Contractual relationships*

Global has a fleet of 35 manned vessels which includes diving support vessels, lift boats, derrick and pipelaying barges. As mentioned earlier much of Global divers work is in support of Global Industries pipe laying barges.

This arrangement of divers working in support of their own company's projects provides an interesting contractual contrast to most diving contractors who tend to work as subcontractors for other firms. While it is difficult to determine which type of contractual arrangement provides the greatest benefit to dive safety, it does provide and area requiring further HOF study.

## *Equipment - individual interface*

Other equipment considerations demonstrated during the visit include the use of a rectifier for conversion of DC power for welding, a muck strainer for wet welding in extremely low visibility areas, and lessons learned involving procedures for operating hot water suits.

The use of an AC rectifier to produce DC current from an AC source is much quieter than traditional direct DC generators. Ideally such a rectifier could be plugged directly into existing AC power sources, but welding machines require a very steady source of power not always available from AC outlets. Usually, the power source is therefore provided by an AC generator and routed through the rectifier for use by the welding machine.

The muck strainer is a device first developed for use in welding repairs to a sheet pile wall in an area of extremely low visibility. This device which was patented as part of an underwater welding procedure is simply a vessel containing clean water with Plexiglas ends through which a welder-diver can peer through to see weld. A similar design was applied to an underwater video camera.

The use of hot water suits was discussed at great length. Hot water suits tend to scald divers because the temperature of the hot water supplied is often readjusted during the duration of the dive as the diver gets progressively colder, but the numbing effects of the cold water prevent the diver from realizing that his skin is being scalded near the inlet source of the hot water. The hot water should therefore be set initially an maintained throughout the duration of the dive in order to prevent burning the diver.

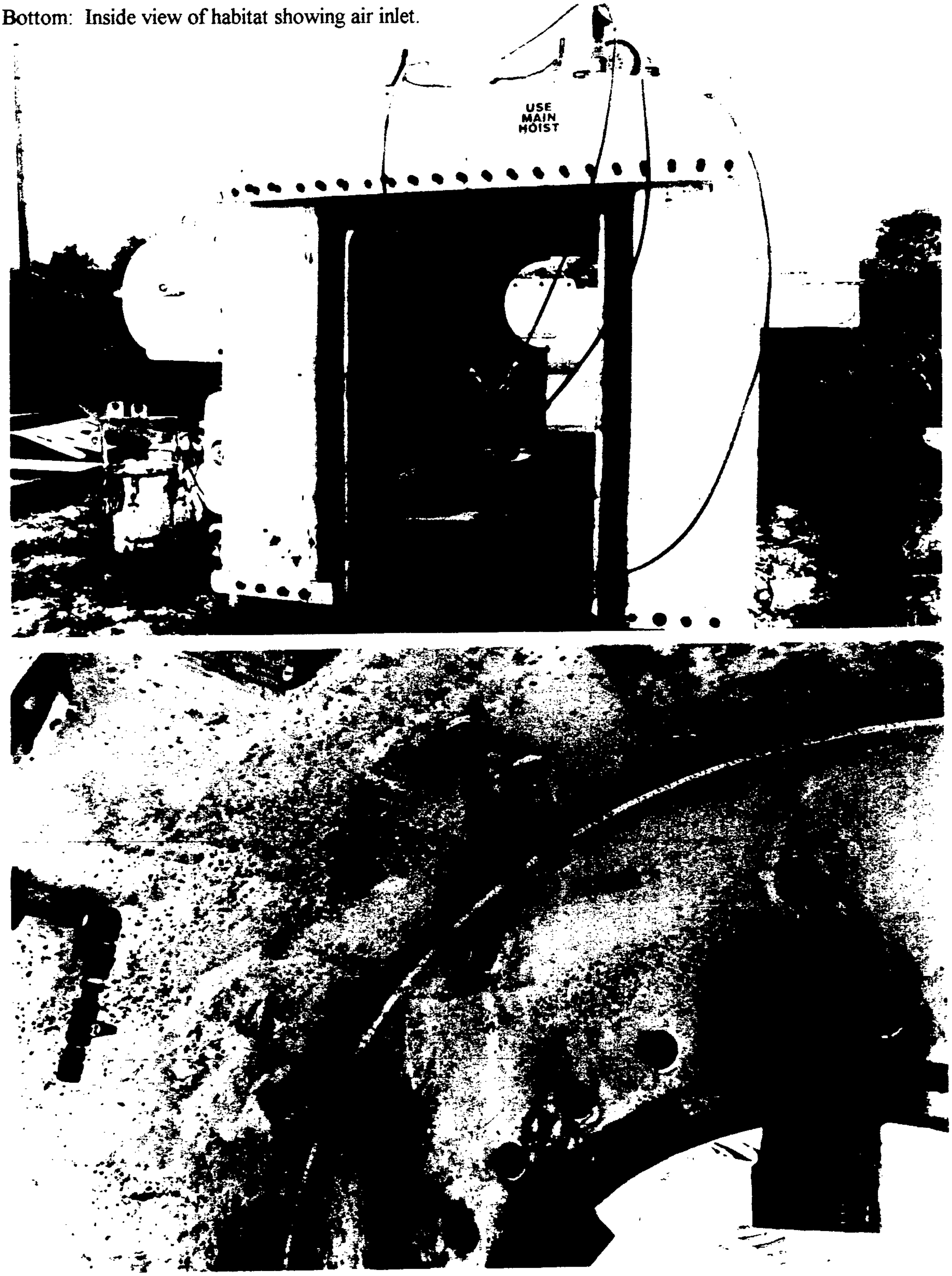
## Conclusion

The visit to Global provided perspective on the role which industry research and structural design play in the underwater welding industry. There is a great potential for incorporating HOF concepts in both of these areas. For example, HOF must be simulated in qualifying procedures and divers.

From an HOF aspect, the most useful qualitative data which came from the visit involved the role of contractual relationships in underwater welding safety, the ability of qualified surface welders to adjust to hyperbaric habitat welding, and the importance of the human-equipment interface as demonstrated by the discussion of the hot water suit and the visibly improvement devices.

Top: Welding habitat for pipeline connections.

Bottom: Inside view of habitat showing air inlet.



# Appendix F - Trip Report for Oceaneering International, Inc. Diving Division

Trip Report

for

## Oceaneering International, Inc. Diving Division

Site Visit

Morgan City, Louisiana

October 11, 1997

## Background On Oceaneering International , Inc.

The diving division of Oceaneering International specializes in the deployment of remotely operated vehicles (ROV), air, mixed gas, and saturation diving. Using these diving modes they support a wide range of underwater operations including underwater wet and hyperbaric welding.

An understanding of Oceaneering's operations was derived based on the observations during the visit and discussions with employees. The company is highly service oriented as a result of performing substantial outsourced work for large companies. In contrast to Global Industries, less of Oceaneering's diving is performed in support of Oceaneering's own operations than in support of other construction and maintenance activities. Though it began as a diving contractor, Oceaneering no longer simply considers itself as simply in the diving business but rather in the hazardous environment delivery business. In other words, the company has branched into many aspects of engineering including ROV's, one atmosphere suits, and even space systems.

Oceaneering's Headquarters office is in Houston. In addition to the regional headquarters located in Louisiana, the company also has regional headquarters in Maryland, Scotland, and Singapore and operations in over fifty locations worldwide.

Interestingly, a large portion of Oceaneering's contracts are with the Navy. These contracts include support services for the Navy's underwater welding program and ROV programs. While most of the government contracts are managed out of the Upper Marlboro, MD office, testing of welding procedures, and the training of the ROV operators occur at Oceaneering's facility in Morgan City.

## *Objective*

The primary objectives of the visit included familiarization with the commercial diving and underwater welding industry, on site evaluation of industry standard commercial underwater welding processes, and the discussion and observation of the role of Human and Organizational Factors (HOF) in underwater welding operations. Specifically the discussion of HOF in underwater welding was focused on the underwater welding repair process, welding safety, diving contractor organizational factors, and example underwater welding repair projects.

The visit included a tour of Oceaneering's ROV production facilities, a tour of the underwater welding facilities, a tour of the diving support facility, a brief on Oceaneering's most recently completed underwater welding project, and observations of wet and dry welding procedures in the land based hyperbaric facility.

## *Personnel*

Once again Dr. S. "Jim" Ibarra, a Metallurgy/Weld Consultant for Amoco Corporation's Worldwide Engineering and Construction Division funded the visit The visit was sponsored by Mr. Jack Couch, Manager of Diving Operations

## *ROV Manufacturing and Operation*

Oceaneering's ROV manufacturing facility and underwater welding facility are housed together in Morgan City with the diving support facility located across town at a separate office and warehouse complex. Though not directly related to underwater welding, the tour of the ROV manufacturing and support facility was quite interesting. Oceaneering manufactures five models based on the same design. The primary differentiating feature among the five models is the power available for propulsion. The company operated ROV's for many years and entered the ROV manufacturing business after discovering that the ROV's which they purchased and operated were difficult to repair due to the lack of available parts. To alleviate this problem they began manufacturing their own models with all five models built on a similar frame using a majority of interchangeable parts.

To date all ROV's have been manufactured for Oceaneering's own use, although the company is currently working on the delivery of its first unit for sale. It is under contract to the U. S. Navy to provide an ROV and training for Navy personnel to operate and maintain the vehicle. The maintenance training includes electronics and hydraulics modules and is conducted at the facility in Morgan City.

Each ROV has two robotic arms equipped with interchangeable tools and a separate torque devise capable of supporting most required socket sets. The vehicle is controlled from inside a fly away control console operated by two people, one navigator and one operator.

A key feature in Oceaneering's ROV operations is their ability to react quickly in the event of a lost ROV. If a vehicle is lost, a new unit can be flown in within one day and be immediately connected to same tether. This quick response minimizes delays to Oceaneering customers.

In addition to ROV operations, Oceaneering also possesses one atmosphere suit capabilities. According to Couch certain activities, such as repairing a series of riser clamps at various depths, are ideal for the one atmosphere suit. By combining surface supplied air and gas diving in shallow water, saturation diving upto 1000 fsw, deepwater ROV's, and the one atmosphere suit, Oceaneering is capable of supporting operations at all possible depths.

## Underwater Welding Facilities

Oceaneering's underwater welding tank operations are adjacent to the ROV facility. The welding tank supports both wet and dry underwater welding. The facility is structured such that wet and dry operations can be conducted simultaneously in two adjacent compartments. The facility is designed to require dry welders to enter the welding habitat by first passing through the water column. Once in the habitat, the welder can then prepare for and perform the weld. This arrangement simulates the conditions in the field and, thus, familiarizes the diver with the process of diving to the habitat, entering the habitat, dewatering the habitat, and changing into a lightweight life support mask.

During my visit, several of Oceaneering's welder-divers were qualifying the Navy's newest procedures found in Navy Ship's Technical Manual (NSTM) Chapter 074. The Navy jointly developed these procedures with the assistance of Oceaneering. The procedures are loosely based on the AWS D3b specifications.

## Oceaneering Diving Operations

Approximately 70% of Oceaneering's operations occur in the warmer summer season and the remaining 30 % is done in the winter. Additionally, all of the equipment such as the compressors, the fly away diving systems, and the welding habitats are overhauled during the winter.

Roughly 40% of Oceaneering's dives used mixed gas due to additional bottom time it affords. This includes many relatively shallow dives which could be performed using air.

Oceaneering has had no confirmed incidences of decompression sickness (DCS) in 2 years; however, roughly six or seven chamber treatments have been performed in an effort safeguard against mistaking other injuries as DCS. Couch pointed out that there is a substantial variance among the dive tables used by different diving companies. As a result different companies have distinct dive safety cultures and reputations. For this reason the transition of divers from one company to another is often undesirable to both the divers and management.

## Underwater Weld Repair Process

The majority of underwater welding is installation of pipelines or structural repair work. The first step in the structural repair process is to conduct a survey of the damage to the structure. According to Couch oil companies typically hire a diving company to do the survey and assist with the welding design. After deterring the project scope and the detailed repair design a bid package is advertised and the project is typically awarded to the lowest bidder provided it is a qualified diving contractor.

In some instances urgency of the repairs necessitates the use of one diving contractor for all phases of the welding repairs, inspection, design, and construction. During the visit to Oceaneering's diving office, the staff presented walked me through a pictorial history of a rush underwater weld repair which was completed in the Fall of 97. The project was completed under a time and materials contract with a firm completion deadline. A damaged shallow water offshore rig had repaired using combination of dry welds, wet welds, grouting techniques. The job involved the replacement of several members carrying heavy loads and therefore required transfer of the loads to temporary braces during welding repairs on the structural members. This job demonstrated the organic nature of underwater weld repairs. Each repair is different so the optimal repair design requires creative thinking.

Another project performed by Oceaneering was the recovery of steel marine structure which turned over and sank in place. The cave in problems caused by the soft soil in the area of the sinking prevented digging out the structure so a giant cofferdam had to be designed to fit around the entire structure. The cofferdam was designed and fabricated to be self-jetting so it could embed itself down below the mudline to prevent cave in.

## ***Welding Safety***

Several wet and dry welding safety issues were discussed including the risk and hazards of electrical shock, underwater explosions, and respiratory issues in underwater welding. While shock is a concern of underwater welders is quite often shrugged off as an inconvenience but not a major threat to the welder-diver.

Death as result of shock is not often viewed as a major concern. Explosions are of great concern due to the potential build up of explosive gases in enclosed spaces at working depths.

A large amount of discussion was focused on the industries use of life support and redundant air supplies. Oceaneering enforces mandatory use of AGA, a full face breathing apparatus, in all welding habitats. Some studies suggest that the AGA rig is safer because of its greater capacity of air volume flow. Other companies in the industry use only a mouth and nose bib which tends to result in larger amounts of soot being deposited in the mouth and nose of the diver. The mouth and nose bib is often preferred because it provides the welder with a larger field of vision for welding. Couch cites one instance where one of Oceaneering's top surface welders was unable to perform in the habitat because of the he couldn't see in AGA. In this instance the simple solution was to bring the welder to the surface in order to familiarize him with welding in AGA without the added constraints of welding under pressure. The approach seemed to work.

One interesting narrative experience was relayed which exemplified both the need for the need for stronger safety requirements within the underwater welding industry and the level of inadequate welder-diver air sources. The episode involved a small Florida Company which was hired to perform an underwater inspection on a pipeline. After the inspectors found damage, they told the pipeline owner that they were qualified to do weld repairs. After building and installing a habitat which leaked extensively, they sent a welder down in the chamber to weld without a direct air source. Instead of using an AGA rig or even a mouth and nose bib, he breathed the ambient air pumped in to ventilate the habitat. Unfortunately this air flow was supplied by undersized compressors and the welder quickly became exhausted. As a result when the welder became incapacitated he would come to the surface, where he laid on the barge breathing 100% oxygen. Once he began to feel better, he would return to the chamber and repeat the process.

Unfamiliar with underwater welding, the pipeline owner hired Oceaneering inspect the pipeline repairs as a 3rd party, unbiased inspector. When the Oceaneering team arrived and saw the operating conditions, the company refused to get involved with the project due to their potential liability for allowing such dangerous practices to continue.

When Oceaneering representatives questioned the company representatives about the qualification of their procedures, they said the procedure was qualified to 33 fsw under D3b. It was later learned that the procedure had been done in a work shop, with only the welder's hands and the weld material in a box. The diver had not been placed under pressure.

The small company continued to work inefficiently for about a month without completing the job, and Oceaneering was eventually called back to finish the job.

Another somewhat controversial safety precaution among welder-divers is the mandatory use of a come home bottle, a small cylinder worn strapped to the back which acts as the redundant air source. According to Couch many companies don't require its use particularly in the habitat. Furthermore, most welder-divers feel the come home bottle's bulk is uncomfortable and would prefer not to wear it. Mr. Couch believes that the come home bottle is one example of why some safety decisions should not be left up to the field level workers. Given there preference, most would not wear the come home bottle in spite of numerous real world examples of incidents where a come home bottle would have saved the diver's life. He cited a recent example of a case in Lake Charles where a young diver diving below a casino boat was welding and cut his air hose. Because of the shallow depth of less than fifteen feet, he had chosen not to where a come home bottle. After cutting his hose, he panicked became disoriented. Instead of swimming a short distance athwartships to safety, he attempted a free ascent by swimming the length of boat and drowned.

## *Organizational Factors*

The majority of Oceaneering's diving contracts are directly with the large oil companies. Shell is the diving group's biggest customer. In addition to these large diving projects, Oceaneering does many smaller jobs. Small dive boats are deployed fully equipped to perform multiple short duration jobs at one outing. Oceaneering's safety organization consists of several safety officers within the company. The diving group has a dedicated dive safety officer. The diving safety officer usually works his way up the ranks from diver to diving supervisor to safety officer. Extensive diving medicine experience is preferred. Additionally, a former diving safety officer currently holds the position of the company's overall safety officer, responsible for the entire company's safety program. Though not required, the company safety officer has traditionally been an ex-diving safety officer due to large amount of diving operations Oceaneering performs. Oceaneering's safety reporting procedures involve only in house safety reporting. According to Couch it is often difficult to acquire an accurate details of accidents from operations grapevine. Operators tend not to give the realistic safety story because of marketing concerns. There is a close network among safety officers in which detailed lessons learned are shared. Normally these lessons learned are relayed to welder-divers through pre-dive informal discussions of previous industry accidents occurring in similar situations.
Couch described an earlier failed attempt by Exxon to stipulate that accurate safety performance data to be supplied as a contract requirement. All of the major diving companies refused on the grounds that the diving companies were responsible for paying the diving insurance premiums, and assuming these risks gave them the right to withhold safety performance information.

## *Sources of Welder-Divers*

Oceaneering's divers come from a wide variety of civilian and military training sources. According to Couch there are many substantial differences among these sources. Civilian programs tend to vary in price, quality of training, duration, the expectations of their graduates. Similarly military programs are an excellent source of divers but often military divers have trouble adjusting to cultural differences in the commercial industry. The tremendous shortage of qualified divers in the industry necessitates that most graduates of reputable diving schools are accepted when they apply for jobs at Oceaneering. Retention of these divers can be difficult and tends to differentiate the dive schools. While couch recognized Santa Barbara City College, The College of Oceaneering, and Ocean Incorporated as the schools providing the most technically proficient divers, he also noted that they were unreliable as sources of dives who will make it in the Gulf. Quite often divers from these sources tend to leave due to the rural living conditions found in the Gulf Coast states. On the other hand, graduates of Young Memorial, a small local Louisiana dive school are not shocked with living conditions in Louisiana so they tend to be a better investment for the company. Couch estimates that as few as few as 10-15% of graduates of the Santa Barbara City College program remain in the Gulf while the majority of the Young Memorial students stay.
The Young Memorial School was started by several local diving companies who donated equipment and instructors in an effort to alleviate the shortage of qualified divers. As a consequence of this retention phenomenon, Couch does not believe the high cost of accredited dive schools is worth the money. It is better to spend less money on a school which will qualify a diver in 120 days than to complete an expensive year long program.
Ex-military divers comprise a large portion of Oceaneering's divers. Usually they are very successful, often breaking out as divers sooner than others. Many breakout in as quick as 6 months. The younger military divers are preferred because of their willingness to adjust to the commercial diving culture and procedures.

If they left the Navy as more senior divers they often have an uncompromising attitude and are not receptive to learning the ways of the offshore oil industry. There is a lot they need to learn about oil rigs. Surprisingly many new employees claim they are underwater welders but are unable to weld on the surface. According to Couch to be a successful underwater welder you must first be a good surface welder.

## *Welder-Diver Traits*

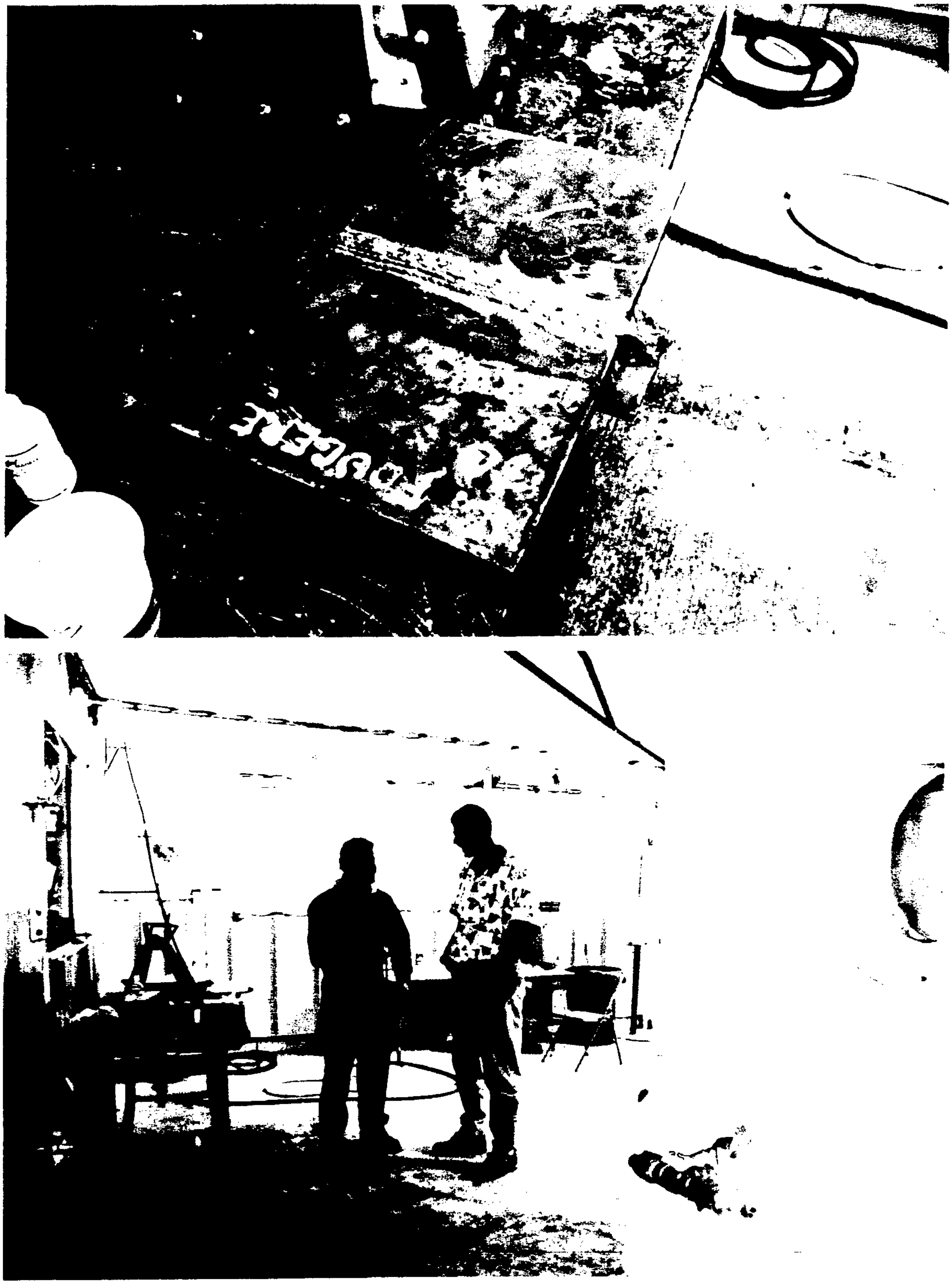
According to Mr. Couch, there are several innate traits which a successful welder-diver possesses. When asked to elaborate on his vision of the role of HOF in the selection of individuals with the skills required for underwater welding, Mr. Couch identified the following key issues:

- Good mechanical skills are necessary. Welder-divers must be able to think mechanically, but more importantly they must be able operate efficiently. Couch claims that he can identify potentially effective divers by simply watching them with a crescent wrench. If they appear at ease with such tools they will be effective underwater as well.
- A reasonable level of intelligence and formal education is desired but by no means a requirement for a welder-diver. Not surprisingly, better educated candidates tend to have less refined mechanic skills. The education tends to be more useful in project management areas. Several exceptions were noted including Dave Rosenberg, a young diver who is both a good mechanic and engineer. He is currently working on his welder qualifications in an attempt to better understand operational constraints which should be applied to design.
- Ambidexterity is preferred. Mechanical skill, dexterity, is essential in underwater operations. Consequently, being able to work equally well with both hands is ideal. According to Couch, truly ambidextrous welder-divers are most desirable, followed by right handed welder-diver, and finally, left handed welder-divers.
- Confidence in welding skills is also an important trait of an effective welder-diver. New welders tend to waste time grinding and rewelding already adequate welds. It is important to complete a quality weld, but often time is wasted making the weld look perfect. Such actions are very inefficient and expensive.
- Two interesting physiological traits were mentioned, electrical shock resistance and heart physiology. According to Couch, an individual's ability to detect electrical shock varies from person to person. Also Couch mentioned a congenital heart condition which is undetectable, may exist in as many as one fifth of all people, and may be hazardous for individuals employed as divers. The condition consists of a small hole in the heart where the infants umbilical cord was connected prior to birth, which fails to heal after birth. This condition can lead to a propensity for hyperbaric injury.
- In saturation diving the effects of Helium on the temperatures of the divers requires a limited tolerance for variation in temperatures. Due to the cooling effects of helium a change of as little as 1.5 degrees can result in a dramatic loss in body temperature and effectively render divers useless.
- The duration of time offshore was cited as a major issue in performance for many welder-divers. Oceaneering's longer projects can require welder-divers to remain deployed for up to three months. This results in many family problems, and, consequently, poorer job performance.
- Saturation diving is one area where human factors are of primary concern. The severe pressures encountered cause bodily fluids to be forced out of joints resulting in loss of joint lubrication and reduced mobility. All tasks must be designed to account for these mobility reductions.

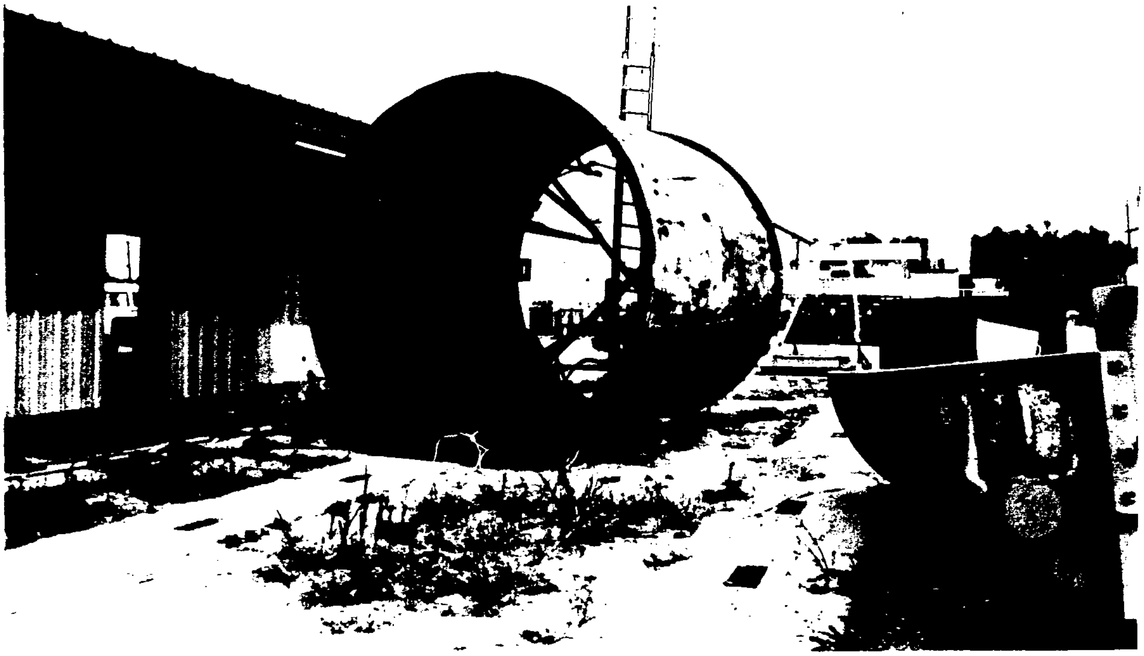
## Conclusion

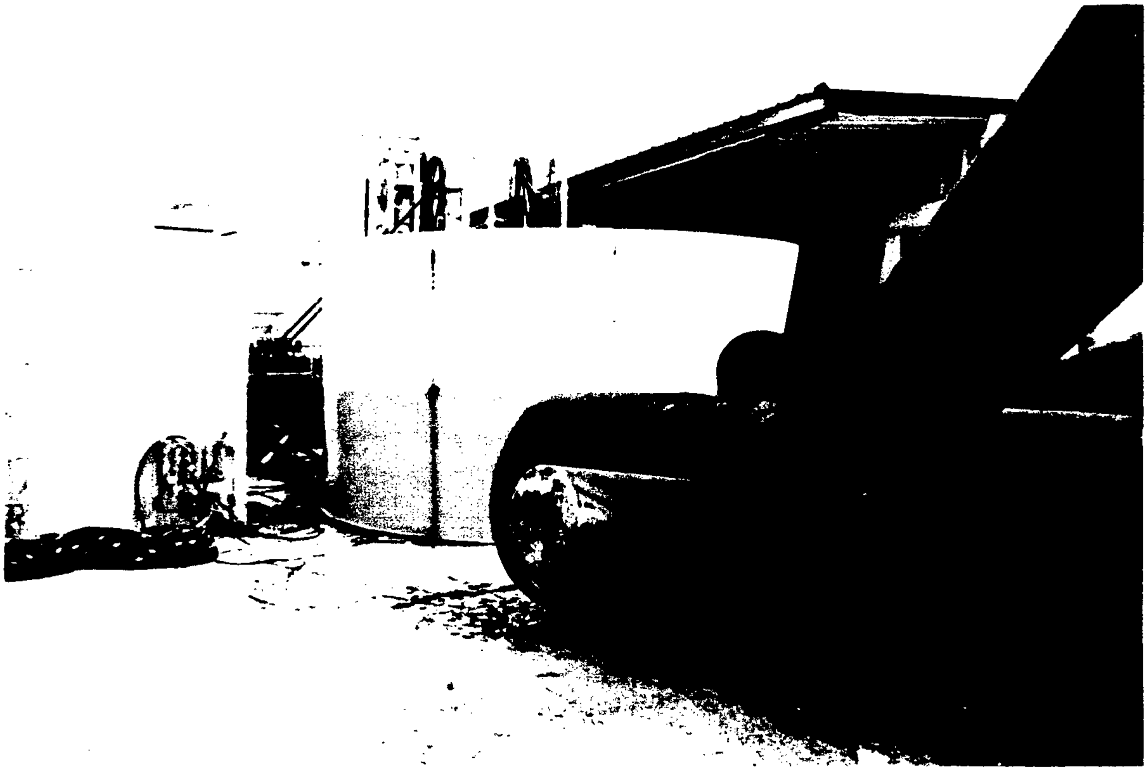
As a result of the observations and informal discussions conducted during the tour of Oceaneering Inc., many insights were made regarding the operational processes involved wet and dry underwater welding and the commercial diving industry in general. Specifically, the visit provided valuable insight into the specific types of underwater welding repairs being performed in the gulf, the organizational and contractual relationships between diving companies and their customers, the dominant perceptions of safety within the underwater welding industry, and the criteria used for the selection of welder-divers.

Top: Weld coupon used for testing of new U. S. Navy underwater welding procedures
Bottom: Jack Couch, Oceaneering Diving Operations Manager discusses procedure with underwater welder.



Top: Oceaneering's custom built large, cylindrical cofferdam.
Bottom: Practice underwater welding tank with scrap platform node in foreground.





# Appendix G - Interfaces

| | **INDIVIDUAL** | **WELDING TEAM** | **ORGANIZATION** | PROCEDURES | STRUCTURES | EQUIPMENT | ENVIRONMENT |
|---|---|---|---|---|---|---|---|
| **INDIVIDUAL** | ■ | | | | | | |
| **WELDING TEAM** | | ■ | | | | | |
| **ORGANIZATION** | | | ■ | | | | |
| PROCEDURES | [illegible] | [illegible] | [illegible] | ■ | | | |
| STRUCTURES | [illegible] | [illegible] | [illegible] | | ■ | | |
| EQUIPMENT | [illegible] | [illegible] | [illegible] | | | ■ | |
| ENVIRONMENT | [illegible] | [illegible] | [illegible] | | | | ■ |

# Appendix H - Electrical Fragility Analysis Calculations

Capacity of the human heart to survive electrical current.
Assume variation of 40% for the amount of current necessary to cause irreversible ventricular fibrillation effect from 3-second shock. Assume lognormal distribution of current.

$I_{c50} := .5 \cdot \text{amp}$ $\quad V_c := .40$ $\quad \sigma_{lnc} := \sqrt{\ln\left(1 + V_c^2\right)}$ $\quad \sigma_{lnc} = 0.385$

Demand placed on the human body given shock from a DC power source set at 167 volt DC. Assume lognormal distribution. Resistance of body is based on resistance of internal body from hand to foot.

$V_{50} := 167 \cdot \text{volt}$ $\quad V_{90} := 175$ $\quad V_{10} := 125$

$R_{50} := 500 \cdot \text{ohm}$ $\quad R_{90} := 600$ $\quad R_{10} := 200$

$\sigma_{lnV} := .39 \cdot \left(\ln\left(V_{90}\right) - \ln\left(V_{10}\right)\right)$ $\quad \sigma_{lnV} = 0.131$

$\sigma_{lnR} := .39 \cdot \left(\ln\left(R_{90}\right) - \ln\left(R_{10}\right)\right)$ $\quad \sigma_{lnR} = 0.428$

$I_{D50} := \dfrac{V_{50}}{R_{50}}$ $\quad I_{D50} = 0.334 \cdot \text{amp}$

Assuming voltage and resistance of the body are not correlated,

$\sigma_{lnI} := \sqrt{\left(\sigma_{lnV}\right)^2 + \sigma_{lnR}^2}$ $\quad \sigma_{lnI} = 0.448$

$\beta := \dfrac{\ln\left(\dfrac{I_{c50}}{I_{D50}}\right)}{\sqrt{\sigma_{lnI}^2 + \sigma_{lnc}^2}}$ $\quad \beta = 0.683$

This Beta value corresponds to $\quad \Phi := .751$

$P_f := 1 - \Phi$ $\quad P_f = 24.9 \cdot \%$

Now assume an AC source is used such as a video camera with a 120 volt, 60Hz power source. The maximimum current which can be withstood by the human body drops to .1 amps. Assuming variation in the body's resistance and the voltage of the power source remains the same:

$V_{50} := 120$ $\quad I_{D50} = 0.334 \cdot \text{amp}$ $\quad I_{c50} := .1 \cdot \text{amp}$

$\beta := \dfrac{\ln\left(\dfrac{I_{c50}}{I_{D50}}\right)}{\sqrt{\sigma_{lnI}^2 + \sigma_{lnc}^2}}$ $\quad \beta = -2.041$ $\quad$ In this case electrocution would occur.

# Appendix I - HOF Applications Model Assumptions

|  | Error Mitigation | Fragility | Detection | Correction | Model Assumptions | Probability of Failure |
|---|---|---|---|---|---|---|
| **Individual Operators - Welder/Divers** |  |  |  |  | BASELINE | 3.48% |
| Medical Examination Standards |  | X |  |  | 10% decrease in fragility | 2.94% |
| Physical Fitness |  | X |  |  | 10% decrease in fragility | 2.94% |
| Dexterity Measurement | X |  | X | X | 1E10% decrease in error rate; 10% increase in correction and detection | 0.37% |
| Age limits |  | X |  |  | 10% decrease in fragility | 2.94% |
| Gender |  | X |  |  | 5% decrease in fragility | 3.21% |
| Diet |  | X |  |  | NOT TESTED | 0.28% |
| Panic and stress screening | X |  | X | X | 10% decrease in error rate; 50% increase in detection detection and correction | 0.28% |
| Capacity Measurement |  |  |  | X | NOT TESTED | NA |
| Aptitude Testing | X |  | X | X | 20% decrease in error rate; 10% increase in detection and correction | 2.70% |
| Education |  |  | X | X | NOT TESTED | NA |
| Entry Level Diving Training |  |  | X | X | NOT TESTED | NA |
| Entry Level Welding Training | X |  | X | X | E10 decrease in error rate; 25% increase in correction and detection | 0.35% |
| Team Preparation Training |  |  | X | X | 25% increase in detection and correction | 3.27% |
| Panic and high stress Training |  |  | X | X | 50% increase in detection and correction | 2.62% |
| Leadership |  |  | X | X | 10% increase in detection and correction | 3.45% |
| Decision Making/Crisis Management |  |  | X | X | 10% increase in detection and correction | 3.45% |
| Conflict Resolution |  |  | X | X | 10% increase in detection and correction | 3.45% |
| Individual Limitations Training |  |  | X |  |  |  |
| In-House Training Program |  |  | X | X | NOT TESTED | NA |
| Communications Training | X |  | X | X | E10 decrease in error rate; 10% increase in correction and detection | 0.37% |
| Experience | X |  | X | X | 50% decrease in error rate; 50% increase in correction and detection | 1.32% |
| Incentives |  |  | X |  |  |  |
| **Operating Teams** |  |  |  |  |  |  |
| Process Auditing | X |  |  |  | Assume perfect positive correlation of errors within each subtask | 2.22% |
| Focus on Reliability | X |  |  |  | Assume perfect positive correlation of errors within each subtask | 2.22% |
| Focus On Teamwork | X |  |  |  | Assume perfect positive correlation of errors within each subtask | 2.22% |
| Effective Crew Resource Management (CRM) | X | X | X | X | 10% decrease in error rate; 50% increase in fragility, correction, and detection | 2.22% |
| Risk Perception |  |  | X |  | Assume perfect positive correlation of errors within each subtask | 2.22% |
| Job Hazard Analysis (JHA) |  |  | X |  | NOT TESTED | NA |
| Emergency Preparedness |  |  | X | X | 50% increase in correction and detection | 2.62% |
| Command and Control |  |  |  | X | 50% increase in correction and detection | 2.62% |
| Frequency of Training | X |  | X | X | E10 decrease in error rate; 50% increase in correction and detection | 0.28% |
| Dive Team Briefing | X |  | X | X | 50% decrease in error rate; 10% increase in correction and detection | 0.74% |
| Two-Way Voice Communications |  |  | X | X | 50% increase in correction and detection | 2.62% |
| Team Requisite Variety |  |  | X | X | 25% increase in correction and detection | 3.27% |
| Incentives |  |  |  |  | Assume perfect positive correlation of errors within each subtask | 2.22% |
| Rest | X |  |  |  | Assume perfect positive correlation of errors within each subtask, 50% decrease in error rate | 1.12% |
| **Corporate Administrative Organization** |  |  |  |  |  |  |
| High Reliability Organization |  |  | X |  | NOT TESTED | NA |
| Adaptive organizational structure |  |  |  | X | NOT TESTED | NA |
| Command and Control |  |  |  | X | NOT TESTED | NA |
| Levels Of Authority |  |  |  | X | NOT TESTED | NA |
| Accurate decision making |  |  |  | X | NOT TESTED | NA |
| Flexibility within formal rules |  |  | X | X | NOT TESTED | NA |
| Communication |  |  | X | X | NOT TESTED | NA |
| Appropriate Checks and Balances |  |  | X |  | NOT TESTED | NA |
| Level of Interdependence |  |  | X |  | NOT TESTED | NA |
| Organizational Culture |  |  | X | X | NOT TESTED | NA |
| Emphasis On Safety And Reliability. |  |  | X | X | NOT TESTED | NA |
| Support of Training Goals |  |  |  | X | NOT TESTED | NA |
| Linking of Accountability with Control Systems |  |  | X | X | NOT TESTED | NA |
| Process Auditing |  |  | X |  | NOT TESTED | NA |
| Management rules and regulations |  |  | X | X | NOT TESTED | NA |
| Work schedules |  | X |  |  | NOT TESTED | NA |
| Diver's Personal Log Book |  |  | X |  | NOT TESTED | NA |
| Diving Company Log Book |  |  | X |  | NOT TESTED | NA |
| Chamber Log Book |  |  | X |  | NOT TESTED | NA |
| Appropriate Risk Perception |  |  | X |  | NOT TESTED | NA |
| Maintenance of corporate memory |  |  | X |  | NOT TESTED | NA |
| Contract types |  |  | X |  | NOT TESTED | NA |
| Employee Reward and Control Systems |  |  | X |  | NOT TESTED | NA |

# Appendix J - Baseline System Failure Probability

**HOF application:** Baseline

**Mechanism for Improvement:** NA
**Cost of Application:** NA
**Inclusion in Specification:** NA

| Underwater Welding Safety Tasks | Key Operator | Hazard | Most Probable Error | Classification of Most Probable error | Mean rate of error (Table 4 ) | Fragility Principle | Relevant Fragility Analysis | P(F\|E) | Method of Detection | P(D) % | P(C) % | P(C)P(D) % | 1-P(C)P(D) % | Probability of Failure (1-P(C)P(D)) xP(F\|E)xP(E) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Connect torch cable to appropriate terminal | Tender | shock | lack of vigilance | mistake, slip | 0.00001 | | | | | | | | | |
| Determining amperage and voltage | Console Operator | shock | miscalculation, lack of vigilance | selection and training, slip | 0.01000 | | | | | | | | | |
| Secure ground to work | Welder-diver | shock | lack of vigilance | slip | 0.00001 | | | | | | | | | |
| Change electrode | Welder-diver | shock | touch body with electrode | selection and training, slip | 0.01000 | | | | | | | | | |
| Keep electrode away from body | Welder-diver | shock | touch body with electrode | slip | 0.00100 | | | | | | | | | |
| Touching metal parts of dive rig | Welder-diver | shock | touch metal with electrode | slip | 0.00100 | | | | | | | | | |
| Adjust welding machine | Tender | shock | current or voltage too high | selection and training, slip | 0.00010 | | | | | | | | | |
| | | | | | 0.02212 | Ohm's Law | *Probability of death given shock* | 0.249 | short or diver shock | 0.00% | 0.00% | 0.0% | 100% | 0.55% |
| Set up and operate (AC) video equipment | Welder-diver | Shock | wrong power source, damaged cable not inspected | mistake | 0.01000 | | | | | | 100% | | | |
| | | | | | 0.01000 | Ohm's Law | *Probability of death given shock* | 1 | short or diver shock | 0.00% | 0% | 0.000% | 100% | 1.00% |
| *Rigging Safety Subtasks* | | | | | | | | | | | | | | |
| Secure welding habitat to structure | Welder-diver | Impact | structure not secure | slip | 0.01000 | | | | | | | | | |
| Ballast habitat | Welder-diver | Impact | not enough ballast or tie down | slip | 0.01000 | | | | | | | | | |
| Ensure secure work area | Welder-diver | Impact | structure not secure | slip | 0.00001 | | | | | | | | | |
| Rig to transfer load | Welder-diver | Impact | miscalculation, bad connection | mistake | 0.00100 | | | | | | 10% | | | |
| Fit members | Welder-diver | Impact | miscalculation, bad connection | communication, slip, mistake | 0.00010 | | | | | | 10% | | | |
| Grind weld | Welder-diver | Impact | item not secure, inattention | slip | 0.00001 | | | | | | | | | |
| Clean work area | Welder-diver | Impact | item not secure | slip | 0.00001 | | | | | | | | | |
| Removal of weld chamber | Welder-diver | Impact | structure not secure | slip, communication | 0.01000 | | | | movement of structure | | | | | |
| | | | | | 0.03113 | Newton's law | *Injury results from impact* | (Ther is not a fragility but an incidence rate) | | | | | | 0.025% |
| *Explosive Safety Subtasks* | | | | | | | | | | | | | | |
| Preheat steel | Welder-diver | explosion | wrong power source, not inspected, explosiveness not | slip | 0.00010 | | | | | | | 0.00% | | |
| Weld root pass | Welder-diver | explosion | explosiveness not detected, bad connection | selection and training, slip | 0.00010 | | | | | | | 0.00% | | |
| Vertical-up weld | Welder-diver | explosion | explosiveness not detected, bad connection | selection and training, slip | 0.01000 | | | | | | | 0.00% | | |
| Down-hand weld | Welder-diver | explosion | explosiveness not detected, bad connection | selection and training, slip | 0.01000 | | | | | | | 0.00% | | |
| Operate electrode oven | Welder-diver | explosion | no detection explosive gas, lack of vigilance | selection and training, slip | 0.00010 | | | | | | | 0.00% | | |
| Overhead weld | Welder-diver | explosion | explosiveness not detected, bad connection | selection and training, slip | 0.00010 | | | | | | | 0.00% | | |
| | | | | | 0.02040 | Explosivity of combustibles | *Death or Injury given explosion* | 0.9 | Detection of explosives | | | 0.0% | 100% | 1.84% |
| *Respiration Safety Subtasks* | | | | | | | | | | | | | | |
| Blow down welding habitat | Welder-diver | wning, Asphyxiation | | mistake | 0.00010 | | | | | | | 0.00% | | |
| Change headgear | Welder-diver | wning, Asphyxi | remove air source in toxic environment | lapse | 0.00100 | | | | | | | 0.00% | | |
| Ventilate welding habitat | Welder-diver | Asphyxiation | limit or shut ventilation | lapse | 0.00010 | | | | | | | 0.00% | | |
| Control background gas | Console Operator | Asphyxiation | improper vigilance in monitoring | communication, slip | 0.00010 | | | | | | | 0.00% | | |
| Enter welding habitat | Welder-diver | Asphyxiation | loss or lower air | mistake | 0.00010 | | | | | | | 0.00% | | |
| | | | | | 0.0014 | Toxicity, Drowning | *Death given Inhalation* | 0.5 | Detection of toxics | | | 0.0% | 100% | 0.07% |

**RISK OF WELDING TASK SAFETY FAILURE 3.48%**

# Appendix K - System Failure Probability

| Rank | Task | Model Assumption | P(F) |
|---|---|---|---|
| | | BASELINE | 3.48% |
| 1 | Panic and stress screening | 10% decrease in error rate; 50% increase in detection detection and correction | 0.28% |
| 2 | Frequency of Training | E10 decrease in error rate; 50% increase in correction and detection | 0.28% |
| 3 | Entry Level Welding Training | E10 decrease in error rate; 25% increase in correction and detection | 0.35% |
| 4 | Dexterity Measurement | 1E10% decrease in error rate; 10% increase in correction and detection | 0.37% |
| 5 | Communications Training | E10 decrease in error rate; 10% increase in correction and detection | 0.37% |
| 6 | Dive Team Briefing | 50% decrease in error rate; 10% increase in correction and detection | 0.74% |
| 7 | Individual Limitations Training | 50% lower P(Welder-Diver Error), Perfect Positive Correlation of HOE | 1.12% |
| 8 | Rest | Assume perfect positive correlation of errors within each subtask, 50% decrease in error rat | 1.12% |
| 9 | Experience | 50% decrease in error rate; 50% increase in correction and detection | 1.32% |
| 10 | Process Auditing | Assume perfect positive correlation of errors within each subtask | 2.22% |
| 11 | Focus on Reliability | Assume perfect positive correlation of errors within each subtask | 2.22% |
| 12 | Focus On Teamwork | Assume perfect positive correlation of errors within each subtask | 2.22% |
| 13 | Effective Crew Resource Management (CRM) | 10% decrease in error rate; 50% increase in fragility, correction, and detection | 2.22% |
| 14 | Risk Perception | Assume perfect positive correlation of errors within each subtask | 2.22% |
| 15 | Incentives | Assume perfect positive correlation of errors within each subtask | 2.22% |
| 16 | Panic and high stress Training | 50% increase in detection and correction | 2.62% |
| 17 | Emergency Preparedness | 50% increase in correction and detection | 2.62% |
| 18 | Command and Control | 50% increase in correction and detection | 2.62% |
| 19 | Two-Way Voice Communications | 50% increase in correction and detection | 2.62% |
| 20 | Aptitude Testing | 20% decrease in error rate; 10% increase in detection and correction | 2.70% |
| 21 | Age limits | 10% decrease in fragility | 2.94% |
| 22 | Medical Examination Standards | 10% decrease in fragility | 2.94% |
| 23 | Physical Fitness | 10% decrease in fragility | 2.94% |
| 24 | Gender | 5% decrease in fragility | 3.21% |
| 25 | Team Preparation Training | 25% increase in detection and correction | 3.27% |
| 26 | Team Requisite Variety | 25% increase in correction and detection | 3.27% |
| 27 | Leadership | 10% increase in detection and correction | 3.45% |
| 28 | Decision Making/Crisis Management | 10% increase in detection and correction | 3.45% |
| 29 | Conflict Resolution | 10% increase in detection and correction | 3.45% |

# Appendix L - Example Model Analyses

**HOF application:** Standard Electrical Mechanisms including gloves, knife switch, buddy diver, comms, GFI

**Mechanism for Improvement:** Detection, Correction, Fragility Improvement

**Cost of Application:** Cost of GFI, gloves, comms, knife switch, and second buddy diver

**Inclusion in Specification:**

| Underwater Welding Safety Tasks | Mean rate of error (Table 4 ) | P(F]E) | P(D) | P(C) | P(C)P(D) | 1-P(C)P(D) | Probability of Failure (1-P(C)P(D)) xP(F}ExP(E) | Correlation Considerations |
|---|---|---|---|---|---|---|---|---|
| *Electrical Safety Subtasks* | | | | | | | | |
| Inspect torch cable | 0.01000 | | | | | | | |
| Connect torch cable to appropriate terminal | 0.01000 | | | | | | | |
| Determining amperage and voltage | 0.00001 | | | | | | | |
| Secure ground to work | 0.00100 | | | | | | | |
| Change electrode | 0.00010 | | | | | | | |
| Keep electrode away from body | 0.00001 | | | | | | | |
| Touching metal parts of dive rig | 0.0010000 | | | | | | | |
| Adjust welding machine | 0.0000000 | | | | | | | |
| | 0.0221200 | 0.249 | 90.00% | 75.00% | 67.5% | 33% | 0.18% | |
| Set up and operate (AC) video equipment | 0.0100000 | | | | | | | |
| | 0.0100000 | 1 | 90.00% | 25.00% | 22.500% | 78% | 0.78% | |
| *Rigging Safety Subtasks* | | | | | | | | |
| Secure welding habitat to structure | 0.01000 | | | | | | | |
| Ballast habitat | 0.01000 | | | | | | | |
| Ensure secure work area | 0.00001 | | | | | | | |
| Rig to transfer load | 0.00100 | | | | | | | |
| Fit members | 0.00010 | | | | | | | |
| Grind weld | 0.00001 | | | | | | | |
| Clean work area | 0.00001 | | | | | | | |
| Removal of weld chamber | 0.01000 | | | | | | | |
| | 0.03113 | (This is not a fragility but an incidence rate) | | | | | 0.025% | |
| *Explosive Safety Subtasks* | | | | | | | | |
| Preheat steel | 0.00010 | | | | | | | |
| Weld root pass | 0.00010 | | | | | | | |
| Vertical-up weld | 0.01000 | | | | | | | |
| Down-hand weld | 0.01000 | | | | | | | |
| Operate electrode oven | 0.00010 | | | | | | | |
| Overhead weld | 0.00010 | | | | | | | |
| | 0.02040 | 0.9 | | | 0.0% | 100% | 1.84% | |
| *Respiration Safety Subtasks* | | | | | | | | |
| Blow down welding habitat | 0.00010 | | | | | | | |
| Change headgear | 0.00100 | | | | | | | |
| Ventilate welding habitat | 0.00010 | | | | | | | |
| Control background gas | 0.00010 | | | | | | | |
| Enter welding habitat | 0.00010 | | | | | | | |
| | 0.0014 | 0.5 | | | 0.0% | 100% | 0.07% | |

**RISK OF WELDING TASK SAFETY FAILURE 2.89%**

**HOF application:** Limitations Training (Perfect correlation of error rates for welder diver activities)

**Mechanism for Improvement:** 50% lower P(Welder-Diver Error), Perfect Positive Correlation of HOE

**Cost of Application:** Two hour classroom training

**Inclusion in Specification:**

| Underwater Welding Safety Tasks | Mean rate of error (Table 4 ) | Relevant Fragility Analysis | P(F]E) | P(D) | P(C) | P(C)P(D) | 1-P(C)P(D) | of Failure (1-P(C)P(D)) xP(F}ExP( |
|---|---|---|---|---|---|---|---|---|
| *Electrical Safety Subtasks* | | | | | | | | |
| Inspect torch cable | 0.00005 | | | | | | | |
| Connect torch cable to appropriate terminal | 0.00001 | | | | | | | |
| Determining amperage and voltage | 0.00500 | | | | | | | |
| Secure ground to work | 0.00001 | | | | | | | |
| Change electrode | 0.00500 | | | | | | | |
| Keep electrode away from body | 0.00050 | | | | | | | |
| Touching metal parts of dive rig | 0.00100 | | | | | | | |
| Adjust welding machine | 0.00005 | | | | | | | |
| | 0.00500 | ***Probability of death given shock*** | 0.249 | 0.00% | 0.00% | 0.0% | 100% | 0.12% |
| Set up and operate (AC) video equipment | 0.00500 | | | | 100% | | | |
| | 0.00500 | ***Probability of death given shock*** | 1 | 0.00% | 0% | 0.000% | 100% | 0.50% |
| *Rigging Safety Subtasks* | | | | | | | | |
| Secure welding habitat to structure | 0.00500 | | | | | | | |
| Ballast habitat | 0.00500 | | | | | | | |
| Ensure secure work area | 0.000005 | | | | | | | |
| Rig to transfer load | 0.00050 | | | | | | | |
| Fit members | 0.00005 | | | | | | | |
| Grind weld | 0.000005 | | | | | | | |
| Clean work area | 0.000005 | | | | | | | |
| Removal of weld chamber | 0.00500 | | | | | | | |
| | 0.00500 | ***Injury results from impact*** | (There is not a fragility but an incidence rate) | | | | | 0.025% |
| *Explosive Safety Subtasks* | | | | | | | | |
| Preheat steel | 0.00005 | | | | | 0.00% | | |
| Weld root pass | 0.00005 | | | | | 0.00% | | |
| Vertical-up weld | 0.00500 | | | | | 0.00% | | |
| Down-hand weld | 0.00500 | | | | | 0.00% | | |
| Operate electrode oven | 0.00005 | | | | | 0.00% | | |
| Overhead weld | 0.00005 | | | | | 0.00% | | |
| | 0.00500 | ***Death or injury given explosion*** | 0.9 | | | 0.0% | 100% | 0.45% |
| *Respiration Safety Subtasks* | | | | | | | | |
| Blow down welding habitat | 0.00005 | | | | | 0.00% | | |
| Change headgear | 0.00050 | | | | | 0.00% | | |
| Ventilate welding habitat | 0.00005 | | | | | 0.00% | | |
| Control background gas | 0.00005 | | | | | 0.00% | | |
| Enter welding habitat | 0.00005 | | | | | 0.00% | | |
| | 0.0005 | ***Death given inhalation*** | 0.5 | | | 0.0% | 100% | 0.03% |

**RISK OF WELDING TASK SAFETY FAILURE** 1.12%