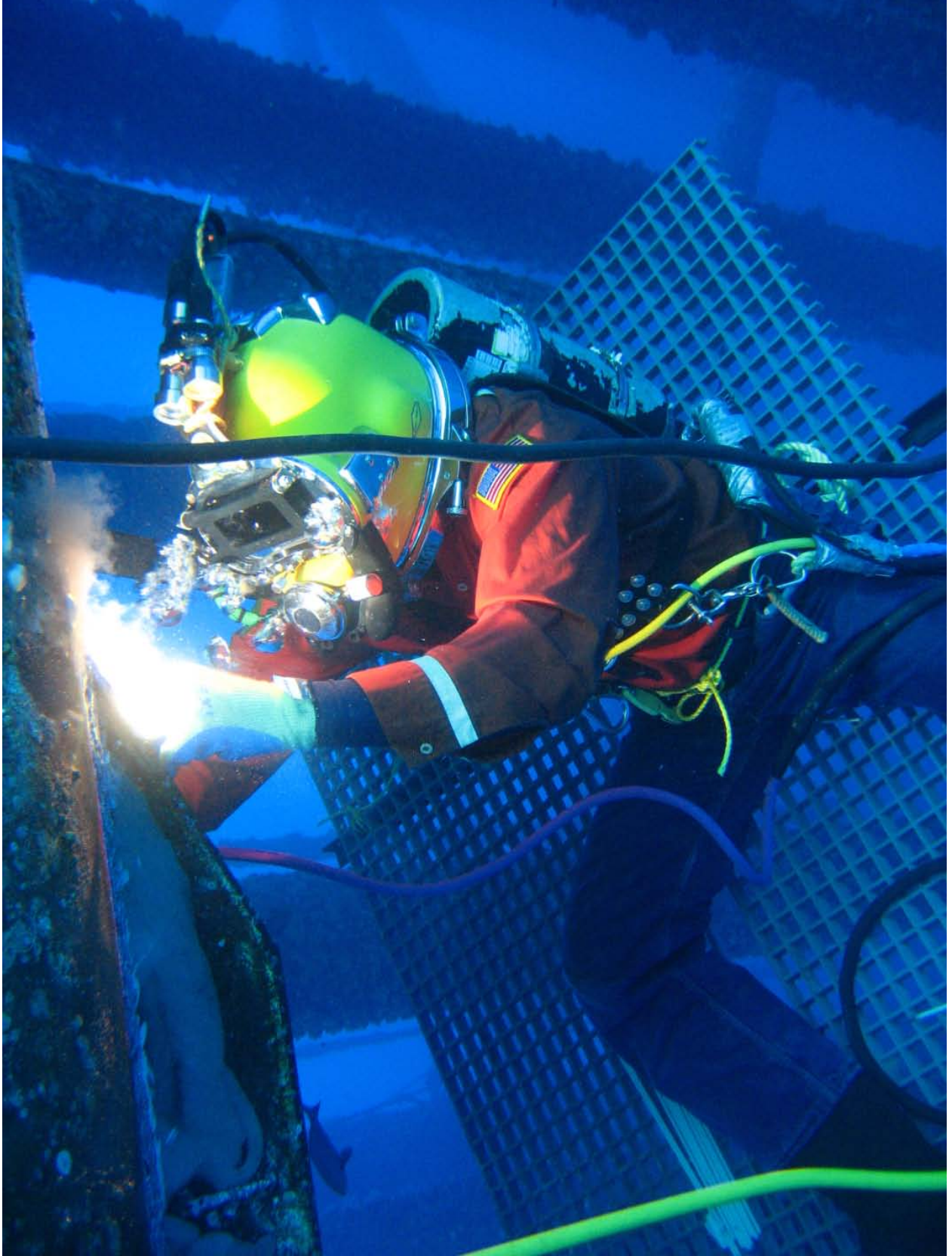




Courtesy of Mr. Tom Reynolds, Global Divers & Contractors



Courtesy of Mr. Jack Couch, Oceaneering International

International Workshop on the State of the Art Science and Reliability of Underwater Welding and Inspection Technology

**November 17-19, 2010
Houston, Texas, USA**

Edited by
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List of Sponsors

Department of Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)
Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA)
ABS
Colorado School of Mines
Global Industries
Leading Industry Development for Economic Region (Leader), Korea
Center for Education of Welding Engineers (CEWE), Dong-Eui University, Korea
Stress Engineering Services, Inc.

Collaborating Societies

American Welding Society (AWS)
Associação Brasileira de Soldagem (ABS) (The Brazilian Welding Association)
American Society of Nondestructive Testing (ASNT)



Executive Summary

During the past 25 years, underwater welding has clearly established itself as a solid and viable fabrication and repair technology. In parallel, inspection has followed suit, developing into a full collection of advanced and capable techniques to ensure the quality of underwater welds. Not only traditional arc welding techniques and hyperbaric welding have been improved, new techniques which include friction processes have been further advanced. Friction welding that was discussed in the 1994 Workshop as an innovative methodology for underwater environment is now a reality, with multiple applications in the industry. It is particularly satisfying that the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Pipeline and Hazardous Materials Safety Administration (PHMSA) and ABS (American Bureau of Shipping) demonstrated great leadership and support in the organization of the third workshop on underwater welding and inspection.

The timely nature of the workshop was certainly demonstrated by the 18 presentations given by leaders and representatives from government agencies, regulatory and certification agencies, and technical experts from a number of industries. In addition to reporting on the state-of-the-art and practice of underwater wet welding and hyperbaric welding, the specialists also discussed about the concept of fitness-for-service and how it can be applied to underwater wet welds. Underwater inspection, which occupied a smaller position in the previous two workshops, gained importance in the discussions in this workshop. Training and qualification of welder/diver remained a strong subject in the deliberations in this event. A wonderful review of the successful underwater welding repair (economics and design) was presented. The discussion centered on materials issues, processing updates, deep water applications, equipment development, inspection, codes and specifications. These presentations also identified some of the research and development needs, opportunities and important ongoing projects, and barriers to the progress and application of underwater welding and inspection.

Six working groups promoted open and active discussion of current technological advances and roadblocks to further progress in the following areas.

1. Impact of Material Quality Control on Underwater Welding, Inspection, and Reliability
2. Standards and Certification for Underwater Welding and Inspection
3. Underwater Wet Welding Consumables Development
4. Training and Certification of Personnel
5. Reliability of Underwater Wet Welding for Offshore Structures
6. Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures

From the deliberations of these working groups, white papers that clearly established industrial and research needs, guidelines and recommendations for the future development of underwater fabrication were prepared. Specially designed welding consumables for underwater welding can, in most cases, produce welds with excellent microstructure and properties. Significant amount of effort has been expended in automation and robotic welding, particularly in deep water applications. Current standards on underwater welding/inspection were reviewed by two work groups. It was determined that for full implementation of the underwater technology, more basic and applied research needs to be done. These recommendations are listed in detail in the following chapters of these proceedings.

Several recommendations, however, received the highest priorities in terms of research and development needs. These are listed in the following.

Category 1 – Materials Quality Control Issues

- Develop industry recommended practice for material sampling to properly determine chemical composition/heat treatment (delivery) condition and stress industry awareness/emphasis on material test report traceability with respect to specific locations in an underwater structure or system.
- Develop a gathering venue on underwater welding applications/successes (CSM, AWS, OTC, API, etc.)

Category 2 – Certification and Standards Needs

- Expand guidelines / commentary on design for underwater repairs and techniques used.
- Develop a marine CWI guideline to improve the quality of CWI performance on underwater welding and inspection.

Category 3 – Welding Consumables Issues

- Develop welding consumables and processes to target Class A wet welds and improve Class B wet weld.
- Develop electrodes that produce welds with diffusible hydrogen content lower than 20 ml/100g, porosity content less than 0.5%, minimum 18% elongation in the all weld metal tensile test, and reduced susceptibility of weld metal root cracks.

Category 4 – Welder/Diver Training and Certification Issues

- Education institution must maintain better communication with on-shore industry regarding 1) the development of education programs with advanced curriculum for students to better suit industry needs, 2) the instruction and training on how to find and report damage, 3) the instruction on existing codes and standards and essential variables of these and how and where to access the information, and 4) the collaboration with industries to better capture and use of data from documented near miss or failure, or proven reliability.
- Educational programs must establish technical advisory board to review and advise commercial schools.

Category 5 – Reliability Issues

- Encourage research institutions to transfer the technology to industry.
- Develop and apply fitness for service concept in underwater welded structures that considers the effect of defect size, defect location and distribution within the weld metal on the stress concentration factor.

Category 6 – Nondestructive Testing and Inspection Issues

- API RP 2SIM needs to be completed with more quantification and published with new focus on life cycle deterioration and life extension of structures.
- Relevant and non relevant indication should be defined, strategy of risk based inspection of the structure as a system regarding what to inspect, reliability of results, probability of detection must be implemented.

Finally, the Workshop strongly supported the premise of holding another underwater welding workshop in three to four years.

Acknowledgment

The organizing committee would like to extend their most sincere gratitude to the Department of Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA), American Bureau of Shipping (ABS), Global Industries, Korean Leading Industry Development for Economic Region (LEADER), Center for Education of Welding Engineers (CEWE) of Dong-Eui University, Korea, and Stress Engineering, for sponsoring this event. Their support went well beyond the financial aspects of the workshop; their staff support in organizing the event and developing the program of the Workshop was greatly appreciated. In addition to the industrial sponsors, the American Welding Society (AWS), the Associação Brasileira de Soldagem (ABS) (The Brazilian Welding Association), and the American Society of Nondestructive Testing (ASNT) are also acknowledged for their support which made this event possible. Their assistance in bring broad announcement of the Workshop to their respective membership is greatly appreciated. In particular, ASNT provided one-day complimentary passes for the attendees of this Workshop to visit their exhibition. Finally, the organizing committee thanks and congratulates each of the participants for their active participation in the working group sessions with questions, comments, and suggestions. Without their support, the program would not have been as successful.

Introduction

It is the third time that the Department of Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) has supported the organization of a workshop on underwater welding and inspection together with the Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) and ABS (American Bureau of Shipping.) From 1985 to 1994, the years between the First Workshop at the Colorado School of Mines in Golden, Colorado, and Second Workshop in New Orleans, Louisiana, there was great progress made in the engineering and practice of underwater welding. Progress was also made in the underwater inspection technology. With significant advances in research in that period, the attendees of the second workshop boldly placed Class A weld quality as target for wet welds. The past 16 years saw similar levels of excitement in the field of underwater welding, much as a result of the horrific damages sustained by many offshore structures in the Gulf of Mexico during the hurricane seasons between 2004 and 2008.

The previous two workshops identified problems associated with design, processes, metallurgy, and inspection. The workshops also prioritized problems and identified opportunities for research, development and education for broader implementation of underwater welding technology. For these reasons, an organizing committee consisting of recognized experts from around the world was established in early 2010 to put together a program that will:

1. Define the status of the engineering and practice for underwater welding and inspection,
2. Identify technical and non technical problems hindering the full utilization of underwater fabrication technology,
3. Identify new and advanced technology with potential in underwater welding,
4. Promote the use of underwater welding incorporating the concept of fitness-for service,
5. Produce an archivable record that thoroughly describes current practice in underwater welding, and opportunities for utilizing underwater technology, and
6. Promote collaboration amongst the practitioners of underwater welding.

A programming committee was also established to plan in detail a program for the workshop. Renowned scientists, engineers and practitioners in the field of underwater welding and inspection were recruited to participate in the 2010 workshop.

Workshop Overview

The format of the earlier workshops in Golden and New Orleans was unique that it carefully balanced the 2-½ day workshop with presentations on current status of engineering practice in underwater welding and inspection and the working group sessions in which discussions on research and development needs were held. The aspect of reliability and fitness-for-service of underwater welds were strongly emphasized in this workshop. Strategies for risk-based inspection regarding what to inspect, reliability of results, and the probability of detection were also deliberated. As in the past two workshops and expectedly, personnel training and qualification was still a hot important topic this time around. A total of 18 presentations were delivered which covered the areas of:

1. State-of-the-art and practice of underwater wet welding;
2. State-of-the-art and practice of underwater hyperbaric welding;
3. Fitness-for-service design and application for underwater wet welds;
5. State-of-the-art and practice of underwater inspection;
6. Training and qualification of welder/diver; and
7. Case studies of success in underwater welding repair (economics and design).

These presentations described the state of the art of the many facets of underwater welding and inspection. They also identified some of the research and development needs, opportunities and important ongoing projects, and barriers to the progress and application of underwater welding and inspection. These 18 presentations provided the background for the deliberation of the working groups.

A total of six working groups were organized to cover the following discussion areas.

1. Impact of Material Quality Control on Underwater Welding, Inspection, and Reliability
2. Standards and Certification for Underwater Welding and Inspection
3. Underwater Wet Welding Consumables Development
4. Training and Certification of Personnel
5. Reliability of Underwater Wet Welding for Offshore Structures
6. Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures

The position white papers were delivered to the participants prior to the session. During the seven hour total working group periods, the participants deliberated on the barriers to the progress and application of underwater welding and inspection, the research and development needs, and the opportunities and important ongoing projects. The participants were also encouraged to visit more than one session to maximize their contributions to the different aspects of underwater welding and inspection. For the final session of the working groups, the participants were charged to prepare lists of prioritized action items to be presented during the final workshop assembly.

The atmosphere of the workshop was extremely positive and upbeat. All participants felt that the technology is undergoing significant progress. Despite the fact that Class A welds have not been achieved in wet welding at deeper depths, it is the resolute of the participants that that standard can be met in the near future. As to hyperbaric welding, there is a need to further expand the application of the technology. In terms of fundamental research, the availability of good consumables continues to be the major problem. Communication and technology transfer between research institutions and industry remain lagging. Fundamental studies coupled with experimentation are needed to understand and control the weld cracking and porosity problems. Process and weld modeling are progressing but in small increments. The last decade has witnessed the development of several new welding power sources with exceptional capabilities for surface welding. There is a great need to examine the performance of the equipment in underwater applications. Friction based processes have proven to be of significance in underwater welding depending on the application and joint design. Finally, weld integrity received strong emphasis and agreement from the participants to be a top requirement exhibited by underwater wet welds. Integrity criteria must be quickly defined for these welds to establish acceptance criteria for repair and maintenance. New systems approach concept regarding repair and maintenance strategies involving planning and execution of planning, data gathering, storage, and analysis, and repair must be

developed to quickly and effectively complete the quality cycle. Finally, complete international standards and certification programs must be developed, accepted and implemented for the industry.

With the broad acceptance of electronic publication, the proceedings of this workshop will be published in two formats, printed and electronic version. In particular, the electronic copy will include all the PowerPoint files of the presentations in addition to the manuscripts.

Research and Development Needs in Underwater Welding and Inspection

A total of seven hours were allocated for the working groups to deliberate the current and future of underwater welding and inspection. Given the Workshop lasted 2½ days, the working group sessions were given great importance, over 30% of the total time. The six working groups deliberated on the barriers to the progress and application of underwater welding and inspection, the research and development needs, and the opportunities and important ongoing projects. The working groups also prepared lists of prioritized action items for presentation during the final workshop assembly.

Recommendations

A summary of the research and development needs and recommended action items is given in the following.

Category 1 – Materials Needs

- Stress industry awareness/emphasis on material test report traceability with respect to specific locations in an underwater structure or system.
- Develop a gathering venue on underwater welding applications/ successes (CSM, AWS, OTC, API, etc.)
- Develop industry recommended practice for material sampling to properly determine chemical composition/heat treatment(delivery) condition.
- For in situ chemical composition testing, there is a need for an acceptable positive material identification (PMI) technique at depths.
- Investigate whether acceptable butt welds can be made underwater using wet welding.
- Investigate the influence of carbon and carbon equivalence on the cracking susceptibility of underwater wet welds (e.g. Graville diagram.)

Category 2 – Certification and Standards Needs

- Expand guidelines / commentary on design for underwater repairs and techniques used.
- Develop a marine CWI guideline to improve the quality of CWI performance on underwater welding and inspection.
- Further develop testing criteria and requirements for marine CWI's.
- Develop criteria for training programs with clearly defined training / qualification requirements and performance expectations for underwater welders, inspectors and UW-CWI and typical.
- Expand provisions unique to ship husbandry, ports, Bridges, locks and dams.
- Expand inspection requirements to include provisions for emerging technology such as alternating current field measurement (ACFM), phased array UT.
- Expand provisions to include new applications such as Friction stud welding.
- Address new training / qualification requirements and for implementation by USDOT.
- AWS continue to work with other standards organizations to collaborate and maintain alignment.

Category 3 – Welding Materials Needs

- Develop welding consumables and processes to target Class A wet welds and improve Class B wet weld.
- Develop electrodes that produce welds with
 - diffusible hydrogen content lower than 20 ml/100g
 - porosity content less than 0.5%
 - minimum 18% elongation in the all weld metal tensile test
 - reduced susceptibility of weld metal root cracks
- Develop electrodes that achieve properties while maintaining electrode operability for 33 ft water depth.)
- Develop electrodes for higher C_{max}: 0.2% and CE_{max}: 0.4% are desirable.
- Develop innovative SMAW electrodes without the requirement of waterproofing layer.
- Review the application and techniques of single or multiple temper beads.
- Develop innovative localized post weld treatments and techniques for reduction of HAZ hardness.
- Develop thermite consumables to reduce HAZ hardness.
- Validate published results related to the reduction of carbon content of core rod with the reduction of porosity in the weld metal of rutile base electrodes.
- Explore the concept of using specific consumables for different ranges of water depth and/or for different parts of the same weld joint (such as root pass, filling and finishing.)
- Establish a database listing historical data (mechanical – yield, Tensile, elongation, Charpy, bend, etc.) of wet welding electrodes.
- Establish a database of commercially available consumables for wet welding with information of manufacturer and trade names.
- Standardize marking system similar to those using in surface or topside welding, e.g. classification printed onto coating, color coding, etc.
- Develop welding systems that utilize self shielded tubular wires.
- Optimize power sources, wire feed systems, and develop new wire Formulations for GMAW or FCAW.
- Develop mechanical devices or automated systems to improve welding performance.
- Develop applications of friction “stitch” welding for crack repairs.
- Basic fundamental research should focus to better understand the physical and chemical phenomena in metal transfer and metal slag interaction in underwater conditions.

Category 4 – Welder/Diver Training and Certification Needs

- Education institution must maintain better communication with onshore industry.
- Educational programs must establish technical advisory board to review and advise commercial schools.
- Training facilities must be more receptive to advice on their curriculum.
- Dive school welding instructors must acquire actual and greater offshore experience.
- Educational programs must develop advances curriculum for students to be better suited for industry.
- Educational programs should instruct and train on how to find and report damage.
- Educational programs should instruct on existing codes and standards and essential variables of these and how and where to access the information.
- Educational programs should collaborate with industries to better capture and use of data from documented near miss or failure, or proven reliability.

- Develop programs to assist students on managing cost of training (school cost are high, students enter work force with debt burden; counseling on loans; opportunities for after hour part-time jobs for students for on the job training to help defray the cost of training.)
- Communicate with students on realistic expectations of profession, industry demand for personnel and time span for work.
- Conduct long range forecast of diver/welder demand.
- Publicize the industry to educators and individuals.
- Create public source of information by professional society such as AWS on the welding industry.
- Industry to promote the establishment and use of uniform standards for inspection of structures.
- Industry to assemble best practices.

Category 5 – Reliability and Broader Use of Underwater Welded Structures Needs

- Encourage research institutions to transfer the technology to industry.
- important developments should be transferred to the industry for field application.
- proprietary information on consumables and welding procedure specifications (WPS).
- Develop and apply fitness for service concept in underwater welded structures that considers the effect of defect size, defect location and distribution within the weld metal on the stress concentration factor.
- Research projects need to continue towards the incorporation of current state of the art and technology into consumable electrodes and making them available to the industry.
- Collaborative efforts should be established between companies, operators, and regulatory agencies to fund field test applications of underwater wet welding (in actual conditions with sea currents, low visibility, etc.)
- AWS D3.6 must be updated with new information and quantitative approaches related to effects due to defect types, size, location and distributions within the weldment.
- Develop database on wet welding application projects (historical data) and lessons learned.
- Develop reliable, reviewed and updated procedures and data interpretation for underwater welding and inspection that Include more cost effective inspection techniques (ACFM, UT, phase arrayed UT, FMD, etc.)
- Develop an updated directory of companies and personnel who are involved in underwater wet welding to set up an industry network.
- Training must be conducted not only in using the tools and methodologies for reliability analysis but also on the input information (MetOcean, material, uncertainties, etc.) required by these tools.
- Develop regulations and procedures for qualification of inspectors and supervisors.
- Standardize and utilize RBI as part of the system integrity management.
- Better define the role and responsibilities of regulatory bodies, industry bodies, classification societies, e.g. API, to integrate the recommendations.

Category 6 – Underwater Inspection Needs

- API RP 2SIM needs to be completed with more quantification and published with new focus on life cycle deterioration and life extension of structures.
- Relevant and non relevant indication should be defined.
- Strategy of risk-based inspection of the structure as a system regarding what to inspect, reliability of results, probability of detection must be implemented.
- Inspector diver or inspector ROV pilot must be qualified and certified.

- Establish system for inspection and repair on site with integrated capability for underwater monitoring and assessment.
- Develop quality based competency map for implementation.
- Engage in public discussion and consensus on fragility curve.
- Promote and build ethics and cultures of risk analysis.
- Promote collaborative effort in the industry as compared with region by region approach.
- Explore the approach of inline inspection of non-pig gable pipes and risers.

Prioritized List of Research and Development Needs in Underwater Welding and Inspection

After the participants of the workshop ranked (post workshop activity) the top two research and development needs and recommended action items from each of the six major categories are listed below. It is the hope of the organizers of this Workshop that government agencies, certification organizations and industries will use these lists of prioritized needs and action items to guide their future development planning and strategy as well as allocation of funding to further develop and implement underwater welding and inspection projects for the technology of underwater welding and inspection is critical to offshore structures, ships, port facilities, and pipelines.

Top Recommendations: Category 1 – Materials Quality Control Issues

- Develop industry recommended practice for material sampling to properly determine chemical composition/heat treatment (delivery) condition and stress industry awareness/emphasis on material test report traceability with respect to specific locations in an underwater structure or system.
- Develop a gathering venue on underwater welding applications/ successes (CSM, AWS, OTC, API, etc.)

Top Recommendations: Category 2 – Certification and Standards Needs

- Expand guidelines / commentary on design for underwater repairs and techniques used.
- Develop a marine CWI guideline to improve the quality of CWI performance on underwater welding and inspection.

Top Recommendations: Category 3 – Welding Consumables Issues

- Develop welding consumables and processes to target Class A wet welds and improve Class B wet weld.
- Develop electrodes that produce welds with diffusible hydrogen content lower than 20 ml/100g, porosity content less than 0.5%, minimum 18% elongation in the all weld metal tensile test, and reduced susceptibility of weld metal root cracks.

Top Recommendations: Category 4 – Welder/Diver Training and Certification Issues

- Education institution must maintain better communication with on-shore industry regarding 1) the development of education programs with advanced curriculum for students to better suit industry needs, 2) the instruction and training on how to find and report damage, 3) the instruction on existing codes and standards and essential variables of these and how and where to access the information, and 4) the collaboration with industries to better capture and use of data from documented near miss or failure, or proven reliability.
- Educational programs must establish technical advisory board to review and advise commercial schools.

Top Recommendations: Category 5 – Reliability Issues

- Encourage research institutions to transfer the technology to industry.
- Develop and apply fitness for service concept in underwater welded structures that considers the effect of defect size, defect location and distribution within the weld metal on the stress concentration factor.

Top Recommendations: Category 6 – Nondestructive Testing and Inspection Issues

- API RP 2SIM needs to be completed with more quantification and published with new focus on life cycle deterioration and life extension of structures.
- Relevant and non relevant indication should be defined, strategy of risk based inspection of the structure as a system regarding what to inspect, reliability of results, probability of detection must be implemented.

Supporting Remarks

Need for Well Developed and Understood Technologies Related to Underwater Inspection and Welding and Reliable Performance of Offshore Structures

Joe R. Fowler, President and cofounder, Stress Engineering Services, Inc.

Some Trends in Ship and Offshore Design, Construction and Operations

Peter Tang-Jensen, Senior Vice President, Technology, ABS

BOEMRE Regulations Applicable to Welding

B.J. Kruse, III, Chief, Office of Structural and Technical Support, U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement

Need for Well-Developed and Understood Technologies Related to Underwater Inspection and Welding and Reliable Performance of Offshore Structures

Joe R. Fowler, President and cofounder, Stress Engineering Services, Inc.

Dr. Liu, Dr. Olson, Members of the Steering Committee, Distinguished Visitors and Guests, Ladies and Gentlemen:

I am honored today to present these remarks in support of the 3rd International Conference on the State of the Art, Science, and Reliability of Underwater Welding and Inspection Technology.

The company that I am privileged to lead, Stress Engineering Services, Inc., provides engineering consulting and testing services to industry, primarily in the fields of mechanical, civil/structural, instrumentation and electrical, and materials engineering. Stress employs approximately 220 engineers who practice in areas such as materials and metallurgy, marine assurance engineering, floating systems engineering, fitness for service, pipeline engineering, and testing.

Last year, Stress served over 750 different clients, performing analysis and/or testing on a number of engineered systems and products ranging from plastic packaging for consumer products to medical devices to the offshore floating production and drilling systems (FPSOs and MODUs) that are principally used for offshore production and drilling for oil and gas. One such structure, Transocean's *Deepwater Horizon*, along with eleven hands were lost recently in an incident with which, I am sure, we are all familiar.

The causes for this tragic event are still under investigation. Nonetheless, it appears safe to say that the attempts to cap the well, which were broadcast on the nightly news and on the internet, brought underwater technologies into living rooms of millions around the world for the first time. Technologies such as remotely operated vehicles (ROVs) and underwater photography provided spectacular images of the damaged well. More importantly, they provided the dedicated group of men and women who eventually capped the well with the ability to accurately assess the situation on the seafloor, which in turn enhanced the planning process and accelerated progress in capping the well. These technologies saved money and they protected divers. So, at the end of the day, I don't believe there is anyone who can reasonably say that the investments that individuals, society and industry make in conferences such as this one, which promote technological development, are not worth it.

Despite these successes, and others, the Macondo incident highlights the fact that there are limits to what we can accomplish in the marine environment. It is now clear that additional investments in underwater technology are required to help us predict and prevent as well as limit the extent of incidents like the Macondo blowout that may occur in the future.

The world's apparently insatiable appetite for low cost energy will continue to push oil companies into deeper and deeper waters in search of economically recoverable reserves of oil and gas. The structures and systems required to safely do so cost billions of dollars. However, for all the advanced engineering and testing involved in the construction of these systems, some of which Stress performs, the effects of the elements and applied loads will continue to take their toll, potentially resulting in unsafe conditions

such as fatigue cracking of welded connections, which if left undetected or unrepaired, could result in another catastrophic failure. If the offshore exploration industry is to survive, it must resolve to provide itself with the technologies required to permit early detection and repair of these conditions. Our government has indicated that failure to do so is no longer an option.

When repairs or modifications to marine structures are needed, it is often too expensive or even impossible to move them to a location where normal inspection and repair welding techniques can be performed, and this is where the technologies that will be discussed during this three-day long conference come into the fore. The ability of industry to apply well developed and understood technologies related to underwater inspection and welding provides industry with an economic way to keep these important structures afloat and in service, while ensuring that they continue to safely and reliably perform the functions for which they were originally intended. Therefore, Stress supports this conference and its goals, which are to promote and advance the art, the science, and the reliability of underwater inspection and welding techniques.

I would like to welcome all of you to Houston. I wish you success as regards this conference and in all your future endeavors.

Some Trends in Ship & Offshore Design, Construction & Operations

Peter Tang-Jensen, Senior Vice President, Technology, ABS

Third International Workshop on State of the Art, Science & Reliability of Underwater Welding, Inspection & Technology

Houston, TX
17 November 2010

**Supporting Remarks:
Some Trends in Ship & Offshore
Design, Construction & Operations**

Peter Tang-Jensen
Senior Vice President, Technology
ABS



1

Overview

- Trends in ship design and construction
- Challenges in welding and NDE
- Underwater welding in FPSOs
- Closing comments



2

Economies of Size



ABS

3

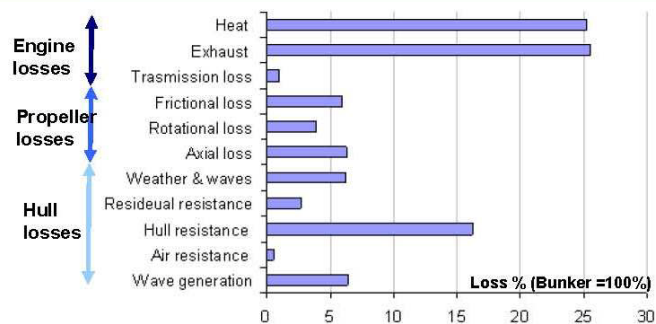
Increased Focus on Environment



ABS

4

Search for Energy Efficiency



Engine

- Improving engine fuel efficiency
- Waste heat recovery
- Low load operations
- Engine de-rating

Propeller

- Propeller optimization
- Cleaning

Hull

- Hull shape optimization
- Anti-fouling coatings/cleaning
- Air bubble lubrication
- Weather routing/trim optimization

Alternative energy source

- Gas
- Renewable energy
- Shore power (cold ironing)

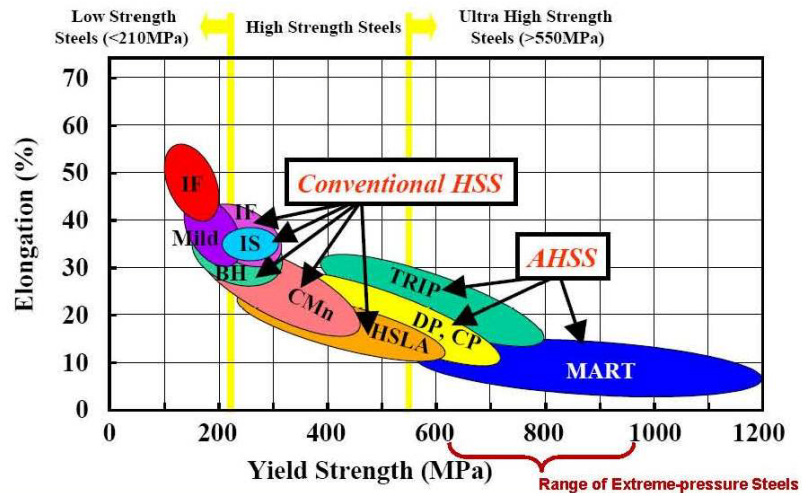


ABS

5

Stronger Steels, Lighter Ships

Higher Strength Steels – Lower Ductility



ABS

6

Composites etc., Lighter Ships

- Use of composites and other non-corrosive materials
- R&D needed to bring cost of construction down, maintain fire safety, recycling, etc.
- Sandwich construction
 - FRP laminates with light weight core material (applied for high speed craft, superstructures, etc.) offer 30% to 70% weight savings
- Sandwich plate system (SPS)
 - Metal plates with polyurethane elastomer core (applied in superstructures, hatch covers, etc.) potential for cost savings
- Greater use of aluminum



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7

Welding: Special Materials

- Welding of LNG tank materials
 - Stainless steel – low temperature toughness
 - 9% Nickel – strength reduction
 - Aluminum – welding deformation



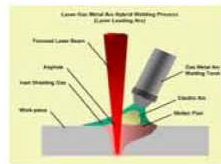
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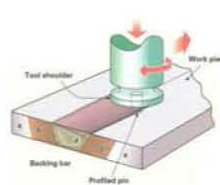
Welding: Advanced Techniques

- Application of advanced welding technique to shipbuilding and offshore structures
 - Laser hybrid welding
 - Friction stir welding
 - Multiple pole EGW for thick plate

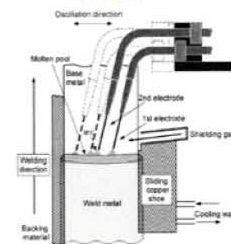
Laser Hybrid



FSW



EGW

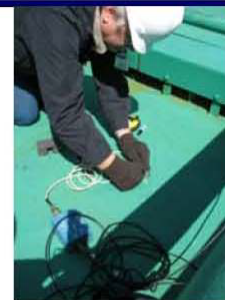


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9

NDE: Advanced Techniques

- Advance UT
 - Phased array – increased efficiency and improved detectability
 - TOFD – improved assessment of internal defect size
- Real time
- Acoustic emission



Portable Computed Digital X-ray Imaging



Ultrasonic Phased Array

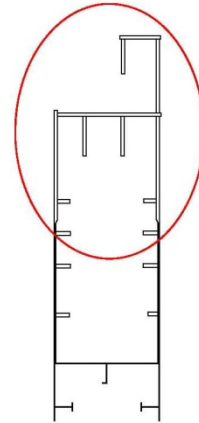
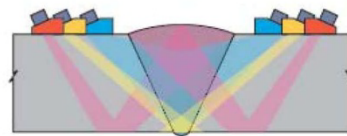


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10

NDE: Thick Plates

- Welding defects are critical for thick plates
 - High stress area
 - Low fracture toughness
- Traditional NDE techniques have limitations
 - Advance UT – phased array



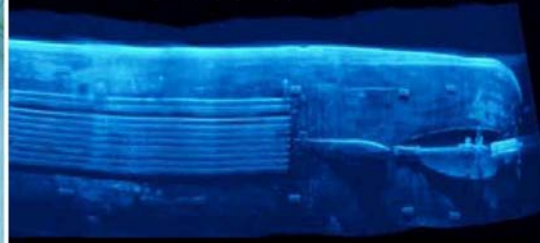
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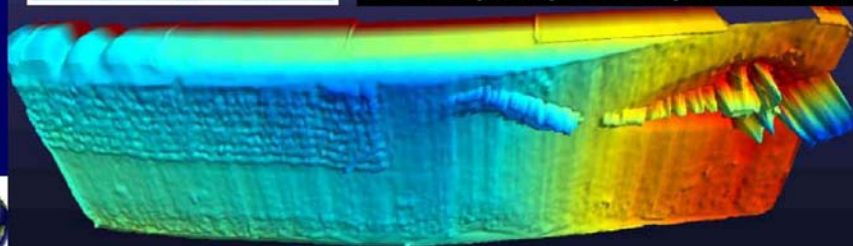
Autonomous Hull Inspection/Acoustic Imagery



2-D Imaging for Flat Sections



3-D Bathymetry for Complex Sections



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12

Challenges

- Demand for stationkeeping
 - FPSOs
 - Fixed platforms
 - Calm buoys
 - TLPs
 - MODUs



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13

Challenges

- Continued operation
 - Pipelines
- Life extension
 - Existing projects
- Drydock availability
 - Ships repairs afloat



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14

Opportunities?

- To gain an appreciation of the current underwater technology
- How will the emerging trends in ship and offshore design/operation influence underwater welding and inspection?
- Will these trends create opportunities for future development and advancement of the current underwater welding and inspection technologies?



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15

Our Wishes to the Workshop

- On behalf of ABS, I would like to express our best wishes to workshop
- We are very fortunate to work with this prestigious group of Colorado School of Mines Professors over the last 20 years in delivering a series of workshops
- Our special thanks to Professor Stephen Liu and Professor David Olson for championing the efforts



ABS

16

BOEMRE Regulations Applicable to Welding

**B.J. Kruse, III, Chief, Office of Structural and Technical Support, U.S. Department of the Interior,
Bureau of Ocean Energy Management, Regulation and Enforcement**

*Bureau of Ocean Energy Management, Regulation
and Enforcement*

Supporting Remarks

*International Workshop on State of the Art, Science and Technology of
Underwater Welding and Inspection Technology*

November 17, 2010
Houston, Texas

*B.J. Kruse, III P.E.
Chief, OSTs
BOEMRE Gulf of Mexico Region*



Outline

- Welcome
- BOEMRE Regulations Applicable to Welding
 - Performance Standards 30 CFR 250.106,107,109 thru 113
 - Alternate Procedures 30 CFR 250.141
 - Fabrication Verification Plan 30 CFR 250.912 (b)
- Closing



Performance Standards

- 30 CFR 250.106 operator responsible for orderly development of lease, prevent injury or loss of life.
- 30 CFR 250.107 operator to perform all operations in a safe and workmanlike manner and use BAST whenever practical.
- 30 CFR 250.109 operator to submit welding plan.
- 30 CFR 250.110 outlines welding plan contents.
- 30 CFR 250.111 designates welding supervisor or person in charge.
- 30 CFR 250.112 sets welding equipment requirements.
- 30 CFR 250.113 outlines welding procedures.



Alternate Procedures

- 30 CFR 250.141 alternate procedures or equipment used must provide a level of safety and environmental protection that equals or surpasses current BOEMRE requirements.



Fabrication Verification Plan

- 30 CFR 250.912 (b) outlines the welding procedures and non-destructive examination for welds and materials used in the fabrication verification plan of platforms subject to the Platform Verification Program.



Questions ?



Plenary Presentations

Service History of Wet Welded Repairs and Modifications

Thomas J. Reynolds, Global Divers & Contractors, Lafayette, Louisiana, USA

Developments in Dry Hyperbaric Arc Welding – A Review of Progress Over the Past Ten Years

Ian M. Richardson, Delft University of Technology, Delft, The Netherlands

N. J. Woodward and M. A. Armstrong, Isotek Electronics Ltd, Leeds, England, UK

J.O. Berge, Statoil, Stavanger, Norway

Friction Stud Welding Testing for Submarine Rescue

W. Jack Couch, Oceaneering International

Robert Murray, NAVSEA

Friction Stud Welding Underwater in the Offshore Oil and Gas Industry

Dave Gibson, Proserv Offshore Ltd.

Nathan Paculba and Ian Grey, Proserv Offshore Inc.

Fitness-for-Service Assessment of Underwater Welds in Offshore Structures

Pingsha Dong, School of Naval Architecture and Marine Engineering,

University of New Orleans, New Orleans, Louisiana, USA

Nondestructive Evaluation in Underwater Environments – Lessons for Other Industries

J. Gray, Center for NDE, Iowa State University, Ames, Iowa, USA

Service History of Wet Welded Repairs and Modifications

Thomas J. Reynolds, Global Divers & Contractors, Lafayette, Louisiana, USA

1.0 ABSTRACT

This paper examines the service history of wet welded repairs and modifications by summarizing selected underwater projects carried out over the past 4 decades as case studies in the U.S. Gulf of Mexico and at several International locations. The case studies addressed in this paper span several decades of jacket design improvements and look into the service life of the structure after the initial repair.

Components repaired and modified consist of primary structural members, such as jacket legs, vertical diagonals and horizontal members and secondary structural members, such as conductor guide framing and control umbilical support structures. By analyzing the repairs and service history, decisions can be made to determine whether the repairs were satisfactory or unsatisfactory.

The Gulf of Mexico structures have experience several hurricane events since completion of the repairs or modification. The structural damage is described, repair method summarized and present status of the structure provided.

2.0 INTRODUCTION

Many structures have been repaired or modified in the Gulf of Mexico since the early 1970's. Wet welding technology also moved into the International arena in the early 1970's as well. Several papers and articles have been published describing those repairs in detail. [Ref. 3] [Ref. 4]. This paper has selected past repair and modification projects as case studies by summarizing what occurred and how the problems were resolved. The service history of these structures and performance of the repaired components are then summarized.

3.0 SUMMARY OF GULF OF MEXICO REPAIRS AND MODIFICATIONS

3.1 Garden Banks 426 A, Auger Tension Leg Platform

The Auger TLP was installed in 1994. It is anchored to the sea bottom in approximately 3000 feet of seawater by multiple tendons. Oil and gas is produced from wells directly beneath the TLP. As production declined, additional hydrocarbon reservoirs were located several miles from the Auger TLP. To produce from these new wells, production risers are brought up through the well bay and well control umbilicals are brought up on the outside columns inside I Tube structures. These I Tube structures provide protection to the control umbilicals as they pass through the waterline up to the top of columns.

Because this was the first TLP installed by this operator in the Gulf of Mexico, design provisions were not made for mechanically attaching control umbilical I Tubes to any of the four, 75 ft (23m) diameter columns. Therefore the operator chose to utilize wet welding techniques for attaching the I Tube structural standoff supports directly to the columns.

In 2003 the Dual 16 in (406mm) Habanero Llano Umbilical I Tubes were installed on the outboard side of the A1 Column. The Dual I Tube was installed in two assemblies, one above the waterline assembly and one below the waterline.

The below the waterline assembly had five doubler plate/I Tube clamp assemblies wet welded to the hull column. The clamp elevation locations ranged from -15 ft (4.5m) down to -95 ft (29m). All clamps were attached to the column by wet welded fillet welds.

The 20 in (508mm) Ozona Control Umbilical I Tube is presently (2010) being installed adjacent to the Habanero Llano I Tube. The Ozona doubler plate connection elevations are the same as those for the Habanero Llano I Tube. During the Ozona installation, inspection/diver-welders cleaned the marine growth from the left side of the -28 ft (8.5m) doubler plate fillet weld and performed an in service visual inspection (VT) of the cleaned fillet weld.

The diver found neither indications nor any areas of concern. In addition, the results of a comparison of as built photos from the 2003 installation time period and those photos taken recently during the in service inspection showed no changes to the weld condition.

To date there are four control umbilical I Tube assemblies attached to three of the four columns. The first was installed in 1998. All control umbilicals remain in service.

3.2 Ship Shoal Area

SS 169 A [Ref. 1] – The SS 169 A platform is an eight leg design sitting in -57 ft (17.3m) of sea water. The structure was installed in 1961. There are two underwater levels on this structure, 31 ft (9.4m) and 51 ft (17.4m). SS 169 A was one of many structures damaged by Hurricane Andrew.

Shortly following the passage of Hurricane Andrew, an API Level II survey was conducted. A crack was found in the base metal of the A2 at the -51 ft (17.3m) elevation. This crack initiated at the eight o'clock position on the -51 ft (17.3m) horizontal diagonal from B1, then propagated up past the A2-B2 vertical diagonal and terminated beneath a riser clamp attached to the A2 leg. The probable cause of damage was high waves striking the cellar deck, thus transferring high forces down to the jacket.

In 1994, a repair procedure was carried out to repair the crack by removing the lower half of the Vertical Diagonal (VD) brace, -51 ft (17.3m) A2 VD/-31' B2. The procedure called for completely removing the existing VD footprint, followed by the installation of a leg doubler and replacement VD (lower half). The doubler plate was attached to the A2 leg with fillet welds. The new lower half of the VD was "spliced" to the existing upper half using a sliding scallop sleeve. This structure had a follow-up in service survey the following year (1995) and no indications were found on any of the repair areas. In 2006 this structure was removed from service.

SS 291 A – The SS 291 A structure is an eight leg design standing in 236 feet of sea water. This structure was installed in 1976. There are five underwater elevations on this structure, -38 ft (11.5m), -83 ft (25.3m), -130 ft (39.6m), -183 ft (55.7m) and -236 ft (71.9m). During a regularly scheduled API Level II survey in 2000, a damaged 24 in (609mm) dia. horizontal member was discovered between the A2-B2 Legs at the -38 ft (11.5m) elevation.

This 24 in (609mm) dia. horizontal member provides support for the conductor guide framing (CGF) members at the same elevation. There are slots for 24 conductors in this CGF and all of the slots contained conductors. There are two rows of four guides on one side of the horizontal member and four rows of four guides on the other side of the horizontal member.

The probable causes for damage of this type is cyclic fatigue due to conductors moving in the horizontal direction within the conductor guides, transferring the energy of their horizontal movement into axial loads through the 24 in (609mm) horizontal member to the A2 and B2 legs. Additional loading caused by the vertical movement of the water column brought in a cyclic bending moment at the horizontal to leg connection as well.

The Level II survey indicated that the horizontal member was completely broken free of the jacket legs at both ends. The reason the member did not drop down was because portion of the leg material attached to the horizontal was still stuck in its original location and could not fall down.

The repair procedure required the damaged ends of the horizontal to be removed from the leg and as close as reasonably possibly to the adjacent CGF members. New horizontal stub members were prepared and attached to doubler plates. The doubler plates were sized to provide a sufficient overlap of the void in the legs as a result of the 100% circumferential crack.

As a mitigation action to help minimize the bending moment at the horizontal to leg connections, “Top Hat” clamps were installed on four selected conductors directly above and below the CGF such that these “Top Hat” clamps restricted any vertical movement of the CGF and minimized the bending moments at the horizontal to leg connection.

The structure was originally operated by Union Pacific Resources. Operation of the structure was taken over by Anadarko Petroleum Corporation through acquisition. Ownership is now with W & T Offshore. This structure remains in service today.

SS 246 A – The SS 246 A structure is an eight leg design standing in 170 ft (51.8m) of sea water. There are four underwater elevations on this structure, -30 ft (9.1m), -70 ft (21.3m), -116 ft (35.5m), and -165 ft (50.2m). This structure was installed in 1974. During a regularly scheduled API Level II survey in 1997, cracks were identified at six locations on members that supported the conductor bay framing guides at the -30 (9.1m) elevation.

The conductor bay framing guide assemblies are framed around with 20 in (508mm) and 14 in (355mm) dia. members. The intersections identified with cracks are described as T, K and X type intersections. There are slots for 24 conductors in this CGF with the majority of the slots between the 1 and 2 Rows. Six of the 24 slots were empty.

The probable causes for damage of this type is cyclic fatigue due to conductors moving in the horizontal direction within the conductor guides, transferring the energy of their horizontal movement into axial loads to the connecting framing members. Additional loading caused by the vertical movement of the water column brought in cyclic bending moments to the connecting framing members as well.

The repair procedure involved locating the distal ends of the cracks and drilling crack arresting holes, then designing and fabricating 3 - T, 1 - K and 2 - X type cruciform full encirclement reinforcement assemblies. These assemblies were designed to provide a 100% reinforcement of the connections. From an engineering perspective, the original connection was no longer in the model. This repair activity took place 1998. The SS 246 A structure is currently still in production.

Earlier this year an incident occurred when a contractor was removing an abandoned conductor from the jacket. Unknown to the contractor at the time, there was an appurtenance attached to the conductor between the -116 ft (35.5m) and -165 ft (50.2m) elevation. This appurtenance was larger in size than the guide slot. As the contractor was hydraulically raising the conductor, the appurtenance damaged the conductor guide framing at the -30 ft (9.1m), -70 ft (21.3m) and -116 ft (35.5m) elevations. The previously reinforced (1998) locations at the -30' elevations remained undamaged whereas similar unreinforced structural intersections at the -70 ft (21.3m) and -116 ft (35.5m) elevations received considerably damaged.

3.3 Eugene Island Area [Ref. 1]

EI 231 CB – The EI 231 CB platform is a four leg design sitting in 112 ft (34.1m) of water. There are three underwater levels on this structure, -27 ft (8.2m), -62 ft (18.9m) and -110 ft (33.5m). This structure was installed in 1971. EI 231 CB was one of many structures damaged by Hurricane Andrew.

Shortly following the passage of Hurricane Andrew in 1992, an API Level II survey was conducted. This survey located a crack at the intersection of the VD member and circumferential ring stiffener intersection at the C1 leg, -62 ft (18.9m). The crack was located in the Toe of Weld (TOW) at nine o'clock of this intersection. The crack was 14 in (355mm) in length with a maximum opening of 3/32 in (2.5mm). The probable cause of damage was high waves striking the cellar deck, thus transferring high forces down to the jacket.

In 1993, the crack was removed with an arc/water gouge and hydraulic grinder. The resulting groove preparation area was filled in by wet welding. No part of the stiffener ring was removed for the repair. This structure had a follow-up in service survey the following year (1994) and no indications were found on any of the repair areas. This structure was removed from service in 2004.

3.4 South Timbalier Area

ST 52 [Ref. 2] – The ST 52 structure is owned by Trunkline Gas Company, a subsidiary of Panhandle Eastern Corporation. This structure is also known as their T-23 platform. This structure is a four leg design standing in about 65 feet of water. There are three underwater levels on this structure, -15 ft (4.5m), -39 ft (11.8m) and -63 ft (19.2m).

This structure was designed and installed in 1972. The design is similar to many intermediate depth four leg jackets, utilizing mid-point T, K, Y braced intersections, rather than the traditional vertical diagonal or X brace design for supplying jacket stiffness and the transfer of loads. This structure was one of many damaged by Hurricane Andrew.

Shortly following the passage of Hurricane Andrew, an API Level II survey was conducted. Divers discovered two damaged, critical midpoint K brace nodes on each side of the structure at the -39 ft

(11.8m) elevation. A close examination of the damage showed the main chords, 18 in (457mm) dia. x 0.375 in (9.5mm) wall thickness members, had experienced punching shear failure.

Rather than trying to make repairs to a heavily damaged, under designed critical node (by Hurricane Andrew standards), a new, upgraded K brace node was designed and fabricated. The damage node was removed by cutting the connecting members at their midpoints and then installing the new node assembly in place of the damaged node. The connecting members were captured and “spliced” with sliding scallop sleeves. Once the repair was completed on one side, the opposite side node was removed and replaced in the same manner.

The T-23 platform continues to serve as a manifold/valve structure for Truckline Gas Company today without needing any subsequent repairs or modifications.

4.0 SUMMARY OF INTERNATIONAL REPAIRS

4.1 Arabian Gulf – Khazzan Offshore Storage and Loading Facility [Ref. 3] [Ref. 4]

The Khazzan facility is located 52 miles (84km) northwest of Abu Dhabi in 155 ft (47m) of water. Khazzan 1 was installed in 1969 and Khazzans 2 and 3 were installed in 1972. Each of the Khazzan’s can store up to 500, 000 barrels of oil.

During the installation phase in 1972, several anodes were torn loose while launching and towing of the K-2 and K-3 structures. The anodes were repaired at site by re-welding the 4 in (100mm) standoffs to the tank wall. The water depth for these repairs was 157 ft (48m).

The K-2 and K-3 tanks were also damaged from dropped piles during pile driving operations. Structural tee stiffeners on both tanks located at the pipe guide ring wall in 137 ft (42m) were crushed due to the falling piles. The damaged 8 ft (2.4m) long structural tee stiffeners were removed by chipping and oxy-arc burning and then new Tee stiffeners were fit in place and installed by wet welding. This work was carried out by Chicago Bridge and Iron welder divers in 1972.

The Khazzan facility is still in operation today, almost 40 years later, producing, storing and loading crude oil.

4.2 Atlantic Ocean – Trinidad, Samaan A Structure [Ref. 5]

The Samaan A Structure is a drilling platform located off of the south east coast of Trinidad. It is an eight leg structure standing in approximately 180 feet of water. This area is below the hurricane belt but subject mid Atlantic storms, ground swells and currents.

During an API Level III underwater survey in 1995, a detached 16 in (406mm) diameter horizontal member was identified at the -125 ft (38m) elevation. The horizontal member was completely detached at one end and partially detached at the other end. An aggressive drilling schedule was scheduled to begin in two months. The structure was modeled without the horizontal member in place with the loads applied from the drilling activity on the main deck. The engineering analysis confirmed that the member needed to be in place to ensure overall structural integrity.

A replacement horizontal assembly was designed that included doubler plates welded to each end of the horizontal member and a telescoping sliding scallop sleeve located near one end. The existing damaged horizontal member was removed, the surface of the legs ground smooth and then the new telescoping assembly installed by wet welding.

This structure has operated continuously since the 1995 repair project. It was recently sold by Amoco Trinidad Oil Company to the National Gas Company of Trinidad and continues producing today.

4.3 North Sea – British Sector, Montrose Structure [Ref. 4]

The Montrose platform is an eight leg design standing in 300 ft (91m) of water. There are five underwater elevations with the first elevation located at the -36 ft (11m) level. This structure was installed in 1976.

Following a vessel collision with the Montrose jacket, an underwater survey was conducted in June of 1987 to determine the extent of the damage. The vessel struck a 30 in (762mm) dia. vertical diagonal member near the waterline. Besides the impact damage, the underwater survey revealed a circumferential crack in the weld joining the vertical diagonal member to the heavy wall stub that connects the vertical diagonal to the leg.

An analysis of the structure without the vertical diagonal in place established that the structure was still fit for duty and an emergency fix was not required immediately.

As a general rule in the North Sea, whenever structural damage of this or a similar nature, hyperbaric dry welding techniques are used to restore the structure to its original design. In this case, the operator, Amoco (U.K.) Exploration Co. chose to investigate wet welding as an alternate technique for reinstalling a replacement brace.

Once wet welding was determined to be suitable for the repair, welding procedures were developed and qualified as well as welders being qualified for performance. The repair method consisted of a modified scallop sleeve that stabbed over the existing undamaged, underwater stub to leg connection. The single scallop sleeve was attached to the stub with a continuous fillet weld. The above portion of the vertical diagonal was connected to the topside leg stub with a pup piece. This repair activity was carried out in 1990. A follow-up survey in 1991 established that there was no delayed cracking.

This wet welded repair marked the first time a primary member had been repaired by wet welding in the North Sea. This structure is still in service today.

5.0 SERVICE HISTORY SUMMARY

Of the 34 structures examined, 29 structures remain in service today. A recent follow-up survey of the structures covered in this paper and additional structures repaired or modified by wet welding are summarized in Table 1. None of the operators of these structures have reported any problems following the repairs or modifications.

Examining the 5 structures removed from service between 2000 and 2008; two were removed because they represented “idle iron,” or no longer supported production or transportation of hydrocarbons. Two

were removed after being damaged by hurricanes to the extent that the cost for repairs exceeded the dollar value of hydrocarbons remaining in the ground. The extent and nature of damage remains unknown as of this writing.

One structure, ST 21 E was sold to an independent producer in 2000 and removed from service in 2008. The reason for removal has not been determined as of this writing.

Many of the structures weathered several head to head or glancing blows from hurricanes. One the structures experienced a hurricane event less than six months after completion of the repairs and received no damage where several nearby structures were severely damaged or toppled. However, a nearby 4 pile structure, installed in 1971 and repaired by wet welding in 1993 (Vertical diagonal – Leg ring stiffener repair) was damaged sufficiently that the cost for repairs exceeded the value of hydrocarbons still in the ground and was removed in 2004.

Another structure undergoing major wet welded repairs due to Hurricane Ivan experienced a hurricane event (Hurricane Katrina) before all of the repairs were even completed and survived with no damage.

In most of the case studies, primary members were either repaired or replaced by wet welding. These primary members consisted of jacket leg repairs (100% separation of legs), vertical diagonal replacements, vertical X brace replacements, horizontal member replacements, horizontal X brace repairs and a few conductor guide framing repairs.

Table 2 summarizes the types of repairs made. It can be seen that vertical diagonal members (along with vertical X Brace members) have received the most damage and subsequent repairs by wet welding. The vertical X brace member may be considered as four separate vertical diagonal members with a common midpoint connection. A total of 2 vertical diagonal members were repaired on each vertical X brace for structures covered in this study.

In a similar line of thought, the T K Y node represent 2 vertical diagonal members, 1 vertical member, 2 horizontal members and 2 horizontal diagonal members with a common midpoint connection. A total of 4 vertical diagonals were repaired on these 2 node repairs.

Looking at the corrected column, it can be seen that the vertical diagonal member repairs (35) and vertical member repairs (2) exceed by over 100% the number of horizontal (diagonal, X brace, and horizontals) members. The vertical diagonal members transfer the major compression and tension loads throughout the jacket through the leg connections and these members/connections received the majority of the damage.

How well did these structures perform? All of the structures described in the above case studies performed satisfactorily for many years after the repairs, some are still supporting production and storage almost 40 years later.

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**Table 1 – Summary of Service Performance of Structures
Repaired or Modified by Wet Welding [7]**

Location	Description	Activity	Year Placed in Service	Year of Activity	Status
Garden Banks 426	TLP	Macaroni I Tube Installation	1998	1998	Still in service
Garden Banks 426	TLP	Serrano Oregano I Tube Installation	2000	2000	Still in service
Garden Banks 426	TLP	Habanero Llano I Tube Installation	2003	2003	Still in service
Mississippi Canyon 807	TLP	Deimos I Tube Installation	2006	2006	Still in service
Mississippi Canyon 807	TLP	Deimos SCR Pull In Padeyes	2007	2007	Still in service
Mississippi Canyon 807	TLP	Produced Water Upgrade Project	2008	2008	Still in service
Mississippi Canyon 809	TLP	Dual Water Flood Caisson Installation	2007	2007	Still in service
Mississippi Canyon 809	TLP	Overboard Water disposal Casing Installation	2007	2007	Still in service
Ship Shoal 169 A	8 Pile	Repair leg to VD fracture	1961	1993	This structure was damaged by Hurricane Rita in 2005. The cost to repair exceeded the value of hydrocarbons still in the ground and was removed in 2006. A total of 98 platforms were either damaged or destroyed by Rita [9].
Ship Shoal 207 AD	8 Pile	Repair CBF cracks	1967	2003	Still in service
Ship Shoal 291 A	8 Pile	Replace both ends of HZ member	1976	2000	Still in service
Ship Shoal 246 A	8 Pile	Repair CBF cracks	1974	1998	Still in service
Ship Shoal 269 A	8 Pile	VD Repairs x 7	1965	2005	Still in service
Vermilion 171 A	4 Pile	Horizontal X Brace Repair	1977	1998	Still in service

Location	Description	Activity	Year Placed in Service	Year of Activity	Status
Eugene Island 231 CB	4 Pile	VD / Ring stiffener repair	1971	1993	This structure was damaged by Lily in 2002. The cost to repair exceeded the value of hydrocarbons still in the ground and was removed in 2004.
Eugene Island 273 B	4 Pile	Replace VD x 2	1971	2003	Still in service
South Marsh Island 48 E	8 Pile	VD repairs x 9	1969	1991	Still in service
South Timbalier 52	4 Pile	K Brace repairs x 2	1972	1993	Still in service
South Timbalier 21 E	4 Pile	Replace VD	1973	1993	Sold to an Independent producer in 2000 and removed in 2008.
South Timbalier 134 W	4 Pile	Replace buckled VD	1981	1993	Still in service
South Timbalier 135 M	6 Pile	Horizontal X Brace Repair	1966	1993	Still in service
South Timbalier 151 Production	8 Pile	Vertical X Brace Replacement	1962	1993	Still in service
South Timbalier 151 L	8 Pile	Vertical X Brace Replacement	1966	1993	The cost to maintain the structure exceeded the revenues from hydrocarbon recovery and was removed in 2000.
South Timbalier 185 A	8 Pile	Horizontal Brace repair	1973	1998	Still in service
South Timbalier 188 CA	4 Pile	Conductor Guide crack repair	1981	1993	Still in service
West Delta 73 A	8 Pile	Vertical X Brace Repair	1963	1971	Still in service
South Pass 54 A	8/6 Pile	HD/VD Repairs and CGF Repairs	1970	1987	The cost to maintain the structure exceeded the revenues from hydrocarbon recovery and was removed in 2002.
Main Pass 313 A	8 Pile	Horizontal Brace repair	1982	2006	Still in service
Main Pass 281 A	4 Pile	Leg repairs x 2 and VD repairs x 2	1998	2005	Still in service
Main Pass 288 A	8 Pile	Conductor Guide Framing Repairs	1976	1985	Still in service

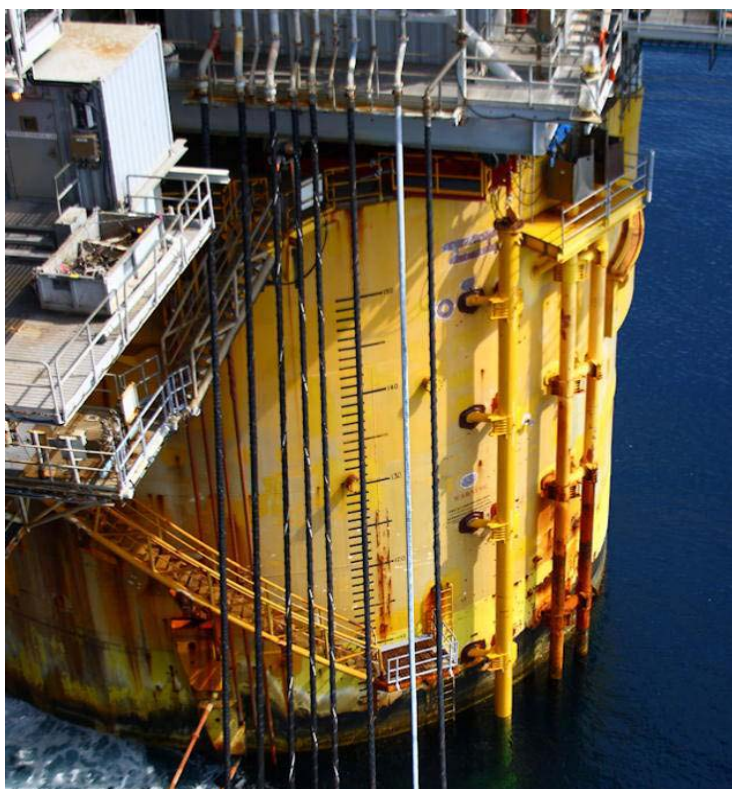
Location	Description	Activity	Year Placed in Service	Year of Activity	Status
Khazzan 2 and 3, Arabian Gulf	Offshore Storage, Production and Loading Facility	Structural tee stiffener repair and anode repair	1972	1972	Still in service
Samaan A, East Coast of Trinidad	8 Pile	Horizontal Brace repair	1995	1995	Still in service
Montrose, Central North Sea	8 Pile	Vertical Diagonal Brace repair	1990	1990	Still in service

Table 2 – Summary of Repair Types

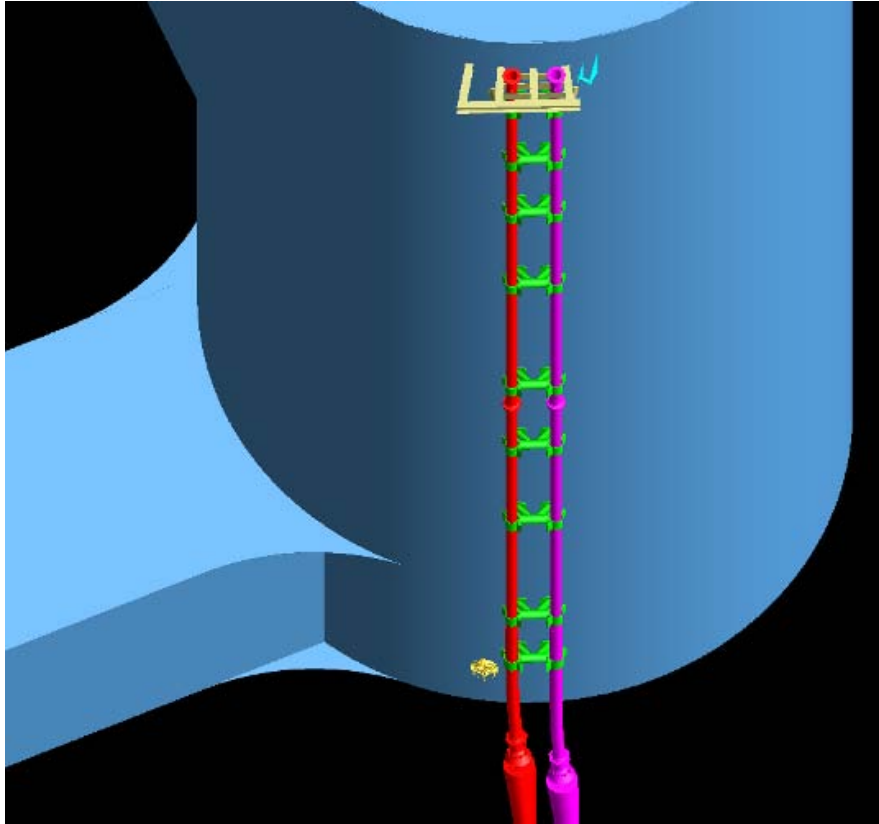
Repair Types	Number of Repairs	Corrected Number of Repairs
Vertical Diagonal (VD) Brace repairs	25	35
Vertical Brace Repairs	0	2
Vertical X Brace Repairs	3	0
T K Y Node replacements*	2	0
Horizontal (HZ) Brace repairs	5	9
Horizontal Diagonal Brace Repairs	0	4
Horizontal X Brace Repairs	2	2
Conductor Guide Framing (CGF) Repairs	4	4
100% Leg Break Repairs	2	2
*Each Node consisted of 1 vertical member, 2 horizontal members and 2 horizontal diagonal members (less the 2 vertical diagonal members.)		



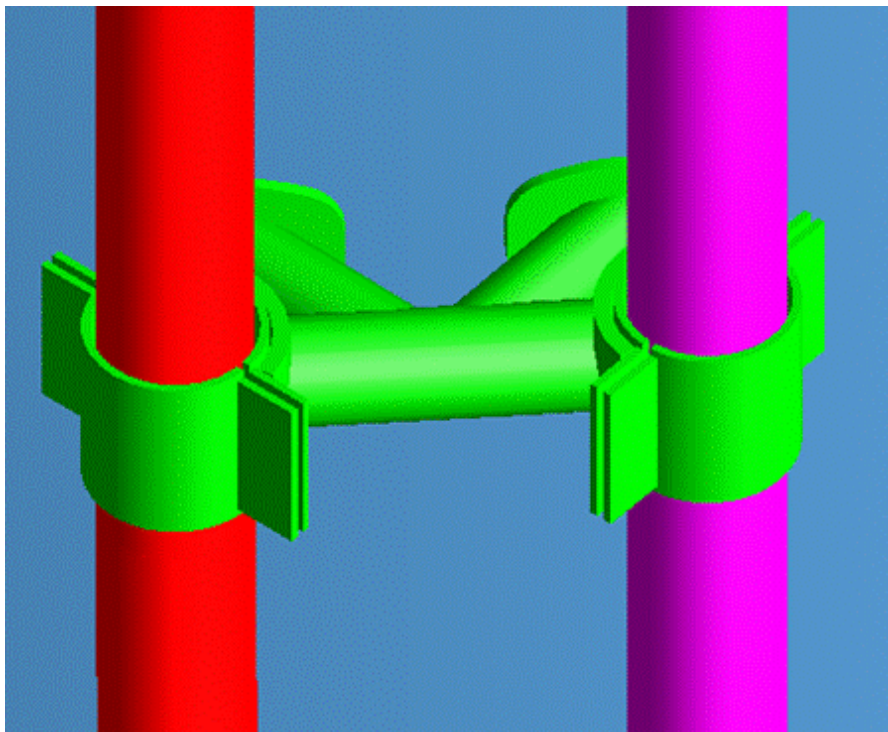
Auger TLP, Garden Banks 426



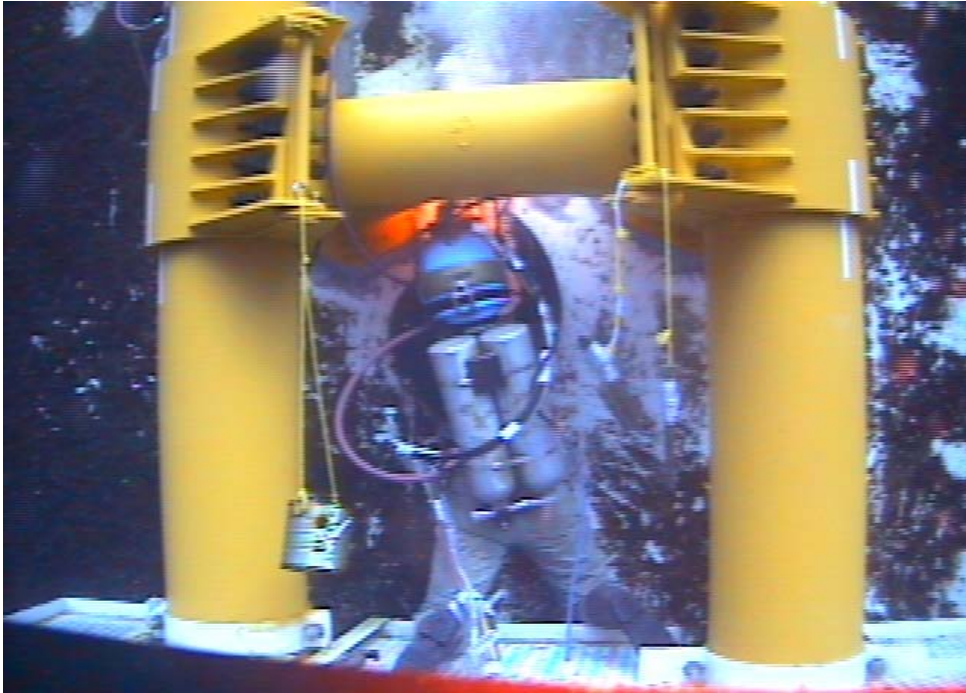
Habanero Llano Dual I Tubes (far side), Ozona I Tube (near side)



Isometric of Habanero Llano I Tube



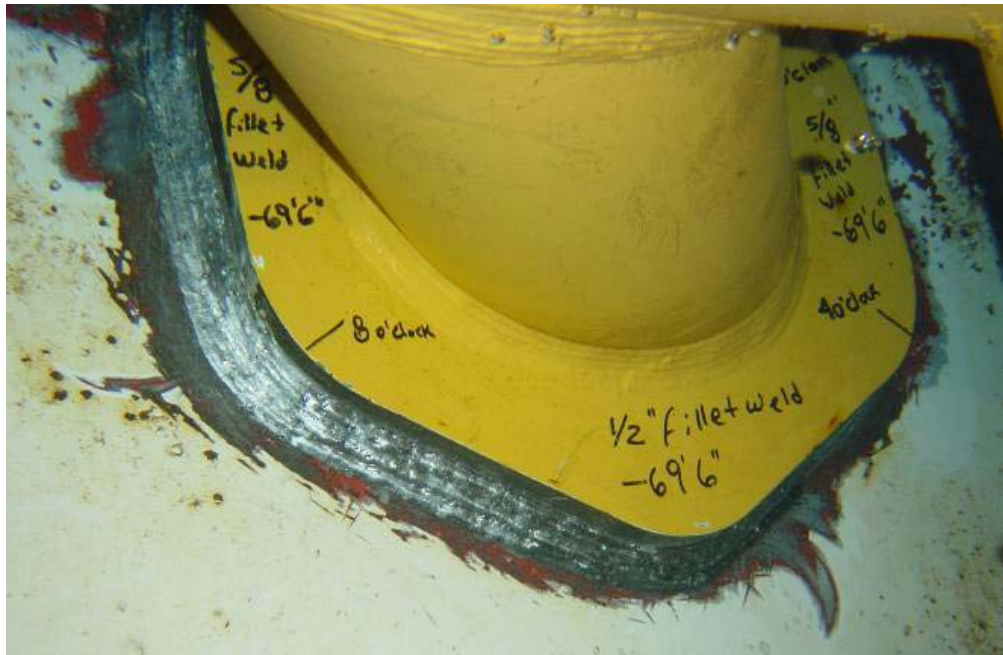
Detail View of doubler plates/I Tube clamps



Installing the Habanero Llano Dual I Tube



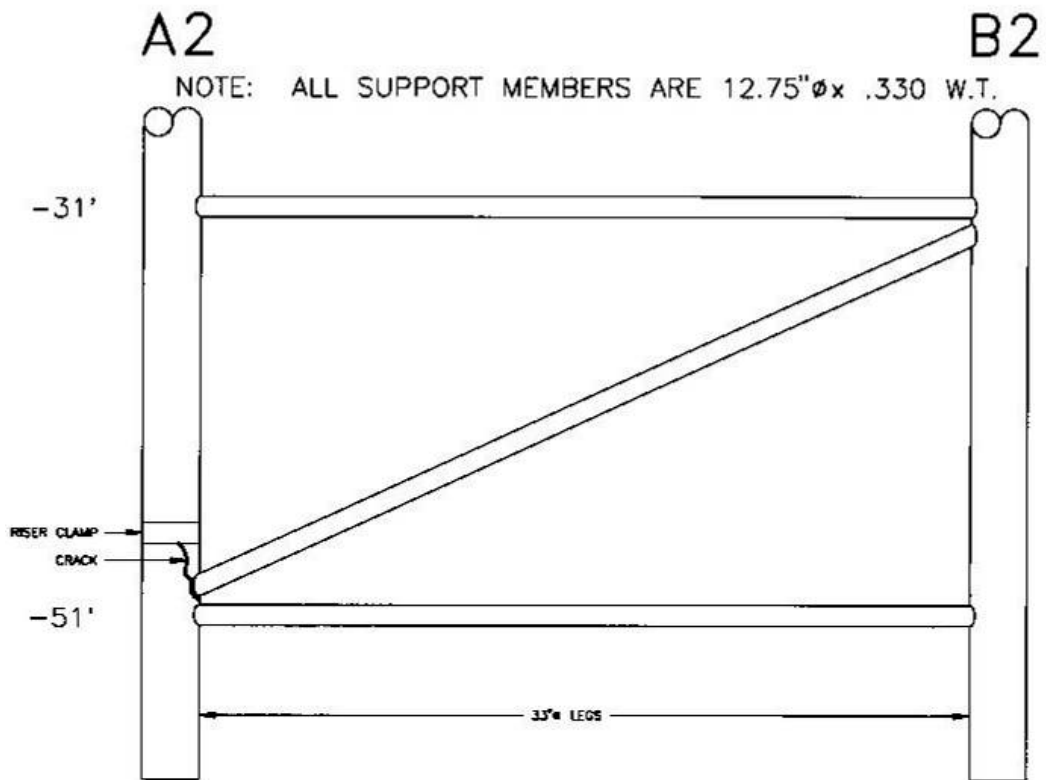
Installing the Habanero Llano Dual I Tube



Habanero Llano Completed Fillet Weld



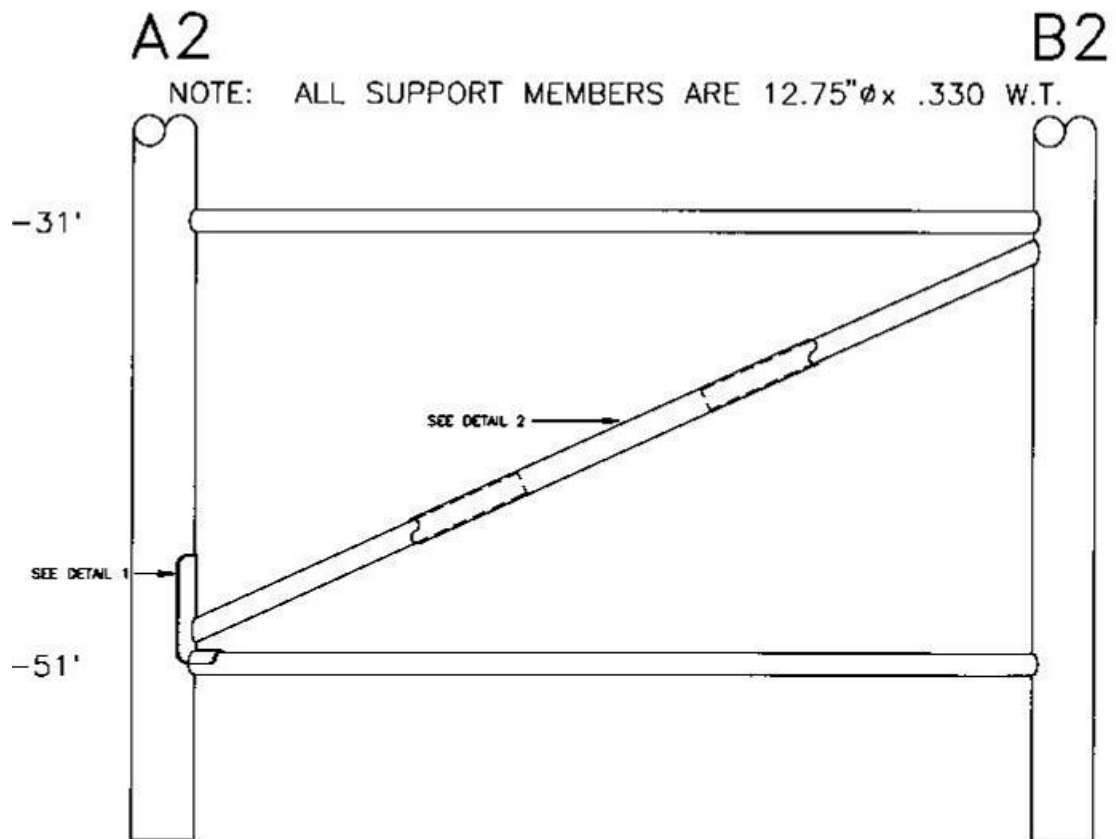
Habanero Llano In Service Inspection



Ship Shoal 169 A – Vertical Diagonal Leg Damage, General Arrangement



Ship Shoal 169 A – Crack Propagation Beneath Riser Clamp



Ship Shoal 169 A, Vertical Diagonal Brace Installation Detail



Ship Shoal 169 A, View of VD Stub and Doubler Plate



Ship Shoal 291 A



Ship Shoal 291 A, Conductor Bays Filled with Conductors



Ship Shoal 291 A, Horizontal to A2 Leg, -38' elevation



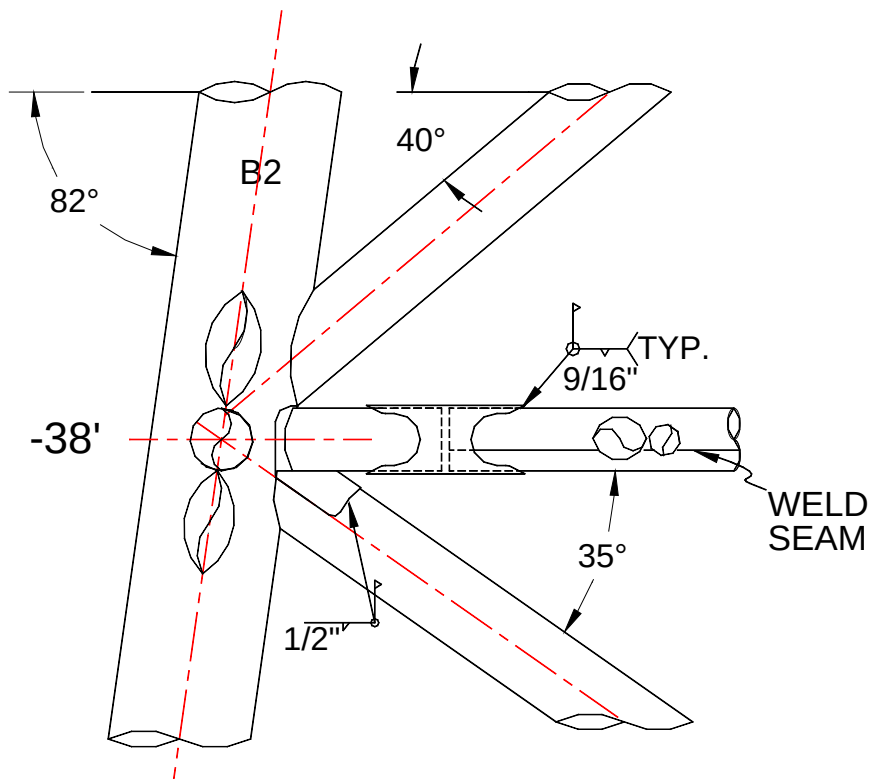
SS 291 A, Close up of the 360° Crack at the A2 Leg



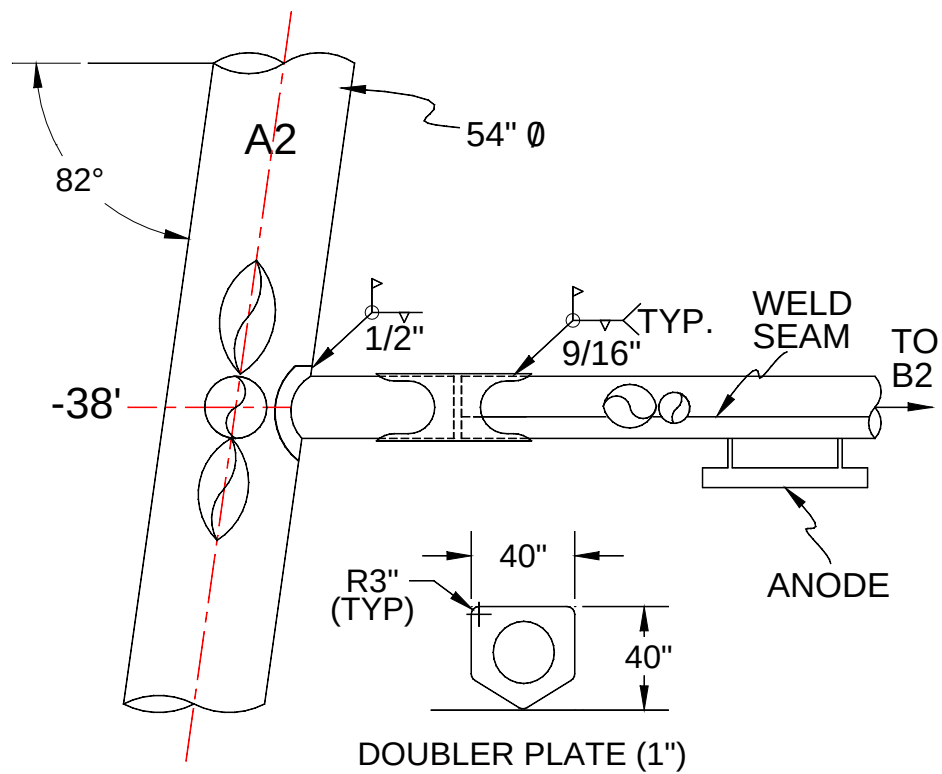
Ship Shoal 291 A, Horizontal to B2 Leg, -38' elevation



SS 291 A, Close up of the 360° Crack at the B2 Leg



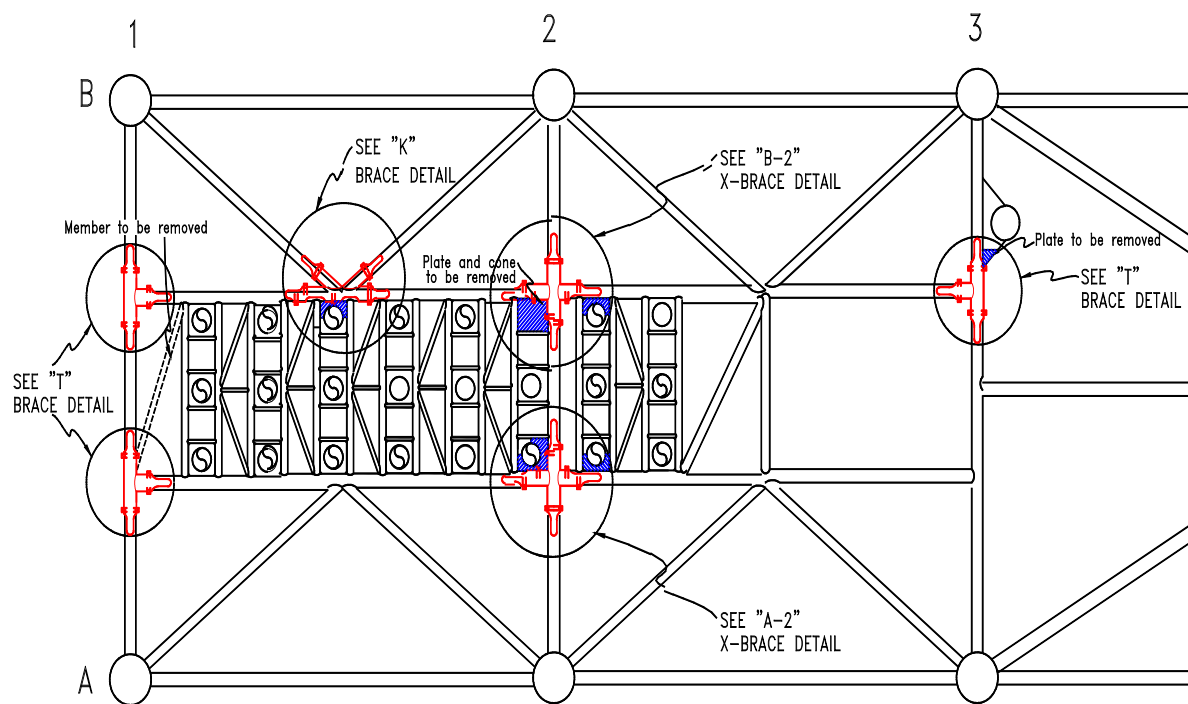
Ship Shoal 291 A – Final Repair Configuration, -38' Elevation, B2 Leg



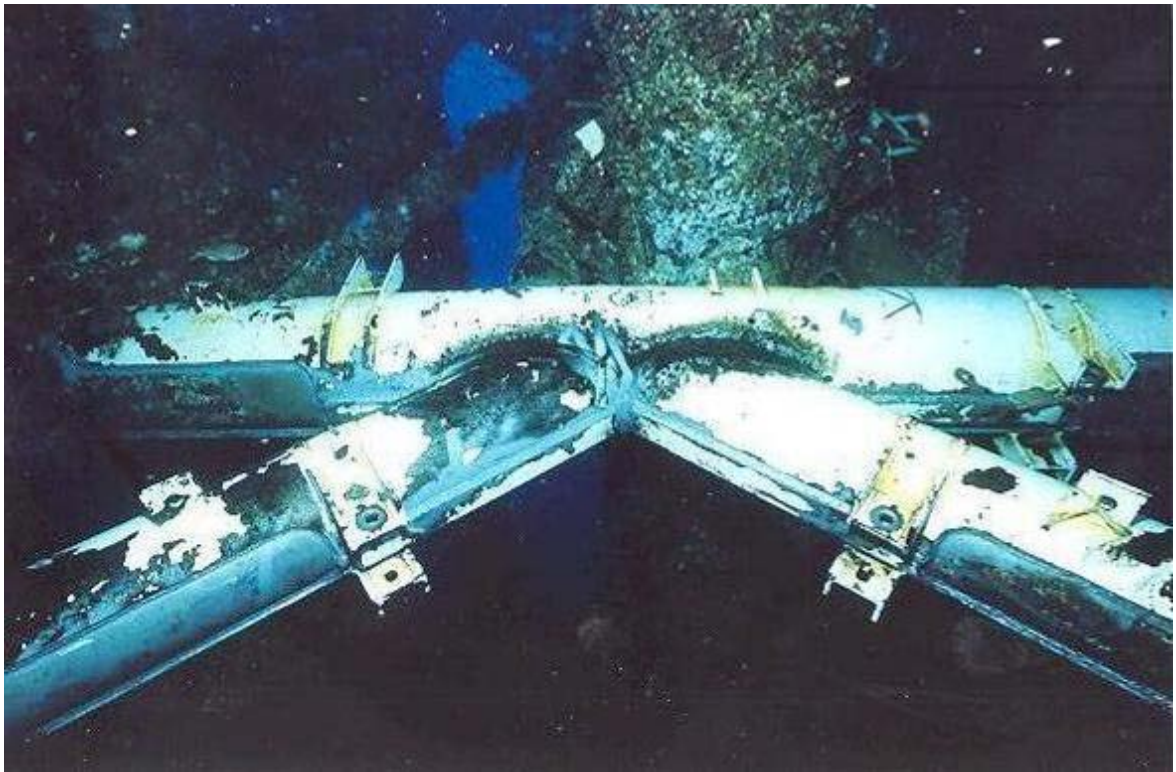
Ship Shoal 291 A – Final Repair Configuration, -38' Elevation, A2 Leg



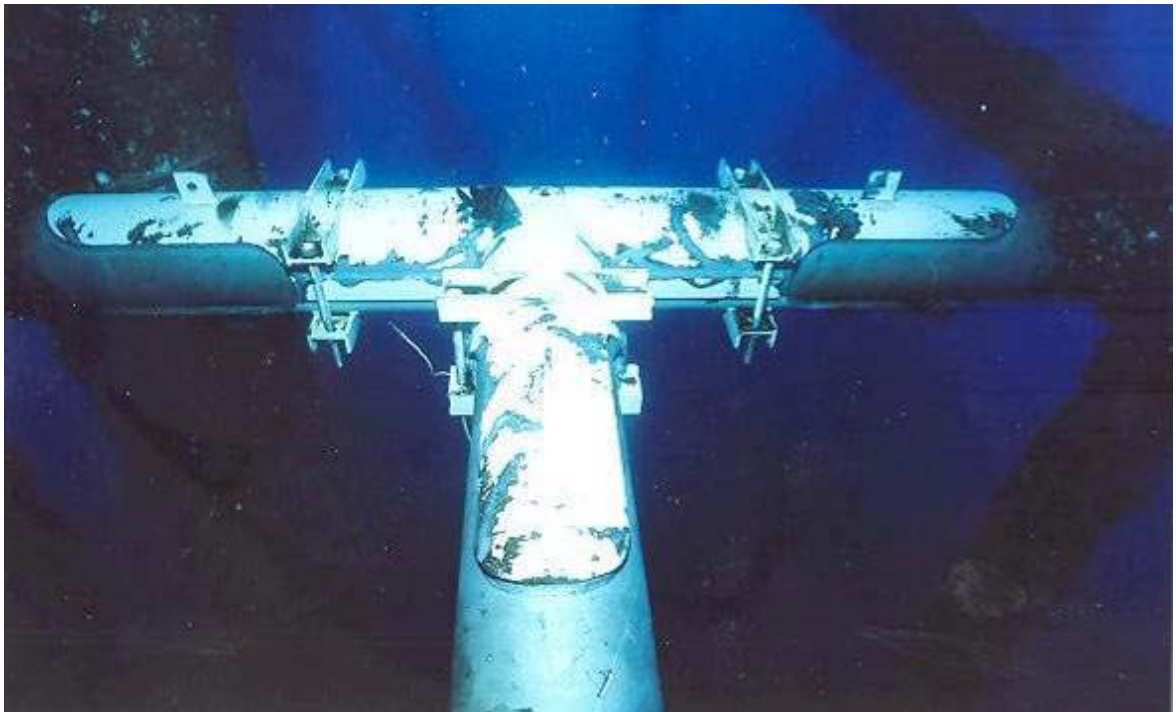
Ship Shoal 246 A



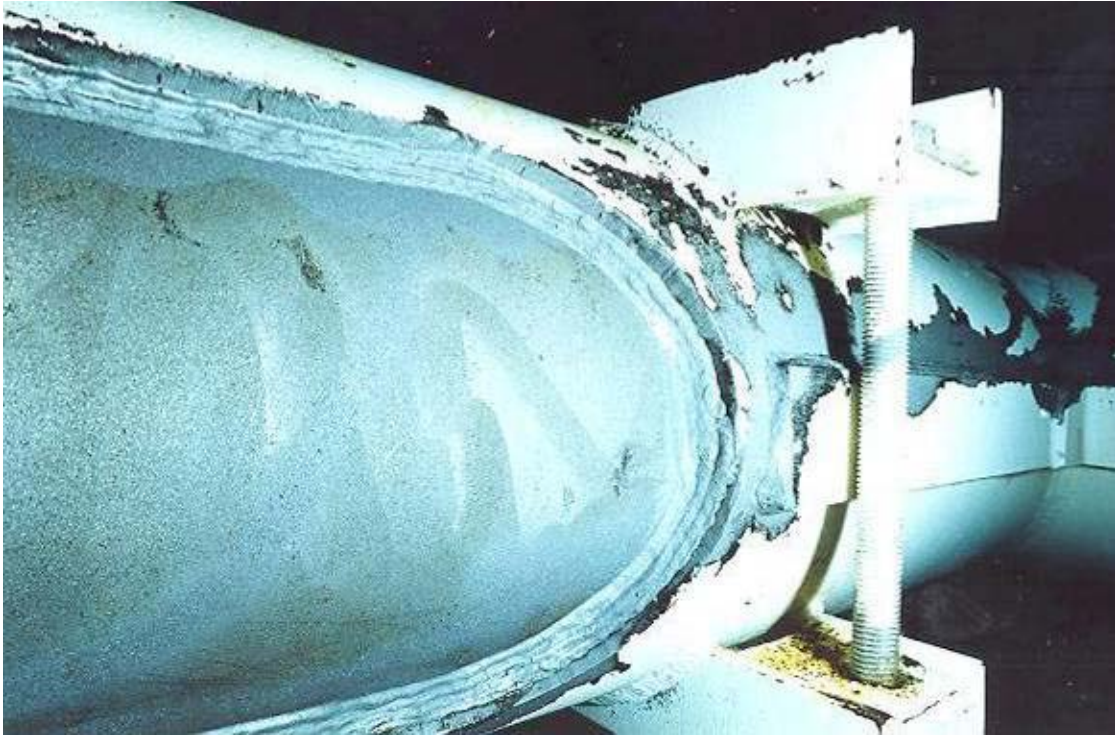
Ship Shoal 246 A, Locations of the Seven Repair Assemblies



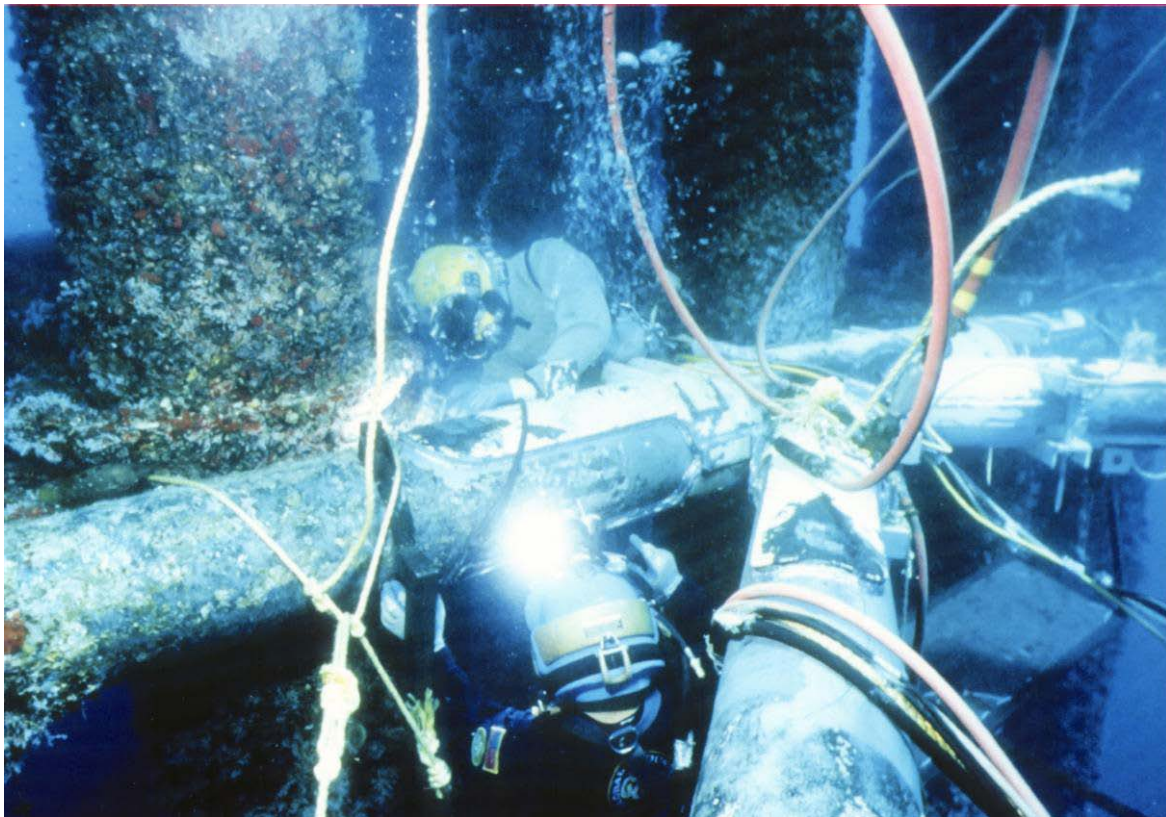
Ship Shoal 246 A, K Type Reinforcement Repair



Ship Shoal 246 A, T Type Reinforcement Repair



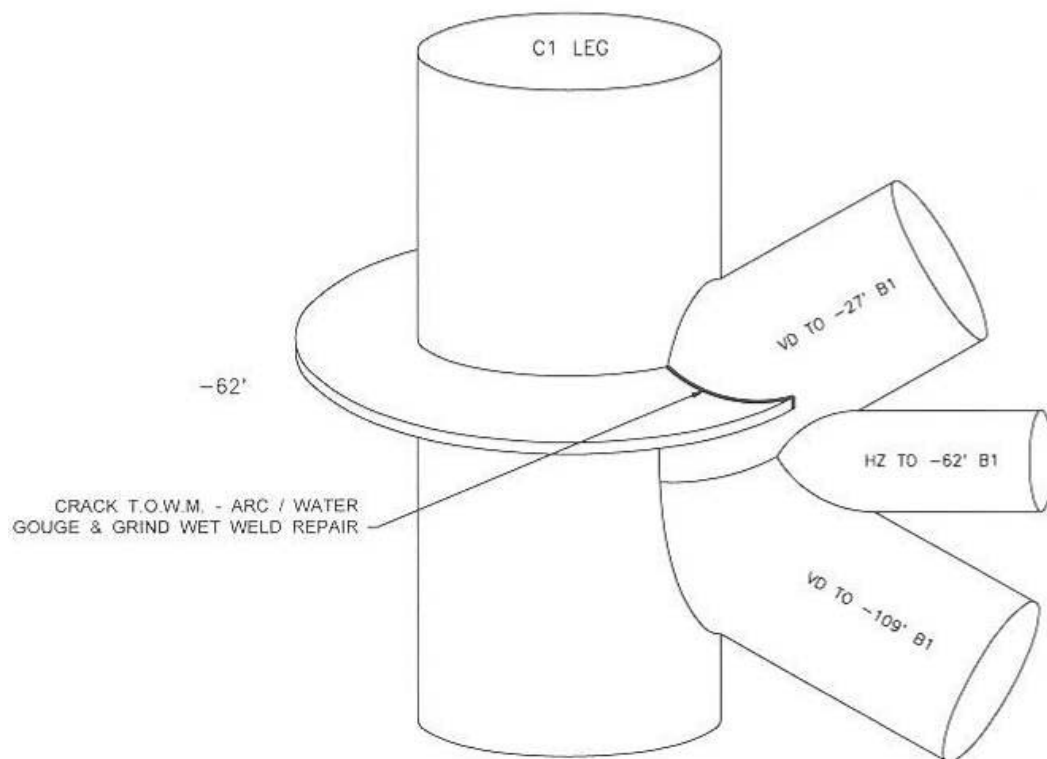
Ship Shoal 246 A, Detail of Temporary Clamp Closure Bolts



Ship Shoal 246 A, Installation of K Type Reinforcement Repair



Eugene Island 231 CB



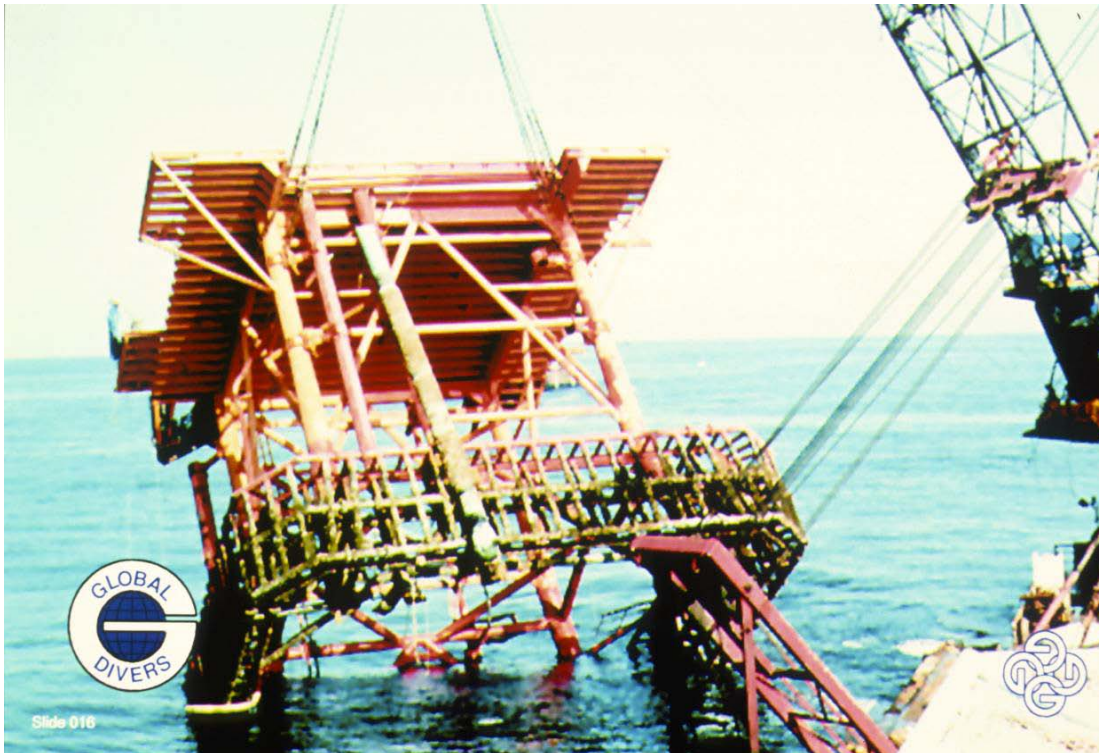
Eugene Island 231 CB



Eugene Island 231 CB, Completed Repair



South Timbalier 52, The T-23 Platform



Nearby South Timbalier 52, A “Sister” structure of the T-23 Platform



Nearby South Timbalier 52, A “Sister” structure of the T-23 Platform



South Timbalier 52, -39' Elevation Midpoint Node



South Timbalier 52, Type T/K node removed and cleaned up



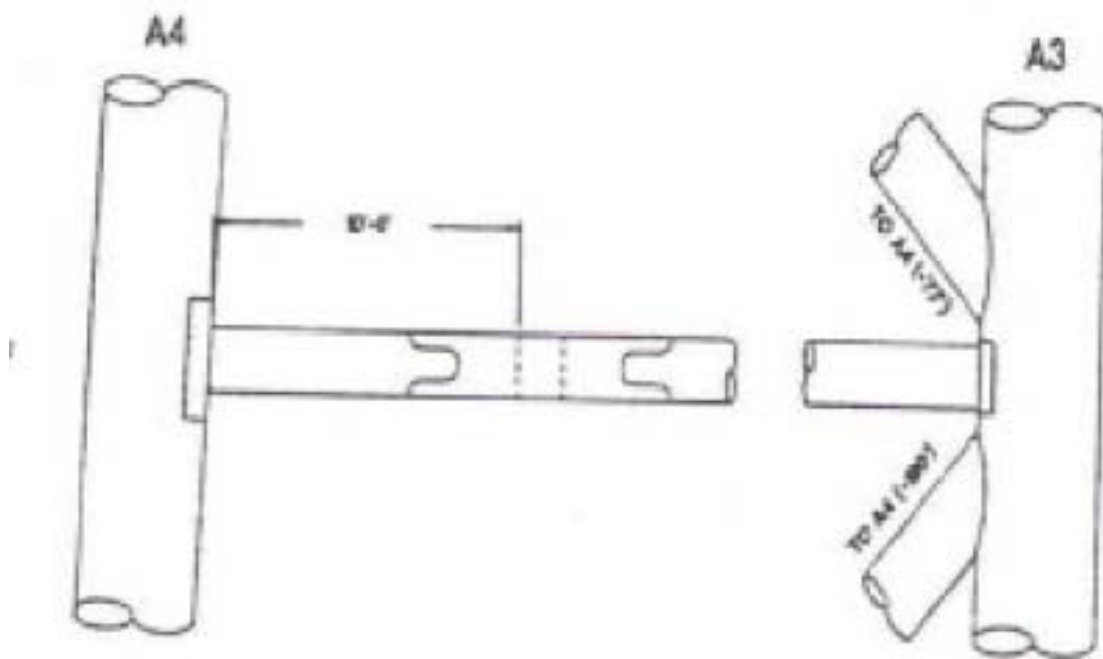
South Timbalier 52, Redesigned T/K Node Ready to be Launched



Khazzan 2 and 3 under construction at Chicago Beach, Abu Dhabi



Khazzan 2 on its way to the bottom of the Arabian Gulf



Samaan A Structure, Offshore Trinidad, -125' Elevation
Horizontal Repair Assembly Repair Sketch



Samaan A Structure, Offshore Trinidad, -125' Elevation Telescoping Horizontal Assembly



Montrose Structure, North Sea, Scallop Sleeve Going Down for Trial Fit on Stub



Montrose Structure, North Sea, New 30" Brace Being Lowered to the Water



Montrose Structure, North Sea, Single Lobe Scallop Sleeve
Used to Accommodate Shore Stub Length and Minimize Overhead Welding

Developments in Dry Hyperbaric Arc Welding – A Review of Progress Over the Past Ten Years

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Abstract

Dry hyperbaric welding has been used for high quality installations and repairs, particularly in the North Sea sector, for many years. Research in the field over the past decade has focused primarily on development of remotely controlled welding, with a view to implementation at depths beyond those attainable by divers.

It is observed that gas tungsten arc welding, used for the majority of semi-automated applications to date, has depth limitations dictated by deteriorating arc stability. Conversely, the behaviour of the gas metal arc welding process is virtually depth independent, at least to 2,500 m (8,200 ft), the maximum depth tested to date. Detailed evaluations of weld properties at elevated pressures, have led to the development of consumables to optimise weld microstructures and properties. Extensive welding trials with both solid and metal cored wires have proven the robustness of the welding process on a range of materials, including low alloy steels and high alloy steels. Parameter and consumable selection has led to the optimisation of strength, ductility, toughness and crack susceptibility.

Implementation of remote welding for deepwater applications requires not only control of the welding process, but dedicated tooling and equipment for placement, material preparation, handling and recovery. This in turn necessitates a change in design concept to meet the limitations imposed by fully remote operations. Developments centering on pipeline sleeve joints and seal welds for hot tap applications have received significant attention. The current status is described in this article and expectations for the future are presented.

Introduction

A large body of literature exists on the development and exploitation of arc welding in connection with the offshore construction and repair industry (see for example [1-9]). The majority of publications consider the influence of environmental conditions on the behaviour of welding processes or the resultant effects on weld metal properties; *e.g.*, [1,2,8]. In the past ten years, research efforts have focused on a move toward the implementation of dry hyperbaric welding for deepwater, diverless technologies. These developments are driven by the need to find cost effective solutions for equipment installation and repair in increasingly remote and hostile environments, whilst protecting the safety of operating personnel and of the environment.

Dry hyperbaric welding (or simply hyperbaric welding) involves welding in a gaseous environment at elevated pressure. The word *dry* is often used to emphasise that the arc boundary is not direct contact with the surrounding water, which is the case in wet welding. However, the term is something of a misnomer in that the welding environment generally has a high water vapour content, which can exert considerable influence on chemical reactions and gas absorption at the weld pool surface, and hence on

the mechanical properties of the resultant welds (*e.g.*, [1,2,4,8,10]). In addition to shifting the equilibrium balance of chemical reactions, the hyperbaric environment gives rise to a modified energy transport behaviour, which affects welding process stability as well as the structure and properties of the resultant weld.

The influence of pressure on welding process performance is governed to a large extent by changes in arc properties. The structure of the arc column is controlled by the thermodynamic properties of the plasma, environmental conditions and the required current flow. Equilibrium operating conditions occur when the rate of electrical energy supplied to the discharge is balanced by the energy losses to the electrode, work piece and surrounding media. As the ambient pressure is raised above one atmosphere the physical properties of the plasma change and particle densities increase (approximately) in proportion to the absolute pressure [11]. Convective and radiative heat losses increase with pressure, contributing to a rise in arc voltage.

A plausible physical explanation of many of the observed phenomena may be made by appeal to the minimum energy loss principle. Enhanced energy transport constrains the arc to contract and adopt a new minimum energy loss configuration, resulting in a smaller cross-sectional area of the electrically conducting core. Electrical conductivity rises with pressure (above 12,000 K) [12] to ensure that the reduced arc column is capable of sustaining the required current flow. Increased energy loss due to radiation occurs as a result of a re-distribution of the arc energy, which may be inferred from the enthalpy term in the energy balance equation [11], leading to arc root contraction. The arc becomes increasingly susceptible to external influences (such as draughts or stray magnetic fields) because the velocity in the arc column falls, the plasma becomes turbulent [13] and the arc roots contract, following increasingly random paths over the electrode and/or work piece surfaces [14], resulting in decreased arc stability. This general behaviour is common to all types of welding arcs presently considered for offshore applications. A review of the physical changes influencing welding processes under hyperbaric conditions is given in [11].

In this article, we present an overview of developments in hyperbaric welding over the past decade, with particular emphasis on diverless, deepwater applications. Throughout this article, we make reference to welds made at various water depths; all the welds have been made in pressure chambers simulating offshore conditions and depths quoted are derived from equivalent operating pressures.

Welding Processes

The range of pressures over which different arc welding processes can typically operate is shown schematically in Figure 1. For the shielded metal arc welding process, the depth range is limited to the permissible manned diving range as the process is inherently manual. The depth limit of the gas tungsten arc (GTA) welding process is dependent on the level of instability tolerable for a given application; for general applications, this is unlikely to exceed 500 to 750 m [15]. The depth limit for plasma welding is governed to a large extent by the robustness of the welding equipment. Laboratory based welding trials have shown stable performance to depths in excess of 1000 m [11]; however, the process remains sensitive to welding torch design and electrode positioning. To date, we are not aware of any offshore repair or installation applications using this process. The gas metal arc (GMA) and flux cored arc (FCA) processes have received considerable attention over the past few years, as these have been shown to

produce stable welds at depths to 2,500 m, with no sign of any pressure dependent process limitation [16].

Non-consumable Processes

Gas tungsten arc welding is a relatively mature hyperbaric welding technique, often employed for automated or semi-automated applications [7,17]. GTA welding has several advantages: it is well understood, produces very fine grained weld metal with high toughness and is clean (producing little or no fume or spatter). The process is versatile in application and has an established history of root pass completion. These factors more than offset the drawback of relatively low metal deposition rates. Whilst remaining effective at depths to at least 400 m (1,310 ft), the stability of the non-consumable arc process gradually deteriorates as ambient pressure rises.

Developments in the non-consumable technologies (GTA and Plasma) have focused primarily on the control of boundary conditions to limit the effect of increasing pressure on arc instabilities; *i.e.*, to enforce arc and process stability [18]. For GTA welding, the stability of the arc and of the welding process at elevated pressures is governed to a significant extent by the condition of the tungsten electrode. Ozden and Gursel [9] have shown that erosion rates, defined in terms of electrode tip shortening are lower for electrodes doped with 2% La_2O_3 than for those doped with 1% ThO_2 [9]. In addition, electrode tip surface preparation (roughness) and the homogeneity of doping agents influences electrode tip erosion and process stability.

Plasma welding has been considered because it offers additional positional stability at elevated pressures when operating in the melt-in mode [11,19], due to radial constriction of the arc close to the tungsten electrode tip. Successful process operation is based on relatively large diameter constrictions (of the order 6 mm) and a short electrode set-back, typically less than 2 mm. Under these conditions, lateral movement of the arc root on the work piece surface can be significantly reduced with respect to that observed during GTA welding; leading to more stable weld penetration [19]. Process limitations are associated with turbulence at the arc boundary and energy transport to the constricting nozzle, ultimately resulting in nozzle melting at high ambient pressures. Plasma process performance is strongly coupled to welding torch design, which in turn determines gas flow geometry, electrode centralisation and nozzle cooling [20].

Consumable Processes

The gas metal arc and flux cored arc welding processes are emerging hyperbaric technologies, particularly suited for deep water application. At water depths greater than about 120 m, the welding arc is fully turbulent, and the arc roots contract on the droplet and weld pool surfaces due to enhanced heat extraction. Electromagnetic plasma jets dominate metal transfer and process stability [15]. The arc roots move rapidly over the molten metal surfaces, with substantial changes in radiation emission and arc position occurring at frequencies exceeding 10 kHz [15,21]. Despite the high frequency variations, the time averaged behaviour of the process remains relatively constant over timescales typically associated with weld pool movement and solidification. The net effect is that a stable welding process can be maintained, provided appropriate control measures are implemented (Figure 2, [22]). At high pressures, the strength of the electromagnetic plasma jets may be reduced by welding with relatively short arc lengths, typically of the order 1 mm or less. This limits radial expansion of the arc column reducing the

difference in current density between the arc roots and plasma column and hence the magnitude of disruptive plasma jet forces [19].

Arc length can be controlled either by applying a relatively high wire feed rate and forcing the process to adopt a dip-transfer condition, or by running a self-adjusting arc. In the former case, the current and voltage waveform is similar to that obtained for a stable condition at one bar, although voltage excursions are somewhat greater and there is a greater spread in time intervals between successive dips, as shown in Figure 3a [4]. For the self adjusting arc, the current variation per unit change in arc length is maintained constant, independent of operating pressure. As the voltage is pressure dependent, the slope of the power source output characteristic, measured in volts per ampere, must also vary with pressure, at least at operating depths to a few hundred metres. At greater depths, the arc plasma is metal vapour dominated and only weakly influenced by pressure. Under these conditions, the optimum self adjusting characteristic is virtually independent of depth. Typical electrical transient signals are shown in Figure 3b [4], and details of process operation can be found in [22,23].

Materials and Properties

The microstructure and mechanical properties of dry hyperbaric arc welds are influenced by factors such as cooling rate, consumable and base metal chemistries and the thermo-mechanical history of the base material, which together with the weld thermal cycle, determines the structure and properties of the heat affected zone (HAZ). The choice of appropriate consumable and welding conditions is important for the execution of high quality welds. For the vast majority of applications, welds should match or over-match the parent material in terms of strength (to avoid strain concentration during loading), whilst exhibiting acceptable fracture toughness and corrosion resistance properties and a high resistance to cracking.

The choice of consumable also influences fluid flow and energy transport in the weld pool. Akselsen *et al.* [24] note that sulphur levels in the consumable can affect penetration during GTA root welding. For an X70 pipeline steel at a depth of 75 m (246 ft), the operational current window between lack of fusion and burn through was found to be greater for a low sulphur (0.006 wt. %) than for a high sulphur consumable (0.013 wt. %) for the joint geometry studied. Corresponding mechanical properties for welds made at 75 and 200 m (246 and 656 ft) showed that whilst overmatching welds of similar strengths were made with both consumables, toughness deteriorated with increasing pressure for welds made with a low alloy wire containing 1Ni 0.5Mo, whilst results were independent of pressure for welds made with a similar consumable containing 2Ni 0Mo. The variation in fracture toughness, measured by Charpy V notch testing at -30 °C, was strongly linked to the microstructure. Toughness was reduced with the formation of high carbon martensite-austenite islands decorating prior austenite grain boundaries. These occurred as a result of partial transformation due to re-heating by subsequent weld passes [25].

Properties of gas metal arc welds at high ambient pressures have been extensively reported [4,5,15,16,26]. Early results indicated that sound all positional welds can be made at depths to 2,500 m (8,200 ft). For orbital GMA welds on X70 pipeline steel at a depth of 1,630 m (5,350 ft) (Figure 4, [26]), the maximum hardness was 264 Hv₁₀ in the weld metal, well within the maximum specified in AWS D3.6 (325 Hv₁₀). Hardness levels also met the requirements of BS 4515 for non-sour service, although the maximum weld metal hardness exceeded the 250 Hv₁₀ upper limit for sour service. Mean and maximum HAZ hardness values were 283 and 327 Hv₁₀ respectively. Weld metal strengths are shown in

table 1, indicating that the weld under-matches the parent material in terms of both the ultimate tensile strength and yield (0.2% proof) stress, whilst ductility exceeds that of the parent material [26]. Under-matching occurred primarily as a result of inappropriate selection of the consumable. Results contrast with welds made on X65 pipeline material at the same pressure where weld metal strengths consistently over-match the parent material. Impact toughness tests carried out at temperatures in the range 0 to -80 °C show a spread of values particularly at higher temperatures. Low impact values were obtained across the entire temperature range when welding with a 41 pass procedure, whereas improved notch toughness can be seen at 0 °C and -20 °C when welding with a 28 pass procedure (Figure 5, [26]). In contrast, the toughness of the supermartensitic joint, welded with a 13Cr 6Mo consumable is acceptable across the entire temperature range. Poor toughness of the X70 welds is associated with a low volume fraction of acicular ferrite in the weld microstructure, which in turn is associated with low weld metal oxygen contents.

Subsequent publications report on the development of metal cored wires for improved toughness in deepwater welds. Weld metal oxygen contents in the range 200 to 350 parts per million are associated with enhanced toughness [27]. Higher weld metal oxygen was successful in producing acicular structures, but these have a low strain hardening rate, leading to a rapid decrease in toughness when inclusion contents exceed the optimum value. Further optimisation of the nickel, titanium and oxygen contents led to welds with average impact energies of 106 J at -30 °C, but the yield and tensile strengths were higher than required to match a target X65 pipeline steel. Reducing the manganese content helped to reduce the yield and tensile strengths to produce a slightly overmatching consumable. For metal cored consumables with elemental compositions in the range 0.05-0.95% Ni, 0.01-0.04% Ti and 216-485 ppm oxygen, no single impact energy below 76 J at -50 °C was observed, providing some confidence that manufacturing and procedural tolerances will not put weld toughness at risk [4].

Weld metal cooling times from 800 to 500 °C, ($t_{8/5}$) for hyperbaric GMA/FCA welding are comparatively low, of the order two to three seconds for joints with preheat levels between 25 °C and 100 °C. Cooling rates are reported to be almost independent of pressure in the depth range 180 to 370 m (590 to 1214 ft) [6]. Such high cooling rates in the presence of high restraint conditions can give rise to hydrogen induced cracking, the presence of moisture in the surrounding environment is therefore of interest. The influence of moisture content on the measured weld metal diffusible hydrogen for welds made with a metal cored wire at a depth of 180 m (590 ft) is shown in Figure 6 [28]. Weld metal hydrogen levels remain acceptable throughout the test range. Tekken tests made with pipeline material at 370 m have also shown that with a 50 °C pre-heat level and above and a 300 ppm moisture level, no cracking occurs [6]. Huisman *et al.* [10] have recently considered the effect of restraint and hydrogen absorption on cracking susceptibility for a sleeve weld geometry at one atmosphere. Restraints measured close to completion of the root weld reached 12 kN mm⁻². For test welds made under simulated restraint conditions, half showed large cracks in the absence of pre or post weld heat treatments (Figure 7, [10]). Cracks formed in the time range 15 minutes to 3 hours after welding. Under high restraint even low levels of hydrogen can give rise to cold cracking. Preheating reduces the cooling speed and can lower the hardness but causes expansion of the overlapping sleeve weld geometry. Upon cooling high stresses form and cold cracking susceptibility increases. Severe cracking was observed with hydrogen levels of 7 ml/ 100 g of weld metal. Post weld heating to lower the level of diffusible hydrogen in the weld metal gave crack free welds when maintaining a temperature of 80 °C for 10⁴ s. These results are applicable for one atmosphere welds; however, these exhibit a significantly different fusion profile to hyperbaric welds and fusion profile strongly influences the crack susceptibility. Crack free welds for sleeve repair

applications (Figure 8) made in a dry hyperbaric environment have been demonstrated by Woodward *et al.* [6].

An alternative to extended post weld heat treatment for reduction of susceptibility to hydrogen induced cold cracking involves modification of the weld microstructure. Recent attention has focused on hyperbaric welds made with an Inconel 625 consumable [1,29]. Welds with yield strengths above 480 MPa and ultimate strengths above 750 MPa have been achieved at a depth of 1,000 m (3,280 ft). Elongation exceeds 40% and Charpy impact energies average 180 J or more are -30 °C, with no single test result below 50 J. Peak hardness levels for a nine pass weld developed for a hot tap application (Figure 9, [29]) are below 336 Hv₁₀. The formation of harmful intermetallic phases is not expected due to the high heating and cooling rates at elevated pressures. An exception is the formation of a Laves phase (Ni,Cr)₂(Nb,Mo), which may be responsible for some of the high microhardness values observed (460 Hv_{0.025}). Small niobium rich carbide particles have also been found in the multi-pass welds. Dilution of the consumable inevitably occurs when welding on low alloy pipeline steels and is greatest in the root pass. Woodward *et al.* [29] report a nickel content reduced from 66 to 56%, and an iron content of 25%. Dilution is dependent on both welding conditions and weld geometry, with higher root dilution levels, (40% Ni, 40% Fe) reported by Akselsen *et al.* [1].

Applications

The majority of hyperbaric welding developments that have taken place over the last decade are related to progress toward diverless installation and repair [4-6,15,16,18-23,26-32]. The body of evidence to date indicates that whilst specific material questions arise and the detailed responses of materials to welding are not always known *a priori*, required material properties can be achieved provided appropriate attention is paid to process and consumable developments. It is equally apparent that the application of hyperbaric welding, especially for diverless deepwater conditions is limited not by welding process or material considerations but by the rate of development of remotely operable implementation technologies.

Welded pipeline tie-ins and repairs offshore have so far taken place in water depths accessible to divers, using either manual or semi-automated welding methods. Existing equipment, which is capable of undertaking pipeline repair welds over the depth range accessible to divers, has been successfully employed at depths to about 250 m (820 ft). The Statoil managed Pipeline Repair System (PRS) operating in the North Sea utilising semi-automated GTA welding, has seen many applications, with diver assistance for alignment and welding head installation.

In a typical subsea operation two large PRS 'H' frames, each weighing 70 tonnes and having a lifting capacity of 120 tonnes, are used for pipeline manipulation. These are capable of moving the pipeline in the lateral and vertical directions, as well as axially. A combined tool cuts the pipe using a high pressure water-grit jet, after which two longitudinal cuts and a full circumferential cut are made in the weight coating, which is subsequently removed. A high-pressure jet is also used to remove the anti-corrosion coating. The replacement part (spool piece), is lowered into position, roughly aligned to the pipeline using the hydraulic 'H' frames and the habitat is lowered over the pipe ends. Remotely operated pipe doors with flexible sealing skirts make the seal around each pipe, allowing injection of pressurised gas to displace the water contained in the chamber. Operations up to this point can be made without diver intervention.

Integral to the habitat, and crucial to the repair, is the fine alignment frame. This is specified to align the prepared pipe ends to within 0, +1 mm root gap and 0, +2 mm high/low under the control of a diver [28]. Over seventy welded tie-ins have been made using this system during the past twenty years [30]. Welding head installation and alignment to the required tolerances is a key factor for successful butt welding and for the present cannot be readily automated. Difficulties arising with preparation and remote alignment of pipelines for example have moved attention from butt welding to a sleeve repair concept (Figure 10).

Statoil are currently developing new equipment employing hyperbaric GMA welding for fillet welded sleeve contingencies, to be deployed and operated remotely, without the use of divers: the Remote Pipeline Repair System (RPRS) [32]. The use of a sleeve repair offers much greater operational flexibility compared with butt welding, both in terms of required tolerances to pipe ovality, as well as radial offset and angular alignment of the pipe ends, since the sleeve is designed to include a root gap. It is anticipated that the sleeve design will incorporate environmental seals to prevent water ingress whilst welding, and that the sleeve inner diameter will allow for the required ovality, alignment and installation tolerances.

To complete a sleeve construction, a section of the pipeline (spool piece) is placed between the two pipe ends and an oversized sleeve is slid over either end and secured with fillet welds; four fillet welds are therefore required for each joint [10,30]. Finite element calculations have shown that the leg length of the fillet welds must be large to prevent excessively high stresses at the weld toe leading to yielding of the pipeline material. Loading the sleeve geometry also results in relatively high stresses at the weld 'root' region. The weld size is determined largely by the stresses induced in the pipe itself, and the long weld leg length is used to spread the load more evenly on the pipe. For the Asgard Transport pipeline for example, with a system test pressure of 242 bar, a leg length of 120 mm is required with a weld height in excess of 30 mm. With the exception of the root and toe however, the majority of the fillet weld metal is not particularly highly stressed [28].

Process performance has been extensively examined for such applications (see for example Figure 11, [31]) and welding conditions have been developed to bridge almost any root gap using welding parameters that are virtually invariant to changes in welding position. Qualification work has been carried out using production wires on X65 and X70 pipelines using a remote repair sleeve of X65 grade. Procedure are suitable for application on the Asgard Transport, Langeled, Troll P10/P11, Zeepipe 2A and 2B and Europipe 2 pipelines in the North Sea sector [6].

Ten years ago, Statoil, on behalf of the more than 40 members of the PRS pool, initiated a programme with the goal of developing equipment necessary to perform a diverless hot tap [33]. The first phase of the remote hot tap project was to develop a cutter and associated equipment suitable for remote installation and operation. A prototype was completed in 2005 and was successfully qualified and used on the Tampen Link hot tap programme at a depth of 145 m (475 ft) on a diver installed retrofit tee. Subsequently, the world's deepest diverless hot tap operations on a pressurized pipeline were performed on the Ormen Lange field in the Norwegian Sea in August 2009. Two hot taps were conducted in a water depth of 860 m (2,821 ft). These were carried out to tie a new seabed template in the southern part of the Ormen Lange field into the existing pipeline infrastructure.

The second phase of the development started in 2003 with the aim of developing a retrofit tee system that can be installed remotely without the aid of divers, based on a clamp and seal weld approach, referred to as a 'remotely installed retrofit tee'. The development of the tee and all associated installation equipment is in progress and is due to be used in 2012 to install two retrofit tees and perform hot taps after installation. The concept is illustrated schematically in Figure 12, shown together with a prototype welding head designed to make the GMA/FCA internal seal welds [34]. An internal saddle shaped seal weld is made between the branch connection and the mother pipe to form a seal (Figure 13, [29]), after the retrofit tee assembly is mechanically clamped to the pipe (Figure 14). Development of the welding requirements for these hot tap operations (processes and materials) have already been described above and further details may be found in [5,27-30].

Summary and Future Considerations

The majority of the welding research and developments reported in the open literature have been undertaken in pressurised test facilities such as the Simweld 1,000 m (3,280 ft) facility at Sintef in Norway or the HyperWeld 2,500 m (8,200 ft) deepwater facility at Cranfield University in the UK (Figure 15a). In order to extend process developments to even deeper waters, Statoil have commissioned a new welding facility capable of simulating depths to 4,000 m (13,120 ft). The system is currently under construction following a design similar to that of the HyperWeld (Figure 15b). When the facility becomes operational, trials will be undertaken to test the current assumption that GMA/FCA process control requirements are (virtually) independent of operating depth.

With respect to welding process developments, attention in the future should be paid to further improvements in process control, in order to reduce or if possible, to eliminate spatter. This may well be achievable based on advances in welding power source designs and control technologies introduced for one atmosphere welding in recent years. Such developments are expected to lead to process increased robustness for fully remote operations.

It is reasonable to suppose that future research will focus on consumable developments to achieve desirable properties for specific offshore applications. These are likely to address a range of materials for which welds with good strength, ductility, toughness, low cracking susceptibility and good corrosion resistance will be essential. A move from a trial and error toward a predictive approach may also be envisaged as deepwater applications become more common place. Here particular attention should be paid to the influence of pressure on gas-metal interactions and the change in kinetics of the liquid metal at elevated pressures.

To date there has been considerable investment in welding research and development as well as in equipment for the Remote Pipeline Repair System. Further development of reliable, robust and flexible tooling and equipment will be required for deepwater diverless weld implementation. Commercial application of the technology is planned within the next 2 years [33] and further developments are expected to follow with increasing exploitation of deepwater oil and gas reserves.

Acknowledgments

We would like to thank all those, who have supported and promoted and contributed to the development of hyperbaric welding technologies. Particular thanks go to BP Exploration, Chevron-Texaco, ESAB, the Engineering and Physical Sciences Research Council (EPSRC) UK, Subsea 7, Isotek Electronics, Norsk Hydro and Statoil for their support and encouragement.

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Table 1 Tensile properties of an X70 pipeline steel and orbital GMA weld made at 1,630 m (5,350 ft) with a solid wire consumable [26].

	Yield (MPa)	UTS (MPa)	Elongation (%)	Yield/ Ultimate
Weld Upper	589	652	23.9	0.9
Weld Lower	626	696	21.6	0.9
Weld Mean	601	667	23.1	0.9
Parent	669	715	20.1	0.94

Table 2 Tensile properties of an X65 pipeline steel and linear welds made at 1,630 m (5,350 ft) with a solid wire consumable [26].

	Yield (MPa)	UTS (MPa)	Elongation (%)	Yield/ Ultimate
Downhand	585	663	23.0	0.88
Vertical	551	637	23.5	0.86
Overhead	578	647	22.4	0.89
Mean	571	649	23.0	0.88
Parent	541	592	20.0	0.91

Figure Legends

- Figure 1 Illustration of approximate depth limits for arc welding processes.
- Figure 2 Transient and time averaged voltage and current signals from a GMA weld made at 2,500 m (8,200 ft) in an argon atmosphere [22].
- Figure 3 Transient voltage and current waveforms for (a) a dip transfer root pass and (b) a self-adjusting pulsed fill pass made at a depth of 350 m (1,148 ft) [4].
- Figure 4 Photo-macrographs of a solid wire orbital GMA weld (0° downhand) made on 29 mm wall thickness X70 pipeline steel at a depth of 1,630 m (5,350 ft) [26].
- Figure 5 Notch toughness of orbital GMA welds made at 1,630 m (5,350 ft) on (a) X70 with a 41 pass procedure (b) X70 with a 28 pass procedure and (c) a 13 Cr supermartensitic pipeline steel with a 13Cr 6Mo consumable [26].

- Figure 6 Relationship between moisture content in the shielding gas and diffusible hydrogen content in the weld metal for welds made with a metal cored wire at 180 m (190 ft) [28].
- Figure 7 Instrumented restraint crack test for a pipe-on-pipe sleeve weld under radial constraint conditions showing cracking in the HAZ in the pipe wall [10].
- Figure 8 Orbital fillet welds made for a sleeve repair at 1,000 m (3,280 ft). (Left) the 12 o'clock position (downhand) and (right) the 6 o'clock position (overhead) [6].
- Figure 9 Inconel weld appearance from a 9 pass hot tap weld application, deposited at 1000 m (3,280 ft) [29].
- Figure 10 Sleeve design concept for pipeline connections and repairs. Inset photograph shows a laboratory mock-up of a sleeve joint [10,30].
- Figure 11 Overhead fillet welds on an X65 pipeline steel made with a metal cored consumable at 370 m (1,214 ft) [31].
- Figure 12 Illustration of a hot tap internal seal welding head (left) and a prototype welding head for GMA welding of the saddle seal [34].
- Figure 13 GMA cored wire weld providing a seal at the saddle intersection between a hot-tap branch and pipe. The transverse macros are taken from a weld made at 145 m (476 ft) at the saddle top (centre) and saddle side (right) locations [29].
- Figure 14 Retrofit tee for hot tap applications [30,35].
- Figure 15 (a) The HyperWeld 2,500 m (8,200 ft) deepwater welding facility at Cranfield University, UK and (b) the shell of Statoil's new 400 bar (13,120 ft) welding facility.

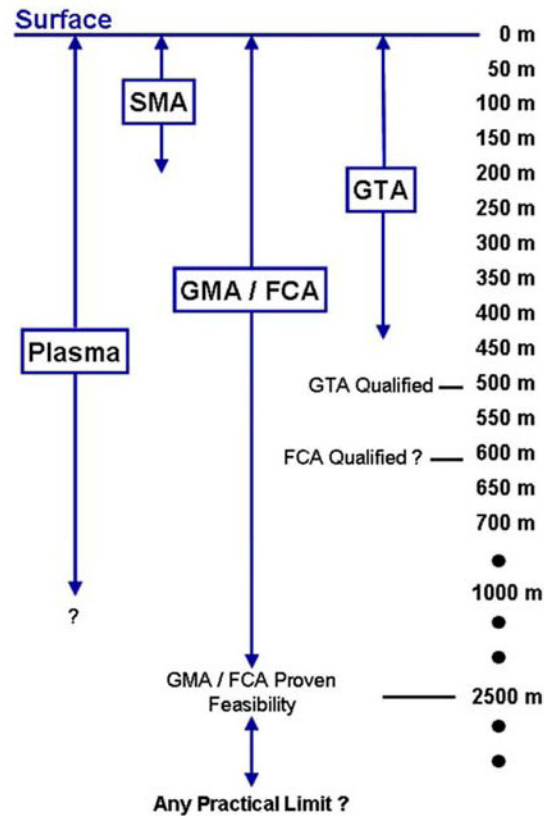


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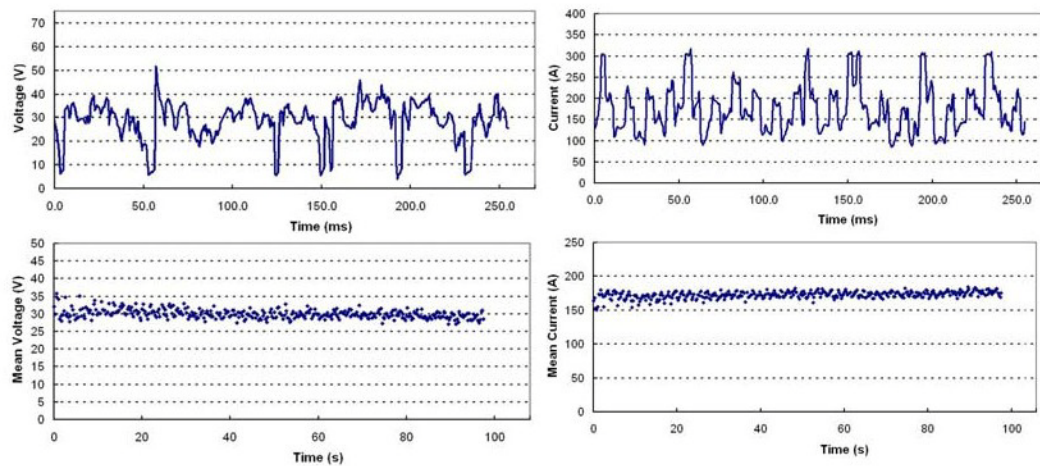


Figure 2 Transient and time averaged voltage and current signals from a GMA weld made at 2,500m (8,200ft) in an argon atmosphere [22].

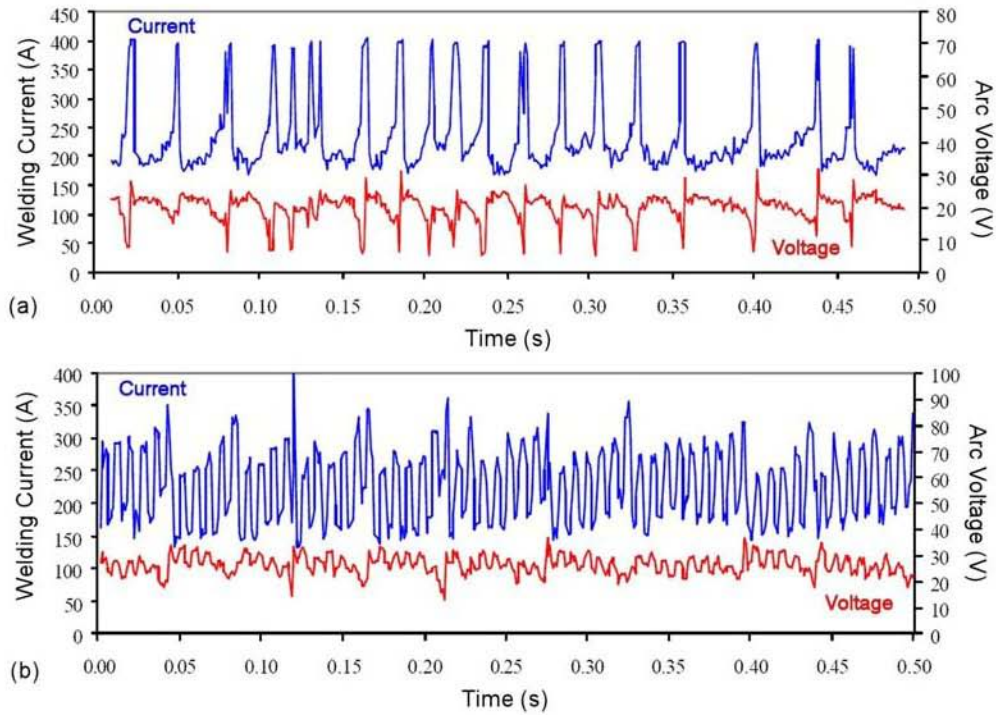


Figure 3 Transient voltage and current waveforms for (a) a dip transfer root pass and (b) a self-adjusting pulsed fill pass made at a depth of 350 m (1,148 ft) [4].

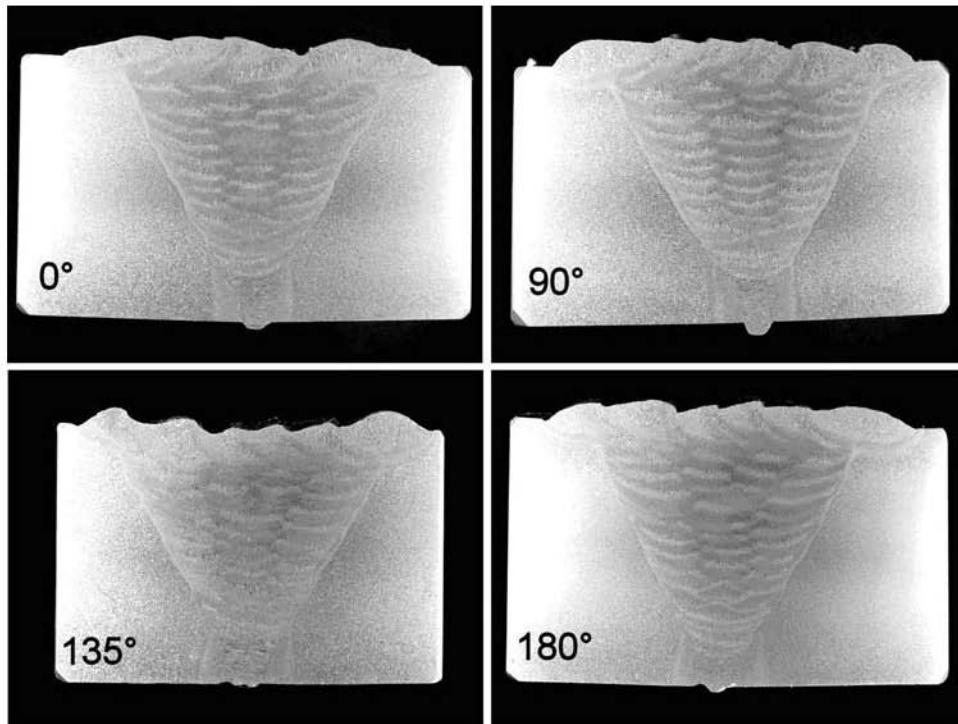


Figure 4 Photo-macrographs of a solid wire orbital GMA weld (0° downhand) made on 29mm wall thickness X70 pipeline steel at a depth of 1,630 m (5,350ft) [26].

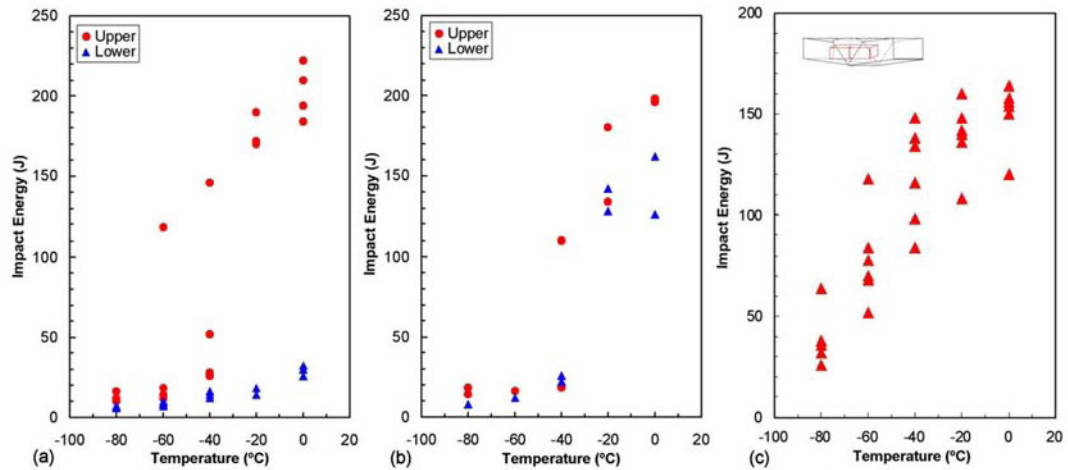


Figure 5 Notch toughness of orbital GMA welds made at 1,630m (5,350 ft) on (a) X70 with a 41 pass procedure (b) X70 with a 28 pass procedure and (c) a 13Cr supermartensitic pipeline steel with a 13Cr 6Mo consumable [26].

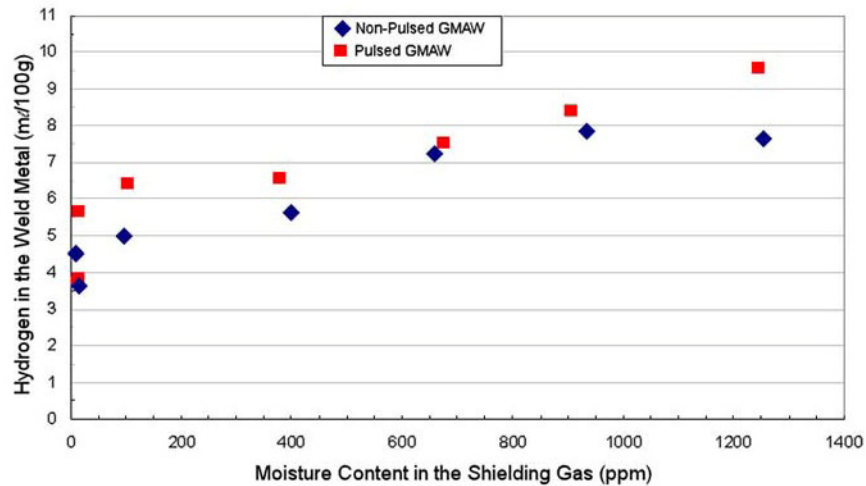


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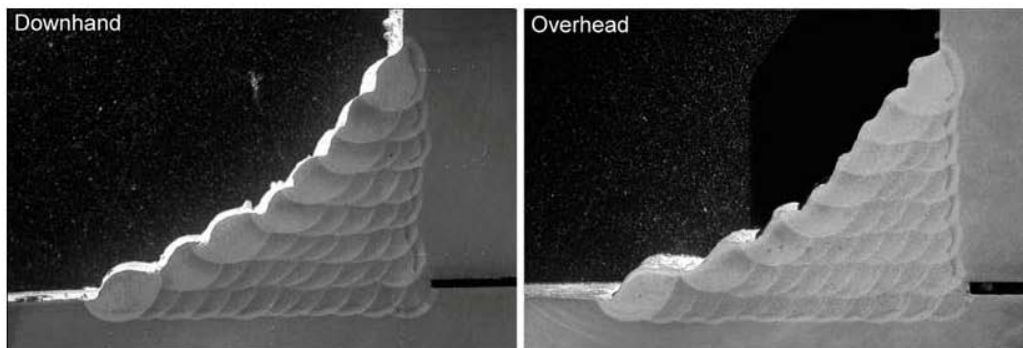


Figure 8 Orbital fillet welds made for a sleeve repair at 1,000m (3,280 ft). (Left) the 12 o'clock position (downhand) and (right) the 6 o'clock position (overhead) [6].

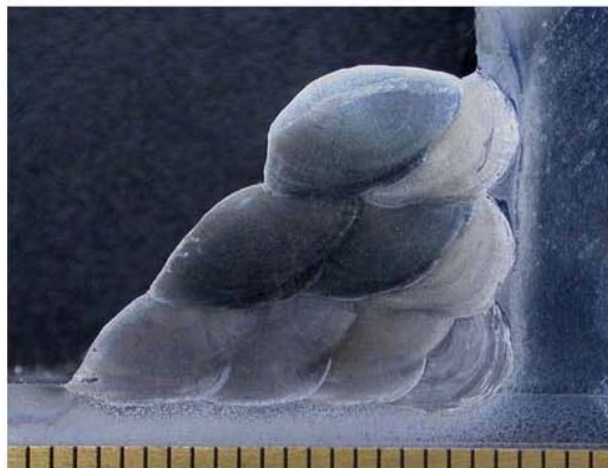


Figure 9 Inconel weld appearance from a 9 pass hot tap weld application, deposited at 1000 m (3,280 ft) [29].

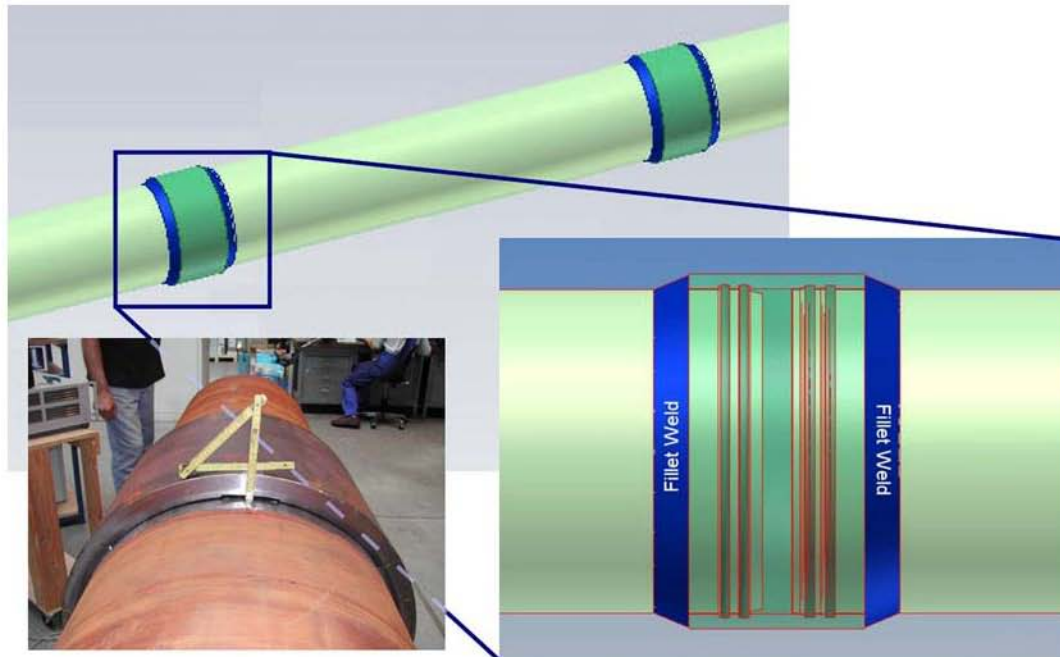


Figure 10 Sleeve design concept for pipeline connections and repairs. Inset photograph shows a laboratory mock-up of a sleeve joint [10,30].

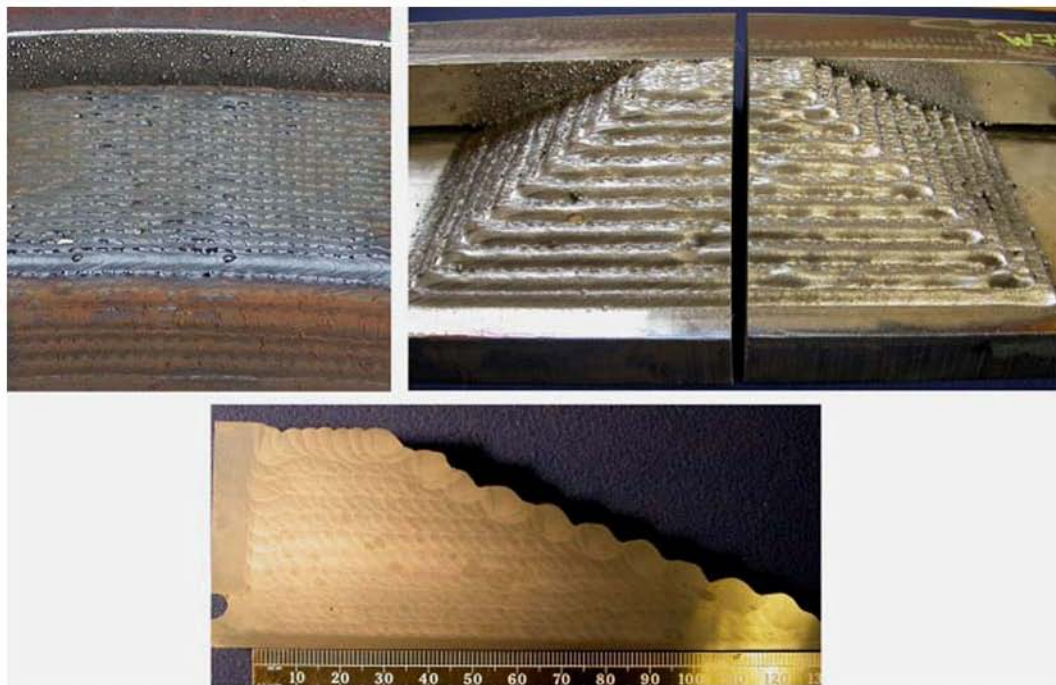


Figure 11 Overhead fillet welds on an X65 pipeline steel made with a metal cored consumable at 370 m (1,214 ft) [31].

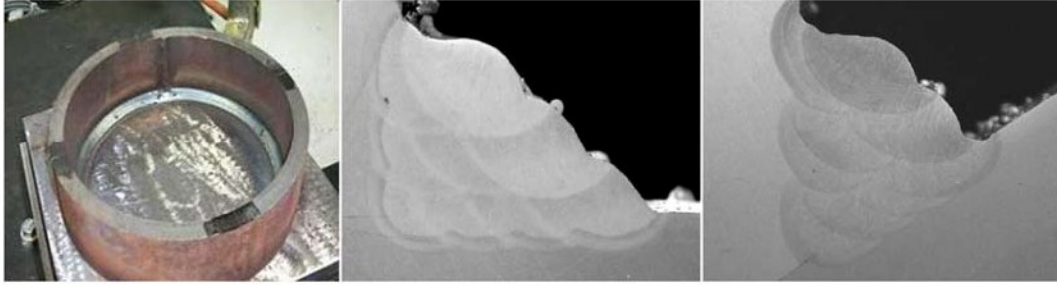


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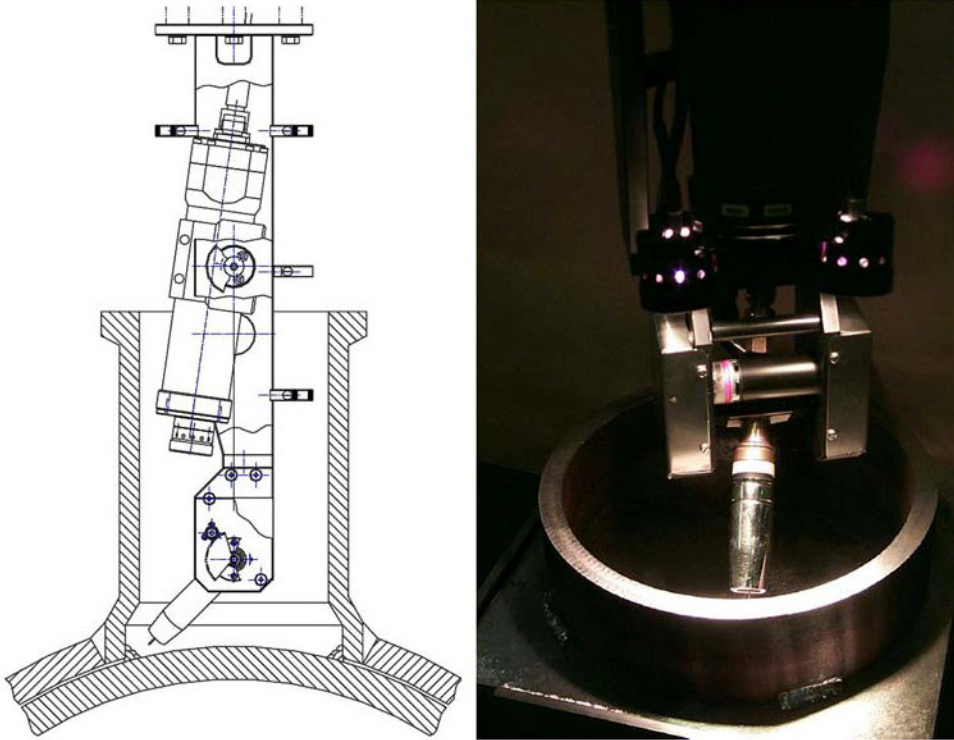


Figure 13 GMA cored wire weld providing a seal at the saddle intersection between a hot-tap branch and pipe. The transverse macros are taken from a weld made at 145 m (476 ft) at the saddle top (centre) and saddle side (right) locations [29].

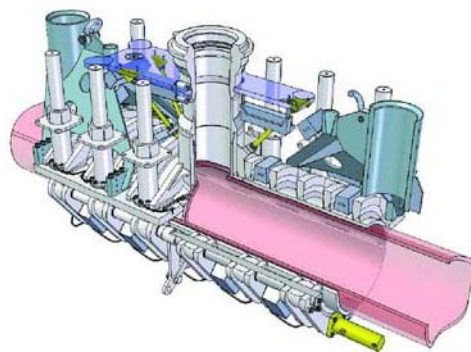


Figure 14 Retrofit tee for hot tap applications [30,35].

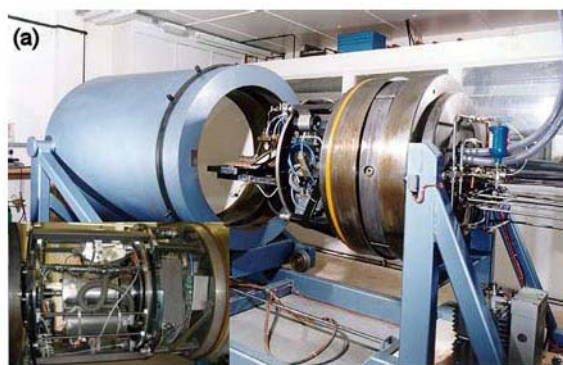


Figure 15 (a) The HyperWeld 2,500m (8,200 ft) deepwater welding facility at Cranfield University, UK and (b) the shell of Statoil's new 400 bar (13,120 ft) welding facility.

Friction Stud Welding Testing for Submarine Rescue

W. Jack Couch, Oceaneering International
Robert Murray, NAVSEA

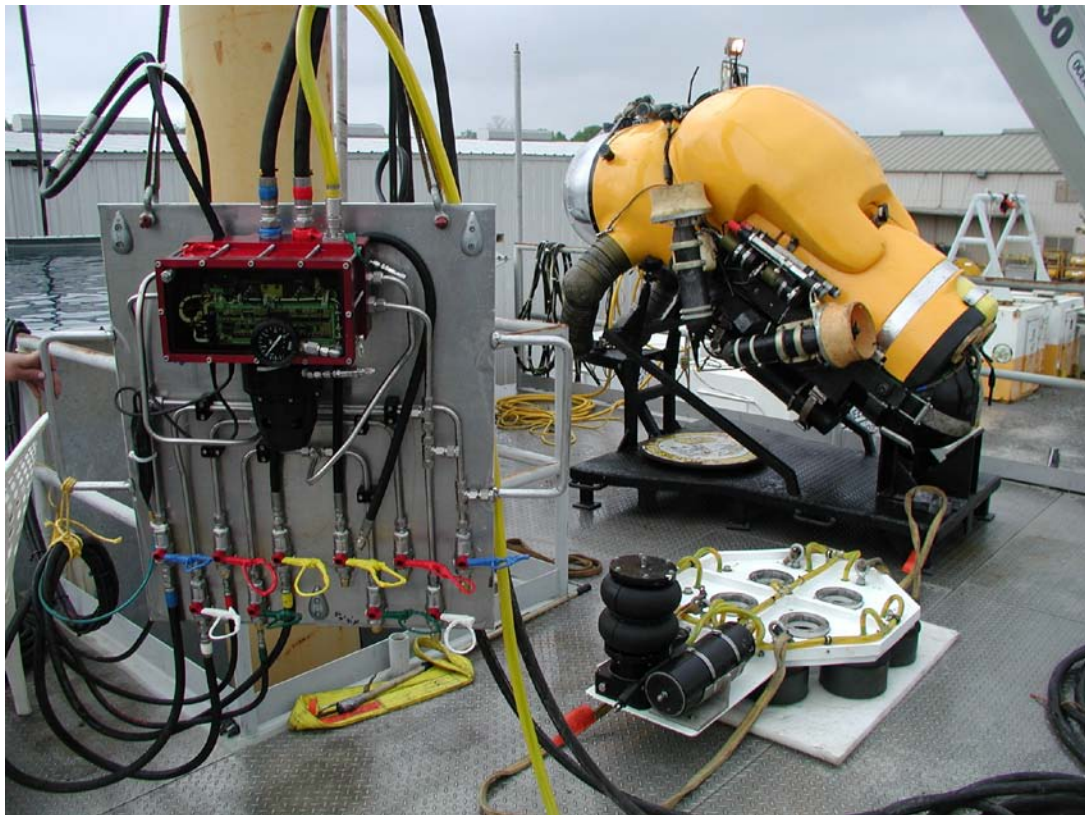
The efforts to expand the use of friction stud welding were initiated in 1992 and the results were reported in Friction Stud Welding for Military and Commercial Use By: NAVSEA's Robert Murray and Oceaneering's Jack Couch.

The initial start and basic testing in friction welding is outlined below Underwater friction stud welding was in its infancy as a commercially viable technique in 1992, the Naval Sea Systems Command initiated a study of this welding specialty to enhance the Navy's overall underwater welding program. NAVSEA's Robert Murray presented the results of this program. The Navy's first attempts at underwater friction stud welding showed some promise, but were not ground-breaking. The program included torque tests and combination torque/bend tests, followed by detailed metallographic examination and Charpy V-notch impact tests in order to evaluate the quality of friction stud welds made on both HY-80 and DH-36 materials. Welding was performed under various combinations of ambient temperature, water depths (maximum 30 feet (9m)), and position. None of the environmental, attitude, or material variables had a significant impact on the mechanical properties of the weldments, which met or exceeded the requirements for fusion welded studs as specified by MIL-STD-1689 and MIL-STD-248 for applications not requiring shock qualification. Although the program was successful, the use of friction stud welding was limited to shallow water applications such as anode attachment, external blanking of sea chests, and temporary attachment points for rigging, all which could be performed by conventional wet welding. Learning from Disaster It was not until lessons learned from the unfortunate sinking of the Russian submarine Kursk that friction stud welding had a meaningful application. Rescue of the Kursk at 350 feet (106m) was hampered by the lack of welding capabilities needed at that depth. The Navy's underwater welding capabilities have been limited to 50 feet (15m) and underwater wet welding in general has not produced sound welds beyond 140 feet (42m). Underwater dry chamber welding, although capable of producing sound welds beyond 750 feet (228m), would not be practical due to the logistics and set-up time. Additionally, Navy diving, for all intent and purpose, is limited to 300 feet (91m). The Navy's submarine rescue ships, which had saturation diving capabilities beyond 300 feet (91m), were decommissioned in the mid 1990s. In regard to the Kursk, deeper welding and diving capabilities were needed to attach a haul-down cable for a submarine rescue chamber (SRC). In addition, the first and most important step during a rescue is the ability to provide life support gas to the survivors, as demonstrated in the 2002 rescue of coal miners in Pennsylvania.

Commercial Successes In early 1998, friction stud welding was performed commercially at a depth of 1,300 feet (394m) and involved the friction welding of anode continuity tails to riser base piles using a work-class ROV. The friction welding equipment used was a Circle Technologies HMS 3000, which is hydraulically-driven, electronically-controlled, and rated to a depth of 3,000 feet (910m). Based on this concept, the Naval Sea Systems Command (NAVSEA) initiated another program to evaluate underwater friction stud welding for use in submarine rescue. The program required interfacing a Oceaneering hydraulic and software control to the outdated HMS 3000 friction stud welder. The feasibility of this concept was demonstrated in 2001 by Oceaneering International using their WASP ADS and a Oceaneering touch screen controlled friction stud welding system. Friction stud welding provides the

capability to weld a pattern of studs to the hull of a disable submarine, to which a pad-eye can be attached for the SRC haul-down cable and life support gas can be provided by means of a hot tap process using hollow studs. Combined with ADS, the system provides rescue capabilities well beyond 300 feet (91m), concurrent with the Navy's application for underwater friction stud welding for submarine rescue.

To prove the capability to perform friction stud welding at 2000 fsw, Oceaneering took the obsolete controls of the HMS 3000 and replaced the hydraulic control system with an off the shelf subsea hydraulic control system from the Oceaneering Intervention Engineering group. The touch screen software allowed complete control of the friction welding variables.



Oceaneering hydraulic controls on the left, custom magnet jig on the right.

From previous deepwater commercial projects, Oceaneering adapted the pressure compensated magnets that we had developed, this gave a quick start to the program by using the data from existing commercial projects where we documented the magnetic holding ability on a variety of different materials, and thickness. The magnets selected had proven far superior in holding power, and provided the smallest foot print.



Components developed and adapted for the friction welding,
tested in the Oceaneering ADS tank

Each component designed or adapted for the US Navy friction welding testing, was functioned tested in the Oceaneering facility tank. The ability of the Wasp to maneuver and position the various components as well, as the ability to operate the valves and other controls were all tested prior to the deepwater testing in the hyperbaric facility in Panama City, Florida.





The US Navy Panama test chamber and support personnel, with the Oceaneering Wasp team



The Oceaneering ADS friction welding team, Jimmy Stinnett, Bob Frangenberg and Robert Shannon, inside the US Navy Panama City test chamber



Friction welding equipment set up inside the US Navy test chamber

While the experimental test facility appeared huge, it quickly filled with the curved test plate which was used to simulate the submarine hull, the hydraulic controls, hot tap assembly, the friction welding umbilical, hydraulic gun and the Oceaneering ADS suit.



Interfacing the array of equipment to the bulkhead penetrators of the US Navy chamber

The hydraulic power and the interface of the software controls from the surface computer to the hydraulic control pack inside the chamber created a challenge, since the chamber had a limited number of available bulkhead penetrators available.



Oceaneering's Bob Frangenberg making the connection from the surface control computer



Hot tap assembly fixture

In addition to the actual friction welding of the stud to the simulated submarine hull, a hot tap assembly was designed to screw onto the friction welded stud and seal to the stud by a O-ring assembly, and by way of a dual valve and packer system, allow the hot tap process to drill through the center of the friction stud into the submarine interior space.



Hot tap drill motor, hot tap drill packer and dual valves
above the friction stud mount

Since the US Navy facility had a limited availability as well as available testing funds, the friction stud welding was proven at 2000 fsw, after wrestling with hydraulic heating issues, since the simulated depth in the chamber does not provide the heat sink you would experience in actual ocean conditions, and while limited surface testing of the hot tap assembly was performed, it was not tested at 2000 fsw.



2000 fsw friction stud with the O-ring seal from the US Navy testing

Friction Stud Welding Underwater in the Offshore Oil and Gas Industry

Dave Gibson, Nathan Paculba and Ian Grey, Proserv Offshore Inc.

Abstract

Friction stud welding is a solid phase process which has been used in underwater operations for over 20 years. The absence of an electric arc and a liquid weld pool avoids potential problems with hydrogen absorption when welding underwater and there is no change in welding parameters or weld chemistry with increased water depth. The operational use of the process is presently limited to the welding of studs and small hot tapping fittings. There are presently two general types of system in operation; air power and hydraulically powered. The air powered systems are suitable for use to approximately 30m water depth. These are simple to use and divers can be trained and qualified to operate them in less than one day. The hydraulic systems are designed to operate to a depth of 1000m but could be modified for deeper work if required. The HMS3000 hydraulic system can be operated by divers or with ROVs. This system has been used operationally to a depth of 395m and has welded under hyperbaric test conditions to a simulated depth of 610m. Typical applications include the welding of studs for anode attachment on live subsea pipelines and FPSOs and the repair of offshore structures. A variation of friction stud welding is Tripartite welding where the stud is welded through a piece of steel already attached to the anode and onto the work piece. This provides a continuously welded connection to the anode which avoids the potential problem of increased electrical resistance due to corrosion whilst in service. Tripartite welding can also simplify anode installation because the welding and positioning of the anode can be done in one operation without having to bolt on the anode after the studs have been welded. Development work has been done on friction stitch welding underwater where a series of overlapping holes are drilled and filled by friction welding to form a continuous butt weld. Underwater friction surfacing techniques have also been under development for potential applications in the repair of marine propellers.

1.0 Introduction

Friction welding is a solid phase process and is done at much lower temperatures than electric arc welding without melting of the metals. The process has been used for welding underwater since the early 1990's. This paper reviews the present state of underwater friction stud welding in the offshore oil and gas industry.

2.0 The friction stud welding process

Friction Stud Welding involves rotating a stud at high speed (typically 8,000 r.p.m.) and forcing it against the metal work piece surface. The heat caused by friction between the stud tip and the work piece raises the temperature of the metals sufficiently for plastic flow to occur. This removes the impurities from the interface surfaces expelling them to the edge of the weld. Rotation is then stopped and the force on the stud is maintained for a few seconds to consolidate the joint and make a forged weld (Figure 1).



Figure 1 – A 25 mm diameter friction stud weld

The process is somewhat more costly to operate than arc stud welding because a rigid clamp is required to react against the force applied to the stud during welding. Friction Stud Welding is therefore applied to niche markets where arc welding may be problematic. These include:

- Underwater welding on offshore structures and pipelines
- Welding on live pipelines for anode or sensor attachment
- Welding through paint and coatings where minimising damage to the coating is important
- Welding dissimilar metals
- Welding in potentially explosive atmospheres such as Zone 1 areas on offshore installations

The main limitation of this process is that it has only been used for welding studs and small pipe fittings.

Friction welding is a solid phase process and the absence of an electric arc and a liquid weld pool avoids potential problems with hydrogen absorption when welding underwater. Furthermore there is no change in welding parameters or weld chemistry with increased water depth as is the case with electric arc welding. With this process the residual stresses in the “as welded” condition are compressive which is beneficial for the fatigue life of the weld.

3.0 Friction Stud Welding Equipment

Air powered friction stud welding systems (Figure 2) are available for use in shallow water typically down to a depth of 30m. This tool consists of an air motor with a flywheel, governor and chuck attached to a shaft. The speed of the motor is limited by the governor and the flywheel stores kinetic energy. A pneumatic piston pushes the stud, which is held in the rotating chuck, onto the work piece. The duration of the weld and the amount of the stud consumed in a weld can be fixed by means of pre set spacers in the tool. This system is simple to operate and a diver can be trained to use it and qualify as a welding operator in one day.



Figure 2 – An air powered R1004 friction stud welding tool attached to a pipe with a chain clamp

Air powered systems are available for welding studs up to 16 mm in diameter.

Hydraulic systems are available for use in deeper water, for welding studs up to approximately 25 mm in diameter and for welding small nipples (Figure 3). The HMS3000 system is designed for operations to 3,000 ft but in principle this type of system could be modified to operate a much greater depths. The tool can be powered from the hydraulic system on a work class ROV or from a separate subsea hydraulic power pack.



Figure 3 – The HMS3000 hydraulically powered friction stud welding tool

These units have electronically controlled valve packs located subsea close to the tool which are controlled from a computer on the surface. Sensors on the system provide information on the rotational speed of the shaft, displacement of the piston and pressure. Graphs generated from these data are displayed in real time on the computer (Figure 4).

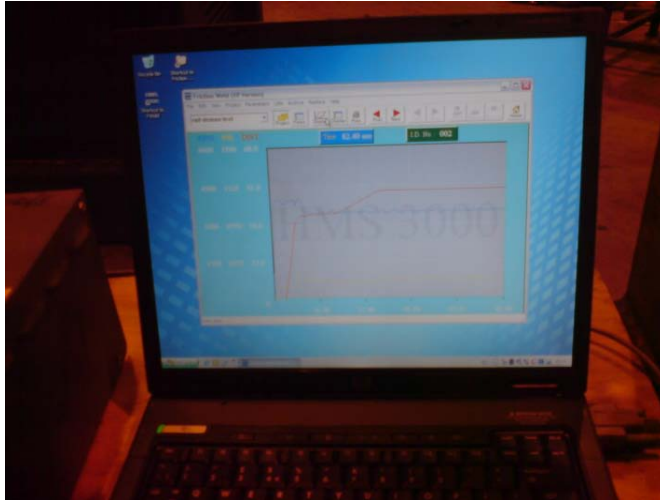


Figure 4 – A screen on the HMS3000 control system showing graphs of welding parameters.

The HMS 3000 and its control system have recently been subject to a series of upgrades funded by the European Commission to permit the system to be used for development work on underwater Friction Stitch Welding and Friction Surfacing.

Friction Stud Welding requires a rigid clamp to secure the tool to the work piece. The design of the clamp and associated jig is crucial to the efficient performance of the work by the diver or ROV and often varies from job to job (Figures 6, 7, 8 and 9).



Figure 6a – An air powered tool in a jig with permanent magnets, used for an FPSO repair



Figure 6b – The jig shown with M12 stud welds at each location

Friction welding tools may have bayonet fittings so that the diver can easily lock the tool into a female bayonet fitting on the jig at the weld location.

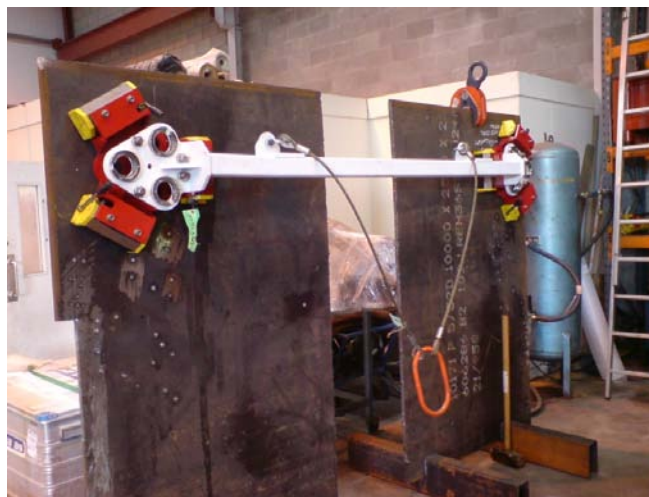


Figure 7 – A jig for retrofitting anodes to an FPSO hull with 3 stud welds at each end



Figure 8 – The HMS3000 hydraulic tool in an electromagnet clamp.

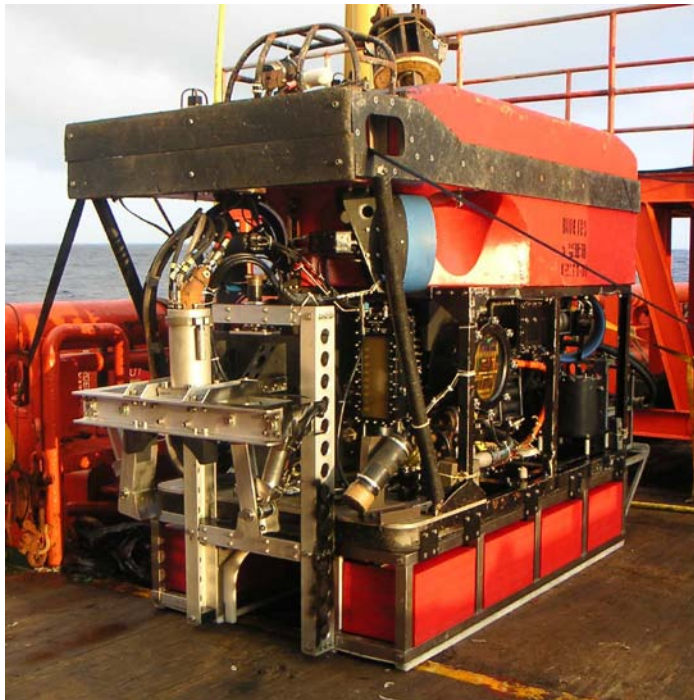


Figure 9 – The HMS3000 on a clamp and tooling system for pipeline anode installation by ROV

For subsea welding the stud is fitted with either a foam shroud (Figure 10) or a grease filled puck to prevent rapid cooling of the weld by the surrounding water. This technique is also used topside for welding in explosive atmospheres where the foam shroud and a water spray are used to isolate the weld from the surrounding atmosphere.



Figure 10 – A foam shroud fitted to an R1004 stud welding tool for underwater welding

4.0 Friction stud welding through coatings and paint

Friction stud welding can be used to weld through many types of coatings and paint. This includes materials such as rubber seals used on habitats for in-water ship repair (Figure 11) and coating on pipelines (Figure 12).

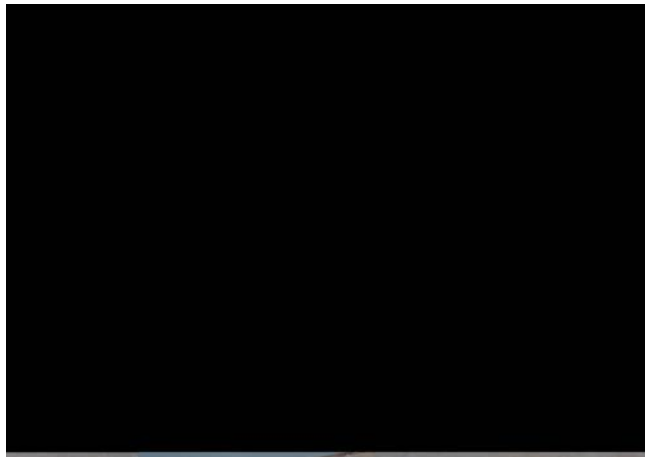


Figure 11 – A stud weld through a rubber habitat seal



Figure 12 – A stud weld done by an ROV through the epoxy coating on a live subsea pipeline

If the subsea pipeline has a concrete weight coating this can be removed locally using a high pressure water jetting tool that can be deployed by an ROV (Figure 13). The steel in the coating is cut using a tool on the ROV's manipulator.



Figure 13 – Local weight coating removal on a pipeline with an HP water jet tool

5.0 Quality Control in underwater Friction stud Welding

Friction Stud Welding procedures are prepared based as far as possible on one of the existing friction welding codes or standards which indicate essential variables for friction welding such as AWS C6.2. Procedure and welding operator qualification has been done typically in accordance with the sections of standards such as ASME IX which relate to stud weld. Although these standards were written for arc stud welding the testing protocol is appropriate to friction stud welding.

During operations subsea stud welds may be non destructively tested by applying a tensile pull to the stud with the hydraulic welding tool. Studs welded with the air tools may be tested by the diver shearing off the hexagonal drive at the rear of the stud using a wrench.

6.0 Tripartite welding

Tripartite welding is a variation on Friction Stitch Welding which offers some particular advantages for retrofitting anodes. In this case the stud welds through a tapered hole in a metal puck or tab already

connected to the anode. The stud, puck and work piece are all friction welded in this operation. This provides a fully welded electrical connection to the structure avoiding possible increases in electrical resistance of the connection due to corrosion during service life. A macro section of a tripartite weld is shown in Figure 14. A stainless steel stud was used for this weld so that the three parts are more easily visible but carbon steel studs would normally be used.

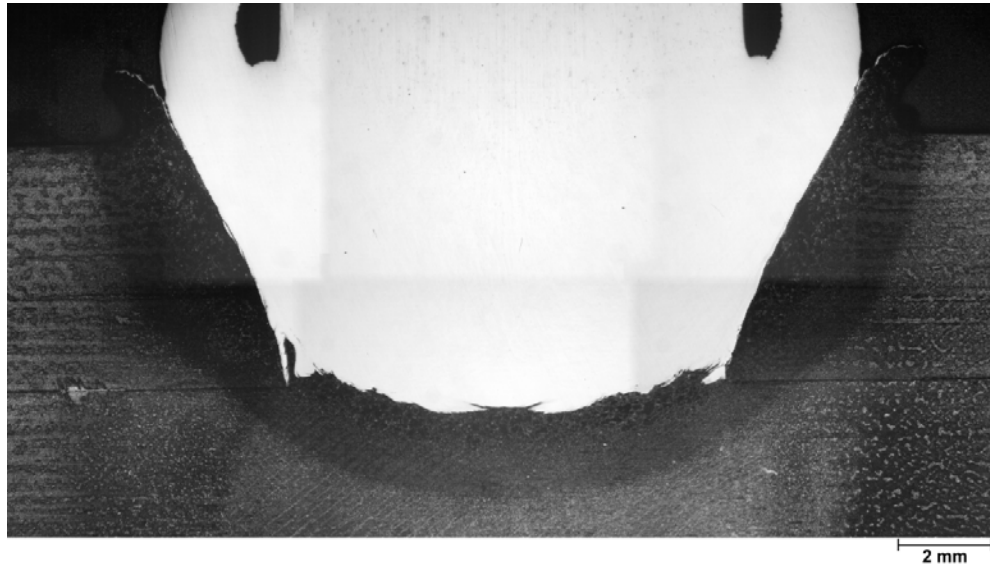


Figure 14 – Macro section of a Tripartite Weld done with the HMS3000
(Courtesy of GKSS Forschungszentrum)

Tripartite welding has been done to a depth of 395 m with an ROV.

Tripartite welding also has some potential advantages for installation of the anodes. The anode can be loaded into a jig with a welding tool at each end (Figure 15). This avoids performing stud welding and then bolting on the anode as separate operations.

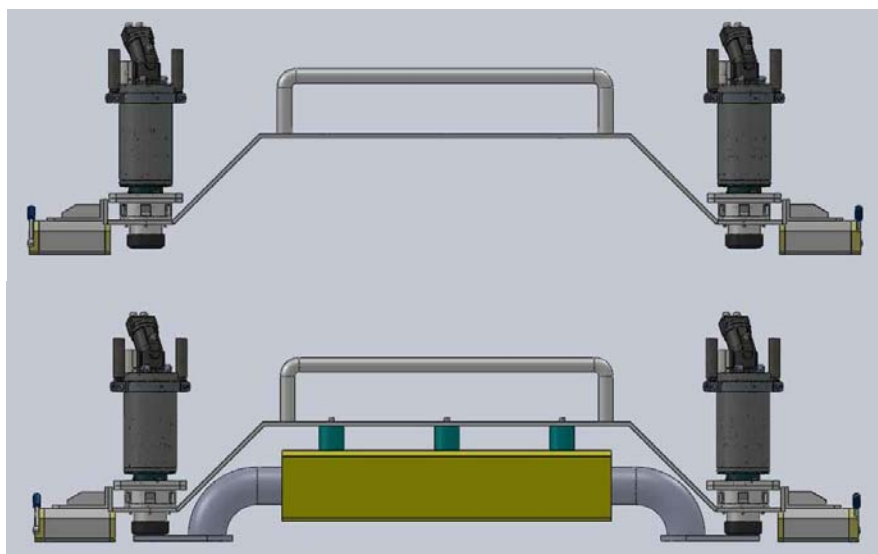


Figure 15 – Sketch showing a tripartite welding jig with and without the anode

7.0 Friction Stitch Welding

The HMS3000 tool has been used in the development of underwater friction stitch welding, which may have potential for crack repairs. This is a hole filling technique (Figure 16) and a continuous weld is formed by drill and filling a series of overlapping holes (Figure 17).

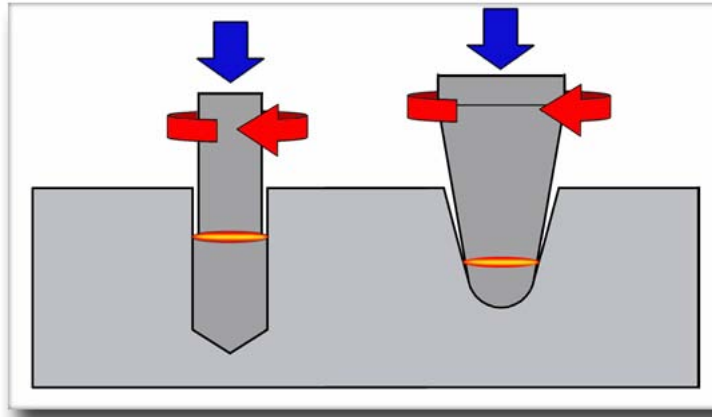


Figure 16 – Friction Welding hole filling techniques (Courtesy of GKSS Forschungszentrum)

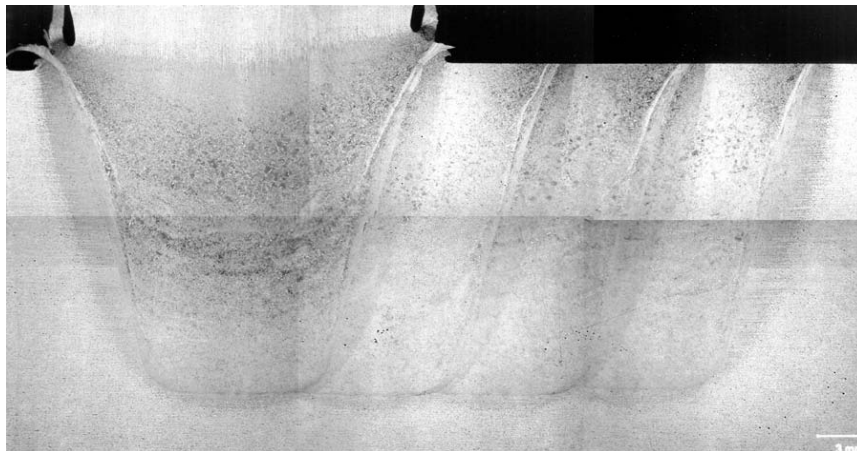


Figure 17 – Macro section of an underwater friction stitch weld (Courtesy of GKSS Forschungszentrum)

8.0 Friction surfacing underwater

The HMS3000 system has also been used for the development of friction surfacing underwater which is an extension of friction stud welding. In this case the stud is the surfacing material and is moved laterally across the work piece whilst being continuously fed (Figures 18,19 and 20).

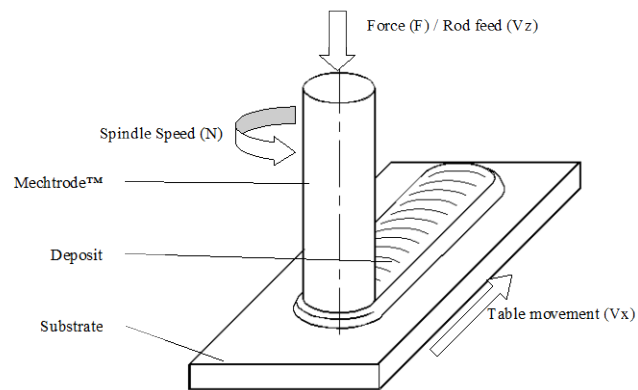


Figure 18 – The friction surfacing process

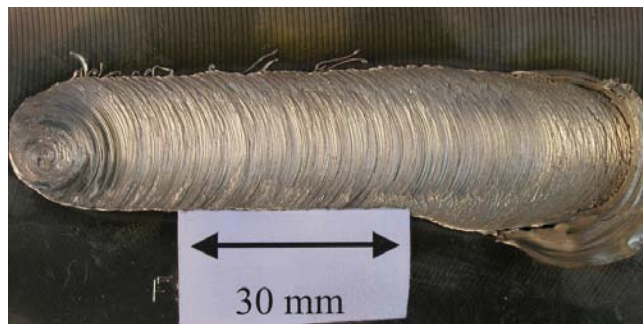


Figure 19 – A single pass with friction surfacing



Figure 20 – Multi pass friction surfacing
(Courtesy of GKSS Forschungszentrum)

Development work has been done on friction surfacing Nickel Aluminium Bronze and stainless steels underwater. This was done with a view to potential markets involving in-water repair to cavitation damage on marine propellers.

9.0 Conclusions

Friction stud welding is a well established underwater welding process and is capable of producing good quality welds both in shallow water and at great depth. It is a relatively simple process to operate. Divers can be rapidly trained and qualified in using the process and it can be readily adapted for deep remote operations with ROVs.

It is also possible to weld small diameter nipples using this process (Figure 21)

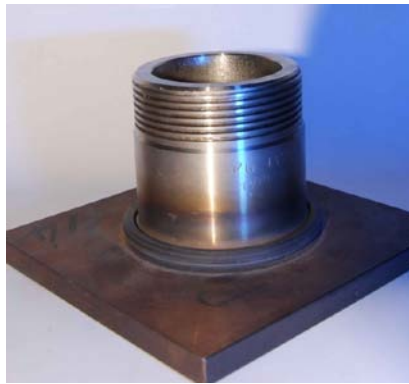


Figure 21 – A two inch o.d. nipple friction welded using the HMS3000 system

Friction stud welding is a solid phase process and as such does not involve the issues of welding parameter and weld chemistry changes associated with electric arc welding. It therefore has potential for welding in extremely deep water with ROVs.

Acknowledgements

The authors wish to acknowledge the work of Gordon Blakemore who designed and developed the HMS3000 system and the work of Dr Jorge dos Santos and his team at GKSS for their research work on Friction Stitch Welding and Friction Surfacing.

Fitness-for-Service Assessment of Underwater Welds in Offshore Structures

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ABSTRACT

Fitness for service assessment of underwater welds in offshore structures poses a series of challenges. These include weld quality definition considering significance of various forms of defects, fracture mechanics based K solutions for typically complex joint configurations, and residual stress distributions that can be significantly different from air welds. This paper provides the author's prospective on some of the recent developments in these areas and applications for performing effective fitness for service assessment for underwater welds in offshore structures.

Introduction

Underwater welding is essential in construction, repair, and retrofit of offshore structures. Fitness-for-service (FFS) technologies, also often referred to as Engineering Critical Assessment (ECA) offer a powerful tool for defining underwater weld integrity and its fitness for continued service or repair/replacement using well-established quantitative fracture mechanics principles. This is particularly relevant in that for underwater wet-welding based repairs, FFS methodologies can be effectively used to establish fitness for purpose based wet weld quality definition or weld defect acceptance criteria. These also include fitness for service assessment of complex structures such as underwater welds in tubular structures and plate structures.

FFS technologies have been widely used for safety-critical structures by nuclear utilities and petroleum refining industries for in-air welds for which standardized FFS procedures can be exercised by following some of the well-known FFS standards, such as BS 7910, API 579 RP, as well as the new 2007 API-579/ASME FFS-1. However, there has not been much documented experience and well accepted procedures for applications in assessing welds produced in underwater environments. Some of the difficulties include:

- 1) Treatment of underwater weld quality, particularly wet welds
- 2) Complexity in structural joints that may be difficult to fit any existing solutions for calculating fatigue and fracture driving force parameter such as stress intensity factor K
- 3) Residual stress descriptions for underwater wet welds that can be drastically different from air welds due to severe cooling environment
- 4) Lack of quantitative fracture toughness data other than Charpy energy, which are typically inferior than air welds

The intent of this paper is to provide a state of the art review of relevant developments to the first three areas highlighted above. Fracture toughness characterization needs to be addressed somewhere else due to space limitation here. With a series of selected examples to demonstrate how some of the technical developments can be effectively used to address some of the concerns. A framework for incorporating some of the new developments for FFS assessment of underwater welds will be discussed, including additional areas of technical developments through collaborative programs to achieve industrial

consensus, eventually leading to the development of FFS procedures for underwater welds in offshore and marine structures.

Fitness-For-Purpose Based Weld Quality Definition

As is well known, underwater wet welding tends to introduce various forms of defects or discontinuities in the form of surface and sub-surface pores, micro-cracks, inclusions, etc. Existing weld discontinuity acceptance criteria (e.g., AWS D3.6 and others) are empirical based. Some recent studies have showed that the existing acceptance criteria [1-2] can become excessively conservative for air welds and severely restricting to the use of underwater welding. Some recent results from a recent fracture mechanics study performed by the author are discussed here. One major finding is that it is the distribution of discontinuities that are more important than sizes of individual discontinuity features.

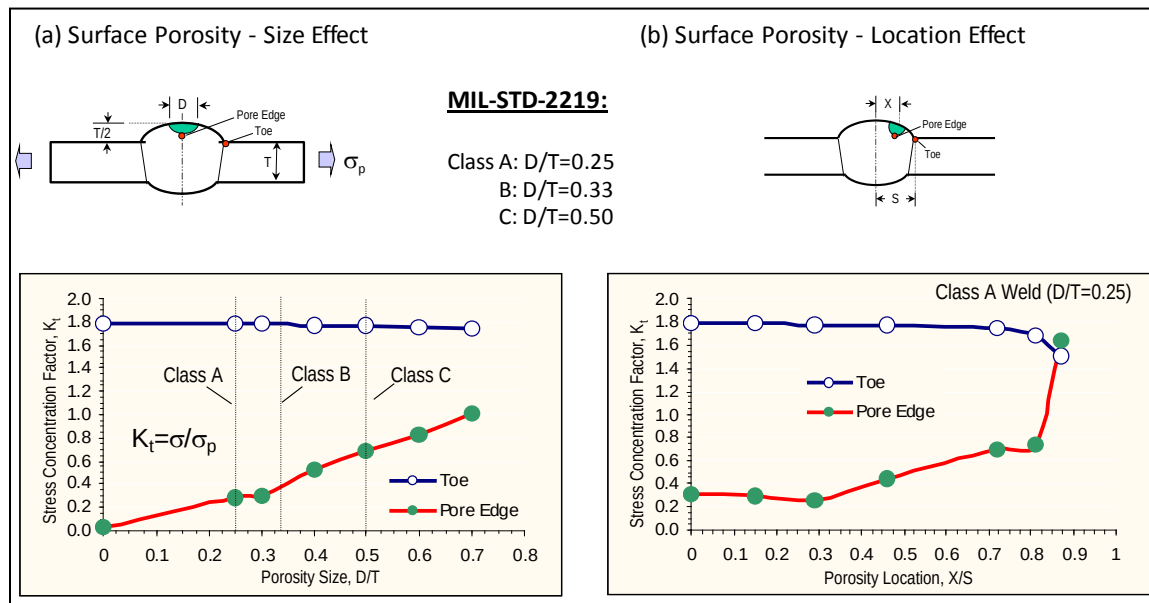


Figure 1: Surface pore size and location effects on stress concentration at weld toe under tension loading

Effects of Weld Defect Size and Location

In this study, weld defect acceptance criteria based on MIL-STD-2219 (2000), maintained by AWS D17 Committee were used as reference as highlighted in the notes given in Figure 1. The specifications for underwater welds in AWS D3.6 are rather similar. The stress concentration factor was defined as local stress at location close to the weld toe notch root using a highly effective hybrid polygonal element (HPE) method [2]. Some of the relevant features of the HPE method are provided in the next section where randomly distributed pores or micro cracks in a spot weld are analyzed.

As shown in Figure 1a, the stress concentration at the surface discontinuity is compared with that at weld toe for pore size spanning Class A to Class B weld definitions. For the entire range of pore size, the stress concentration at the pore remains lower, although increasing monotonically, than that at weld toe, which remains essentially unaffected by the pore size. This suggests that such a surface pore can be tolerated up to a larger size than that required to meet Class C specification for this case without degrading the joint structural integrity. In other words, this particular weld can theoretically perform like

a Class A with a larger size comparable with that in a Class C weld. Obviously, before such a finding can be generalized, other loading conditions and failure modes must be examined and validated by experimental testing.

However, if a surface pore size of $D/T=0.25$, beyond which a joint is deemed unacceptable for Class A weld, is considered by varying its position with respect to weld toe, Figure 1b shows that a surface pore can overtake the effects of weld toe stress concentration and control the structural integrity of the joint if a surface pore is relatively close the weld. The results highlight the importance of defect locations, which has not been adequately taken into account in all major existing weld defect acceptance criteria.

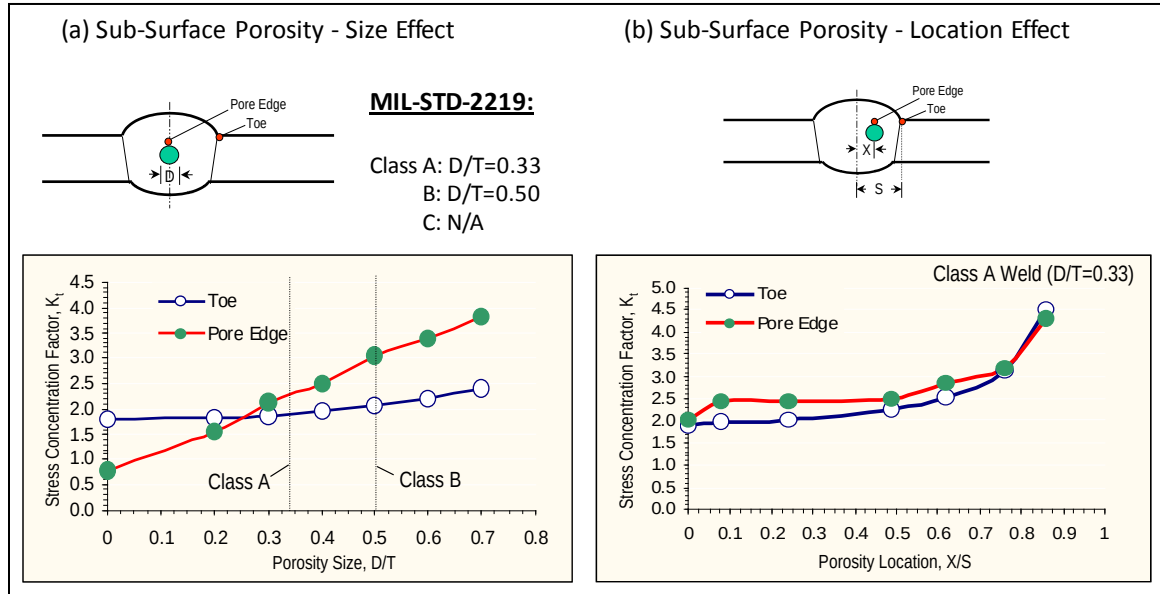


Figure 2: Effect of sub-surface pore size and location on stress concentration at weld toe

A sub-surface pore is considered in Figure 2. Pore size effects on weld toe stress concentration are shown in Figure 2a. Comparing with Figure 1a, sub-surface pore size has a much stronger effects on weld toe stress state shown in Figure 2a. This is because as pore size increases, load transfer path from one side of the weld to becomes severely altered due to the presence of a large size pore in the middle of a weld, while for surface pore, the change of load path is much less significant with increasing pore size. If a Class A weld is considered with the maximum possible allowable sub-surface pore size, the stress concentration at pore remains dominant, but remain constant until the distance between the pore and weld toe becomes close. The results suggest the effects of sub-surface pore on joint integrity are more strongly dependent on size rather than its location with respect to weld toe or weld root. As for surface pore, its effects on joint integrity are mostly dependent upon its location, rather than size.

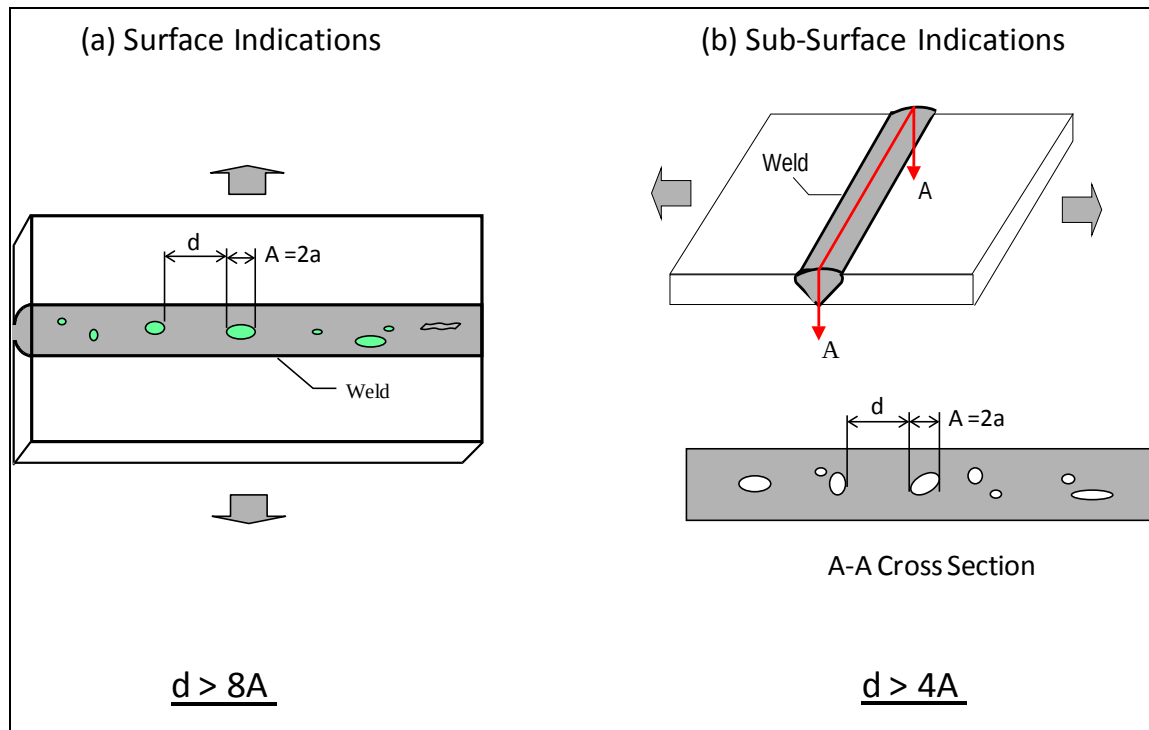


Figure 3: Equivalency and interactions of multiple defects

Interaction Effects of Distributed Effects

In underwater wet welds, pores and other form of discontinuities may be illustrated as shown in Figure 3 on both weld surface (Figure 3a) or within weld metal (Figure 3b). In existing weld acceptance criteria, empirically based defect interaction criteria are typically used (e.g., D3.6, MIL-STD-2219), as noted in Figure 3. For instance, if a surface indication has a size of A , Class A welds require that the distance between any two adjacent defects should be larger than $8A$ for surface defects and $4A$ for internal defects.

To quantitatively assess the actual effects of multiple defects, two cases are considered here, as summarized in Figure 4. One is with two internal pores, but treated as two co-planar elliptical cracks and the other with three internal pores. The maximum stress intensity factor calculated at individual elliptical crack fronts are compared with the equivalency-based acceptance criteria, which for instance produces an equivalent crack size of $2 \times 2a + d$ for the case in Figure 4a. As shown in Figure 4a, the actual maximum K calculated is much smaller than the K if an equivalent crack size is used. The conservatism rapidly increases as the two co-planar cracks are situated further apart, i.e., less interaction effects. Such conservatism due to the empirical nature of the existing weld acceptance criteria can severely penalize underwater welds. The degree of conservatism further increases if a series of three co-planar defects are considered, as shown in Figure 4b.

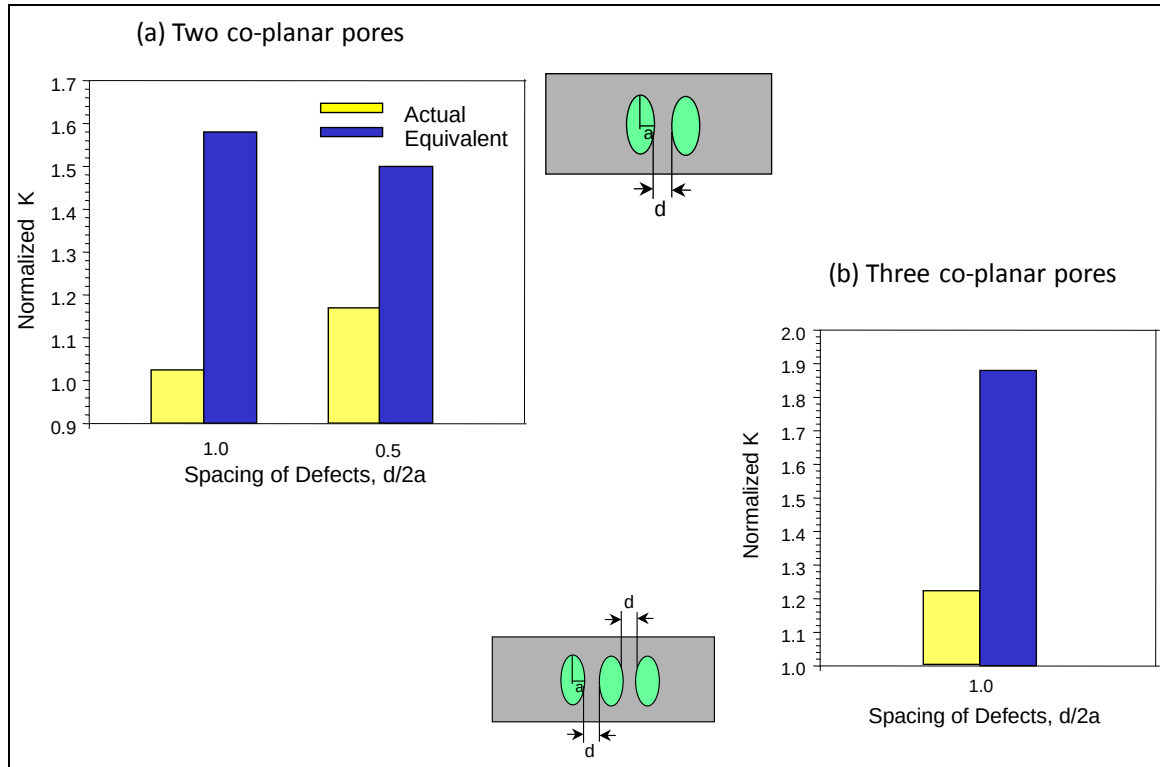


Figure 4: Comparison fracture mechanics calculation results versus equivalent size in existing acceptance criteria

When examining interactions of multiple defects within certain proximity illustrated in Figure 3, crack shielding must be, which can be very beneficial in reducing peak stress intensity factors if cracks are oriented parallel to each other, as shown in Figure 5. As fracture mechanics calculations shown, the closer is the distance between the crack like defects, the lower the stress intensity factor becomes. Such a shielding effect can be important in developing quantitative weld acceptance criteria for under water wet welds due to their propensity to develop distributed pores and other defects within weld metal.

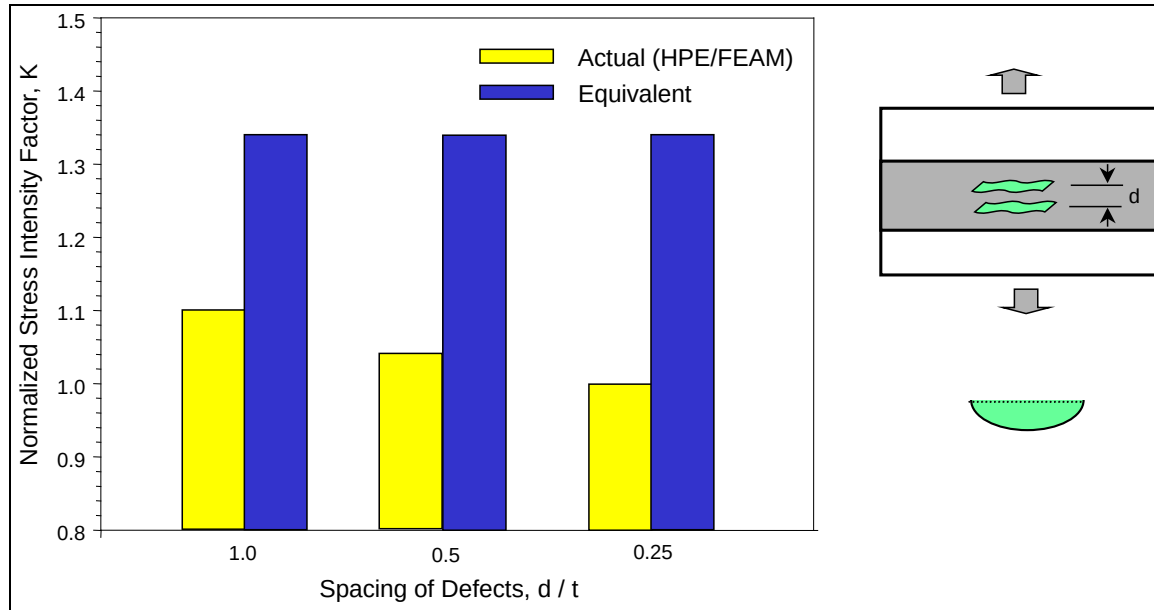


Figure 5: Interaction and shielding effects of parallel defects

A Case Study – Porosity Acceptance Criteria

The practicality of the analysis techniques and the results presented above can be demonstrated by a more comprehensive study [2] which led to weld acceptance criteria that have already been implemented in production environment.

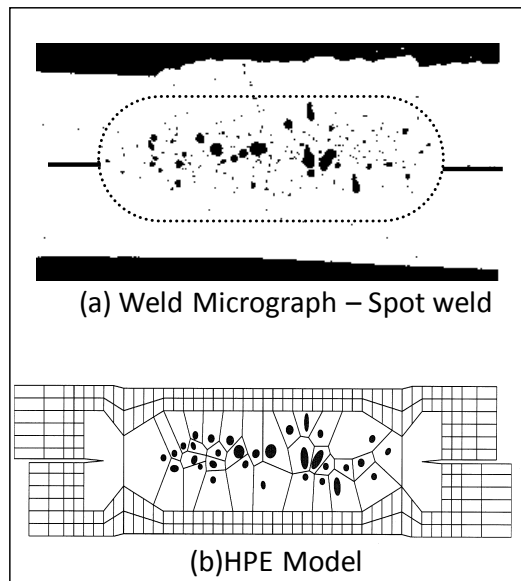


Figure 6: Illustration of Hybrid Polygonal Element (HPE) model for modeling randomly distributed micro pores in a spot weld

As shown in Figure 6, a hybrid polygonal element (HPE) can be used to simulate randomly distributed micro-pores and micro-cracks. One advantage of this method is a geometry feature such as a micro

crack or pore or inclusion can be considered in one single element with its size and position described analytically. Therefore, one HPE model can be used to simulate many possible distributions of defects, defect sizes, and locations. For example, as shown in Figure 7, the single HPE model is used to simulate a total of 242 cases of random distributions of micro pores including some of the typical cases illustrated in the Figure. Two typical loading cases are examined, i.e., peel and lap shear. In all cases, the stress intensity factor at the main crack along the interface of the two plates is calculated for each case.

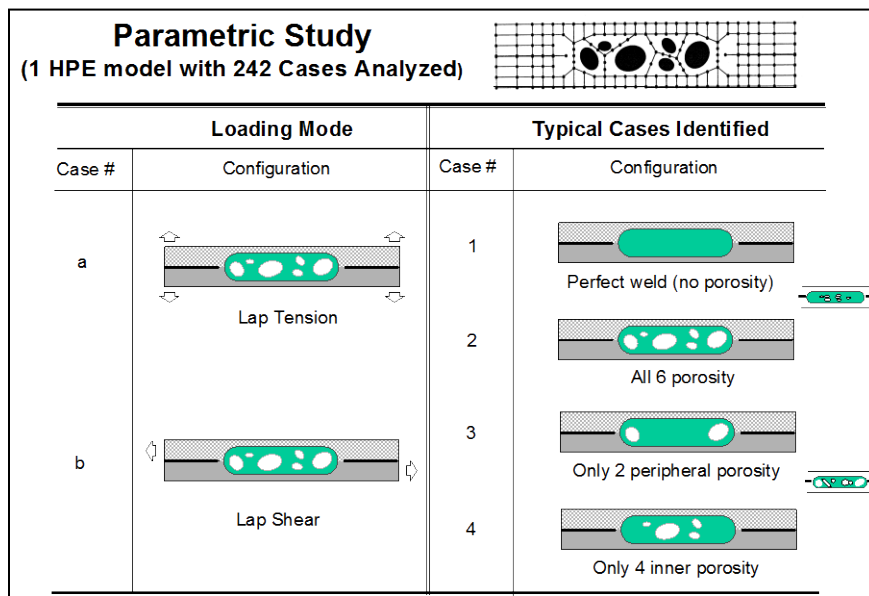


Figure 7: Illustration of a single HPE model and typical cases considered for examining effects of randomly distributed micro pores on joint integrity

Although 242 cases have been investigated, the implication of the final results can be simply summarized by presenting a few characteristic cases, as shown in Figure 8. These characteristic cases bound effects seen in all other cases. The stress intensity factors calculated are normalized by the reference case K_0 corresponding to a “perfect weld” without any pores. It can be seen for both loading cases that the distribution characteristics of pores or indications within weld are far more important than their sizes. If pores are located within the middle of the weld, i.e., away from edge of the spot weld, their effects on K is negligible, can be treated as “perfect welds.” If pores are located more towards the periphery of the spot weld, a rapid increase in K can be seen. Knowing such effects of randomly distributed discontinuities can be very important in NDE-based implementation of weld quality acceptance criteria. The results in Figure 8 can be used to determine if a weld fail the acceptance criteria based on distribution characteristics of indications with respect to the critical locations of a weld. Samples of NDE results and their pass/fail determination are shown in Figure 9.

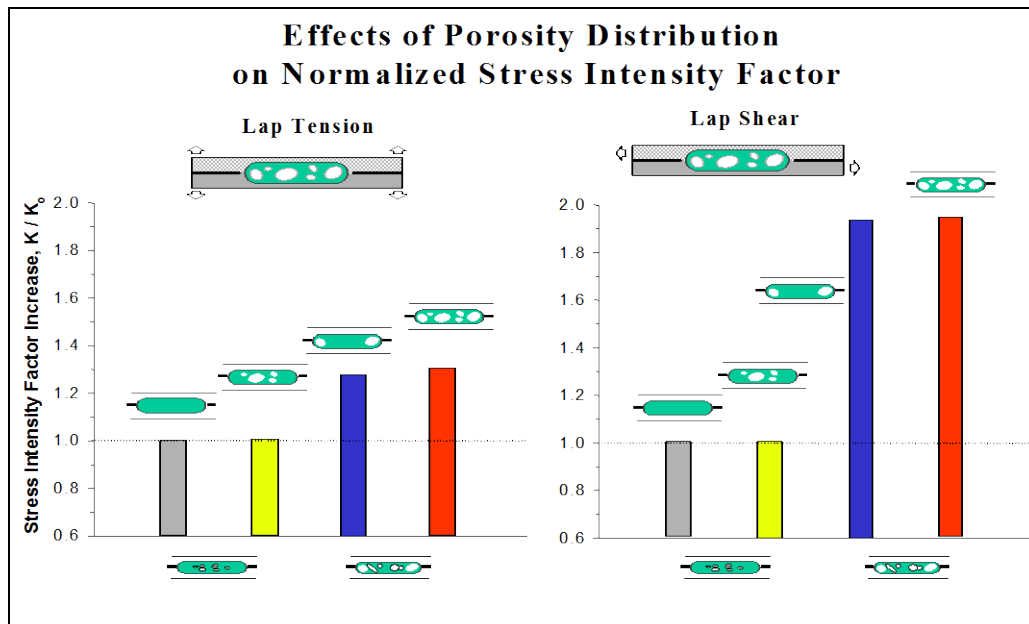


Figure 8: Stress intensity factor results normalized by K_0 without pores

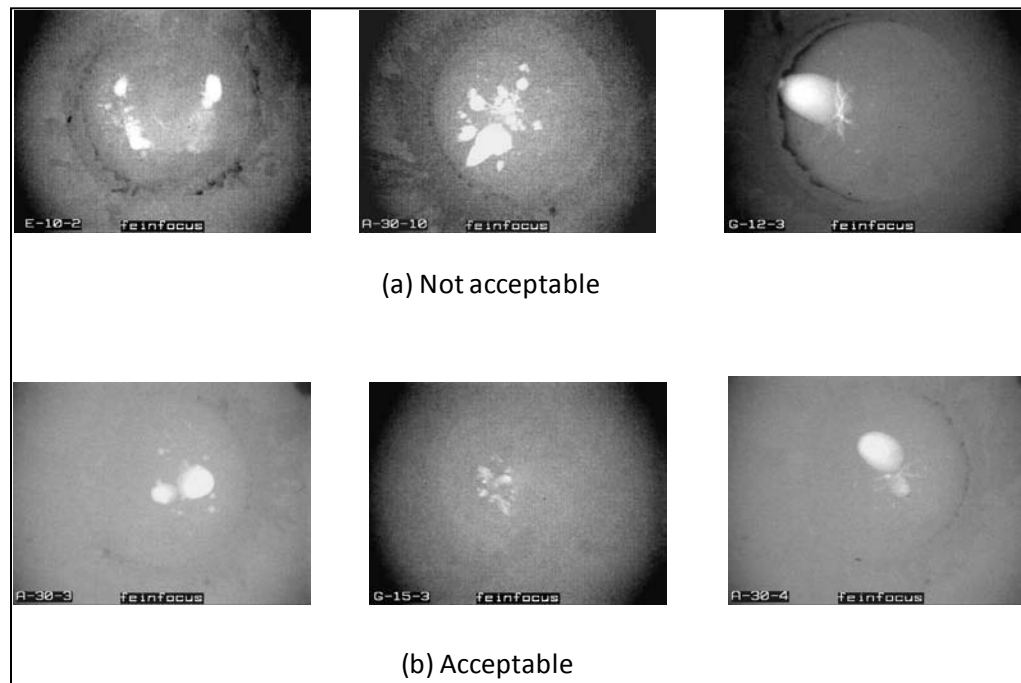


Figure 9: Radiography samples of pass/fail in shop floor weld quality monitoring based on criteria developed according the calculation results shown in Figure 8

Rapid K Solution Technique for Complex Joints

Traction Stress Calculation Method

Over the decade, a traction stress calculation procedure [6-7] has been demonstrated its ability to provide a simple and effective K estimation for complex joints, in addition to its mesh-insensitivity in charactering stress concentrations. The traction stress definition (Figure 10) is based on fracture mechanics considerations. By considering a hypothetical crack plane (A-A or A-A-C-C in Figure 10) at weld toe, Mode I stress intensity factor is determined by the normal traction component σ_s , Mode II determined by the transverse shear component τ_z , and Mode III by the in-plane shear component τ_s . For applications in offshore structures, only are σ_s and τ_s dominant, and τ_z is typically negligible. The traction stress procedures are given in a number of papers and the recent 2007 ASME Sec. VIII Div 2 Code and 2007 API-579/ASME FFS-1.

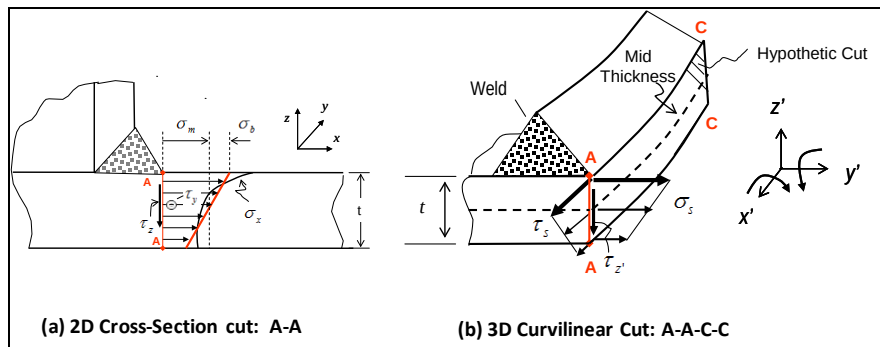


Figure 10: Traction stress definitions in 2D and 3D

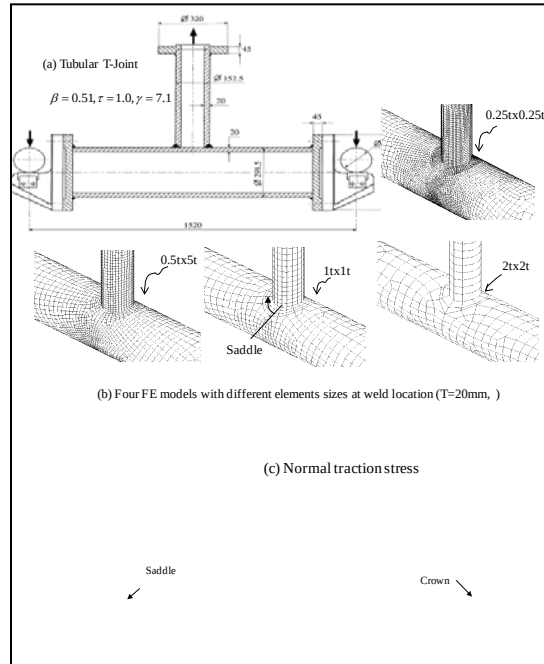


Figure 11: Normal traction stress normalized by brace tension stress along weld toe on chord

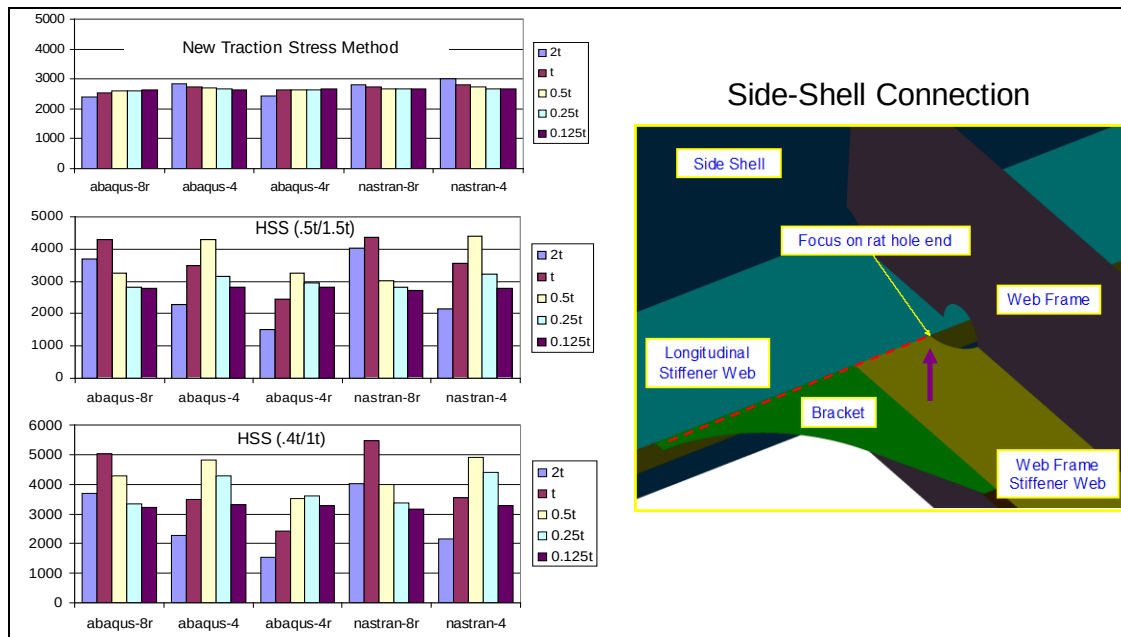


Figure 12: Normal traction stresses normalized by side shell pressure at rat hole end in a full-scale side shell connection joint (Healy, 2004)

With the traction stress method, traction stress component of interest at any given through thickness cross-section cut along an arbitrary weld line can be calculated with a great deal of consistency, or referred as mesh-insensitivity. Two examples relevant to offshore structures are summarized in Figs. 11-12. The normal traction stresses calculated along a cut along weld toe on the chord are summarized in Figure 11. The traction stress is normalized by applied nominal stress on the brace. The results (Figure are shown to be mesh-size insensitive as element size varies from $0.25t$ to about $2t$ (t is chord wall thickness). A similar trend can be seen from the traction stress calculation results for a side-shell connect joint in a ship detail, see Figure 12. However, if the conventional surface extrapolation based hot spot stress (HSS) procedures gives significant variations on the hot spot stresses, depending which software package is used (ABAQUS versus NASTRAN), element type used (e.g., S4 versus S8), and element sizes (e.g., $0.125t$ versus $2t$).

Rapid K Solution Technique

In addition to its mesh-insensitivity in traction stress calculation for complex joints, the properties of the traction stress method greatly simplifies stress intensity factor solution. As illustrated in Figure 13, the very definition of traction (Figure 10) is consistent with the far-field stress definition (σ^∞) in fracture mechanics. Therefore, the traction stress calculation process can be viewed as a stress transformation process from an actual complex joint in a structure under arbitrary loading to a simple fracture specimen, in which the complex loading and geometry effects are captured in the form of membrane and bending. As a result, K for any crack size along the weld can be estimated by using the existing K solution for a simple plate fracture mechanics specimen subjected to both membrane tension and bending, by considering either an edge crack or a surface elliptical crack.

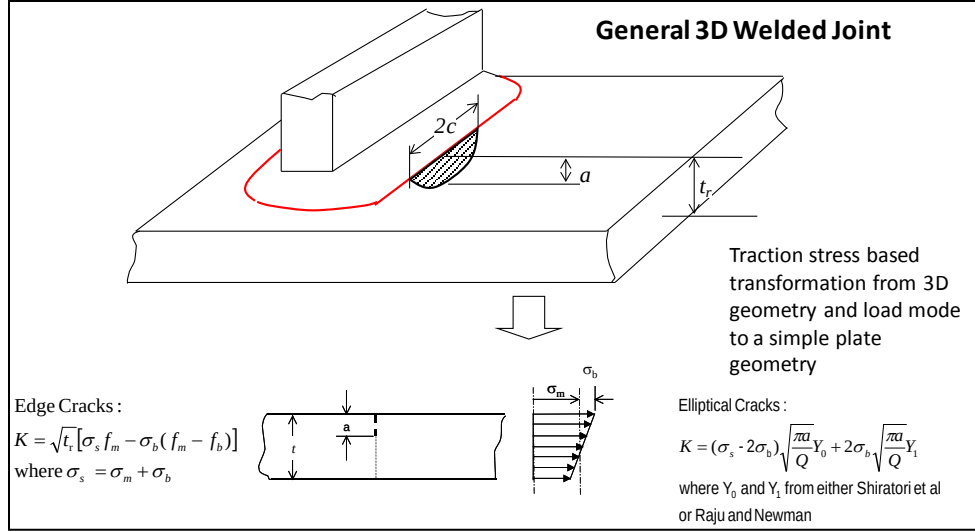


Figure 13: Traction stress based K solution technique for a crack situated at weld toe in a general 3D joint configuration

The detailed derivations and validations can be found in [6-7]. For demonstration purposes, Figure 14 shows the validation for considering an edge crack in a T fillet weld. In Figs. 14a and 14b, attention should be given to the case labeled as “W/ notch effects” and its comparison with the solution represented by square symbols which were published by Glinka et al (1991) based on a weight function method. Other solutions are based other forms of approximation methods and plotted here only for comparison purpose. It can be seen that the traction stress based K solution compares well with the weight function solution over the entire crack size range considered. The same can be said for 3D elliptical crack, as shown in Figure 14c.

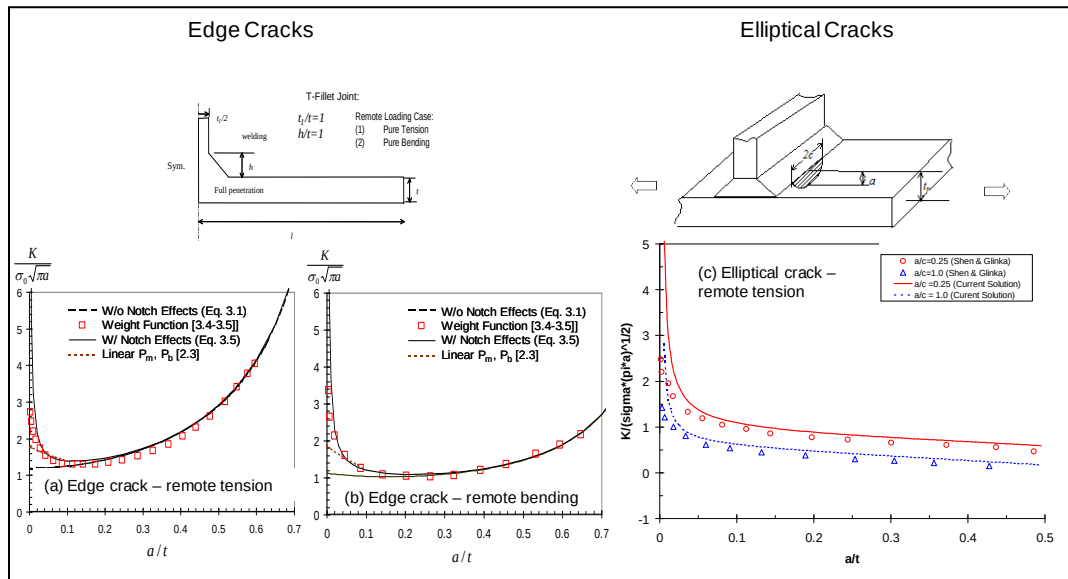


Figure 14: Traction-based K solutions for edge and elliptical cracks and comparison with weight function based solutions by Glinka et al (1994)

Residual Stresses and Fracture Mechanics Treatment

Underwater wet welding subjects weld to a rapid cooling environment. The resulting residual stresses should be significantly different in distributions from those typically seen in air welds. All FFS or ECA procedures require consideration of residual stresses in fatigue and fracture driving force calculations. However, an improved understanding in residual stress development mechanisms over the last decade [3-5] suggests that residual stress induced K for a wet weld should not be as severe as one would first thought, or even less severe than an air weld. Some available residual stress results under similar conditions such as high convection cooling seems to confirm such a hypothesis, as shown in 15 for an axisymmetric pipe girth weld. The transverse residual stresses due to “high convection cooling” are rather benign (actually rather beneficial), contrasting to that corresponding to “low convection cooling” simulating ambient air conditions. Note that it is the transverse stress component that directly contributes to fracture driving, e.g., K in performing FFS assessment. For the case of “high convection cooling,” weld metal upon deposit cools much faster on the surface than in the plate, resulting compressive residual stress near surface and tension near mid-plate thickness. A more comprehensive study is certainly needed under various underwater repair welding conditions in order to establish recommended practices in residual stress distributions for performing FFS assessment for underwater repairs.

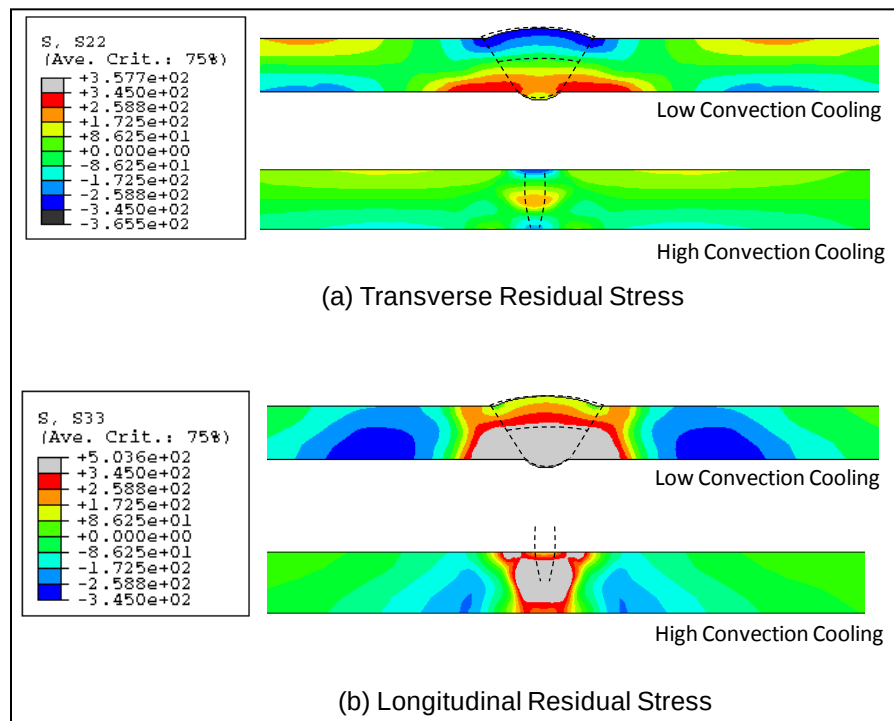


Figure 15: Comparison of residual stress distribution in a pipe girth weld under air and rapid cooling conditions

To quantify the two types of residual stress distributions, some recent developments in fracture mechanics treatment of residual stresses are used. One effective method is the residual stress distribution deposition method [5] in which any given through-thickness residual stress distribution can be decomposed into three fundamental parts, i.e., membrane, bending, and self-equilibrating, as shown in Figure 16. Such a decomposition of the stress distributions in Figure 15a will approximately result in

though-wall bending for the air cooling case and through-wall self-equilibrating for the high convection cooling case (see Figure 15a).

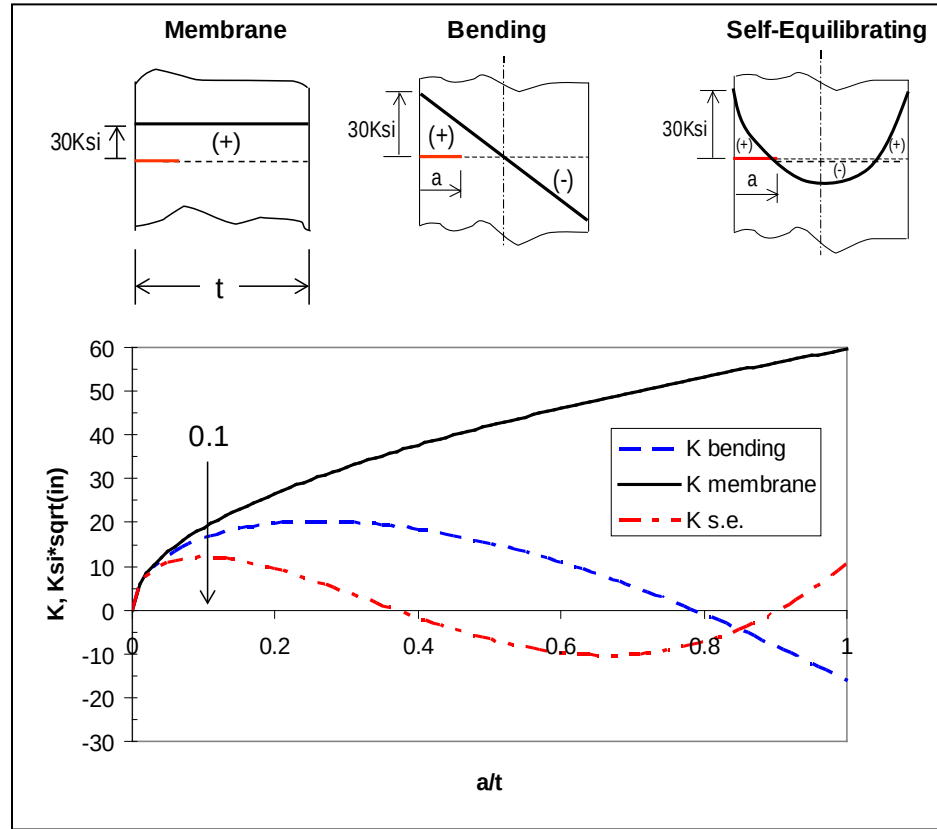


Figure 16: Three characteristic residual stress distributions and their effects on stress intensity factor for a growing crack

As seen in Figure 16, the stress intensity factor K corresponding to “K-bending” approximately describes K as a function of crack size as a result of the transverse residual stress distribution for the case of air cooling or “low convection cooling” in Figure 15a while “K-s.e.” for the case of “high convection cooling.” The residual stress induced K for the latter peaked at a relative crack size of $a/t \sim 0.1$ and then dies out at $a/t \sim 0.35$. Under air cooling conditions, K remains significantly higher and is capable of driving a crack to a much longer size, e.g., $a/t \sim 0.8$. Therefore, recognizing such a change in residual stress distribution characteristics can offer an enormous benefit for FFS for underwater wet welds.

Concluding Remarks

Some of the recent developments in fitness-for-service methodologies are reviewed and discussed in the context of their potential applications in assessing fitness for intended service upon damage through service or environment. These new developments can greatly facilitate the assessment of significance of a damage, needs to repair or retrofit, and adequacy of repair scenarios to ensure cost effectiveness and adequate margin of safety for continued operations.

References

1. Dong, P., "A FITNET Procedure for FFS-Based Fatigue Evaluation Using the Master S-N Curve Approach," 1st FITNET International Conference on Fitness for Service (FITNET 2006), Amsterdam, The Netherlands, May 17-19, 2006, pp. 169-178.
2. Zhang, J. and Dong, P., "A Hybrid Polygonal Element Method for Fracture Mechanics Analysis of Resistance Spot Welds Containing Porosity," *Engineering Fracture Mechanics*, Vol. 59, No. 6, 1998, pp. 815-825.
3. Dong, P., "Residual Stresses and Distortions in Welded Structures: What We Know Today and Beyond," Proceedings of 6th International Conference on Trends in Welding Research, April 15-19, 2002, Pine Mountain, Georgia, USA
4. Dong, P. Hong, J.K., and Bouchard, J.P., "Analysis of Residual Stresses in Repair Welds," *Int. J. of Pressure Vessel and Piping*, No. 82, 2004, pp. 258-269.
5. Dong, P. and Hong, J.K., "Recommendations on Residual Stress Estimate for Fitness-for-Service Assessment," WRC Bulletin, No. 476, *Welding Research Council Bulletin*, January 2003, New York, New York.
6. Dong, P., "A Robust Structural Stress Method for Fatigue Analysis of Offshore/ Marine Structures," ASME Transaction: *J. of Offshore Mechanics and Arctic Engineering*, February, Vol. 127, 2005, pp. 68-74.
7. Dong, P., Hong, J.K., and Cao, Z., "Stresses and Stress Intensities at Notches: 'Anomalous Crack Growth' Revisited," *International Journal of Fatigue*, 25 (2003), pp. 811-825.

Nondestructive Evaluation in Underwater Environments – Lessons for Other Industries

J. Gray, Center for NDE, Iowa State University, Ames, Iowa, USA

State of the Art, Science, and Reliability of Underwater Welding and Inspection Technology

Nondestructive Evaluation in Underwater Environments Lessons for Other Industries

**J. Gray
Center for NDE
Iowa State University**

November 17-19, 2010

Houston, Texas



Outline

- **Overview of the Center for NDE**
- Examples of CNDE Activities
- Summary of Extreme Radiography Workshop
- Emerging Directions and Observations
 - quantitative NDE
 - structural Health Monitoring



Center for Nondestructive Evaluation Iowa State University



**R. Bruce Thompson
Director**



Center for NDE

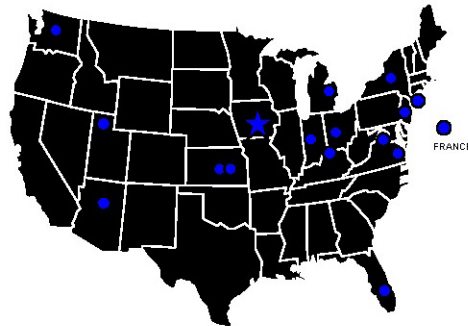
Objectives:

- Industrially relevant NDE research
- Technology transfer
- Education
 - all levels (K-12, community college, university undergraduate and graduate)
- Integration of NDE throughout component lifecycle



NSF Industry/University Cooperative Research Program in Nondestructive Evaluation: 1985-present

AIR FORCE RESEARCH LAB
AREVA
ATK-THIOKOL
THE BOEING COMPANY
EATON CORPORATION
FEDERAL AVIATION ADMINISTRATION (FAA)
HONEYWELL ENGINES AND SYSTEMS
KAPL, INC. (KNOLLS ATOMIC POWER LAB.)
NATIONAL AERONAUTICS AND SPACE
ADMINISTRATION (NASA)
NATIONAL SCIENCE FOUNDATION
PRATT & WHITNEY
ROLLS-ROYCE CORPORATION
TEXTRON AIRCRAFT
TOYOTA MOTOR ENGINEERING AND
MANUFACTURING NORTH AMERICA INC.
LOS ALAMOS NATIONAL LABORATORY
SPIRIT



Major Programs

- NSF Industry/University Cooperative Research Center
- FAA Airworthiness Center of Excellence
- Quality Assurance Program – US AF
- NERI –
Design of On-Line NDE for IRIS Reactor
Inspection Methods for Gen4 Reactor Fuel
- NASA
Application of NDE Models
for Inspection Protocol Development
- Industry funded research



Core Competencies

- Non-Invasive Measurement Techniques
 - Ultrasonics
 - X-Rays
 - Electromagnetic Techniques
 - Magnetic Techniques
 - Fluorescent Penetrants
 - Novel Sensors
 - Thermal and Sonic IR
- Data Analysis Techniques
 - Signal Processing
 - Image Analysis
 - Statistical Analysis
- Applied to
 - Flaw Detection
 - Flaw Characterization
 - Material Characterization



Outline

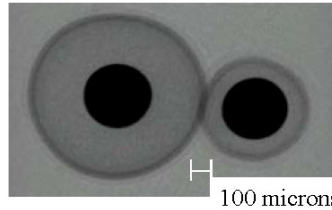
- Overview of the Center for NDE
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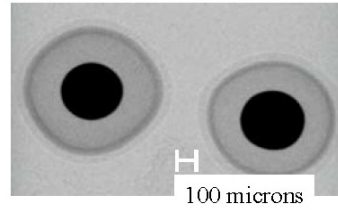
Digital High Resolution Radiography next generation reactor fuel

Irregular Fuel Pellets:

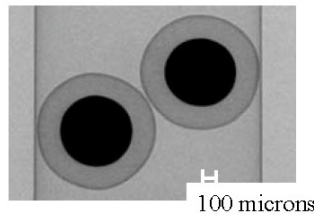
3.5 micron pixel size



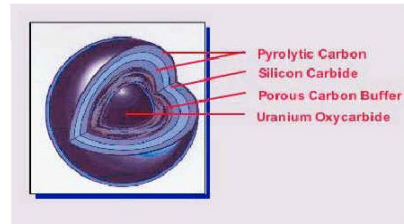
Missing carbon buffer



Irregular shape



Oversized core

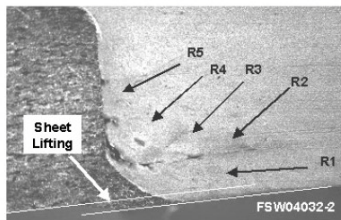
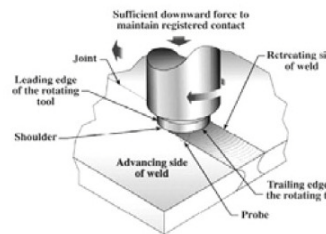


Schematic of a Fuel Pellet



Friction Stir Weld

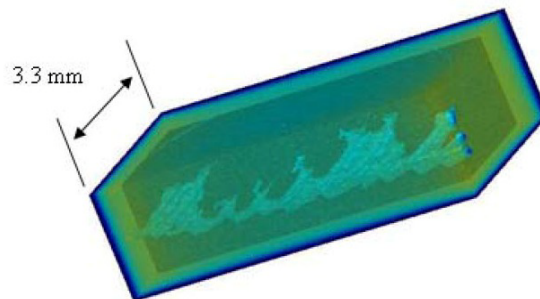
High Resolution CT:
Friction Stir Weld



-Y direction

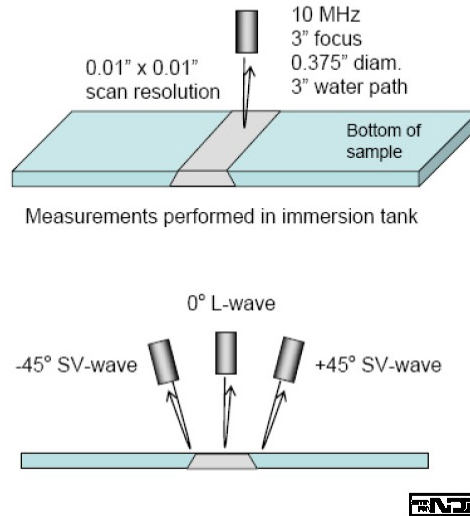
High Resolution CT
Ultrasonic inspection

High Resolution Image of Defect



Friction Stir Welds:

- UT Scan results from bottom (root side) of FSW specimen (T. Gray)

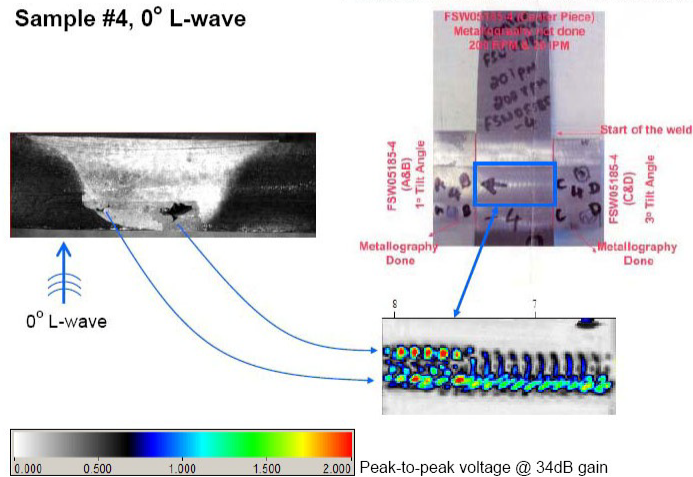


Feature sizing

Friction Stir Welds:

Sample #4, 0° L-wave

Trial welds to CNDE
FSW05185-4 200 RPM & 20 IPM

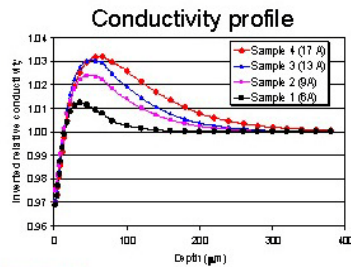
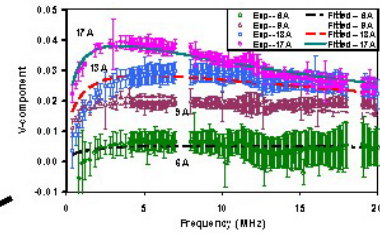




Residual Stress Measurement by High-Frequency Electromagnetic Methods

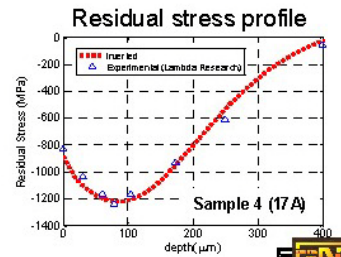
- Model-based layer inversion of conductivity profile to determine
 - Residual stress profile
 - Deviations of other material conditions (e.g. cold work)

EC data from shot peened Inconel 718



Model-based inversion

Piezoresistivity theory

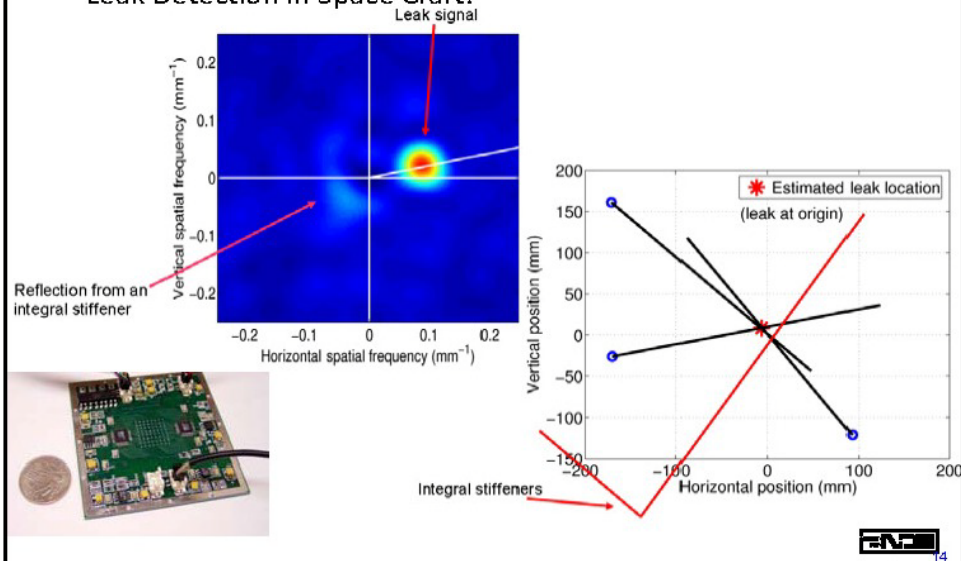


IOWA STATE UNIVERSITY

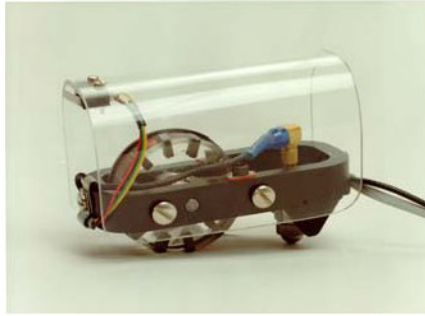
END

Prototype Development

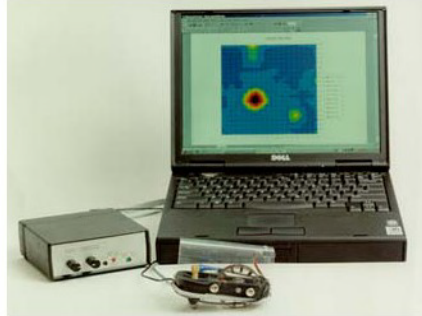
Leak Detection in Space Craft:



Computer Aided Tap Tester (CATT):



Magnetic Tapper

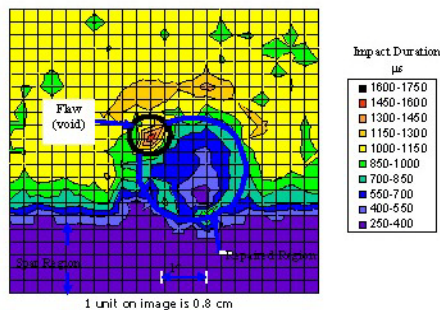


The CATT System

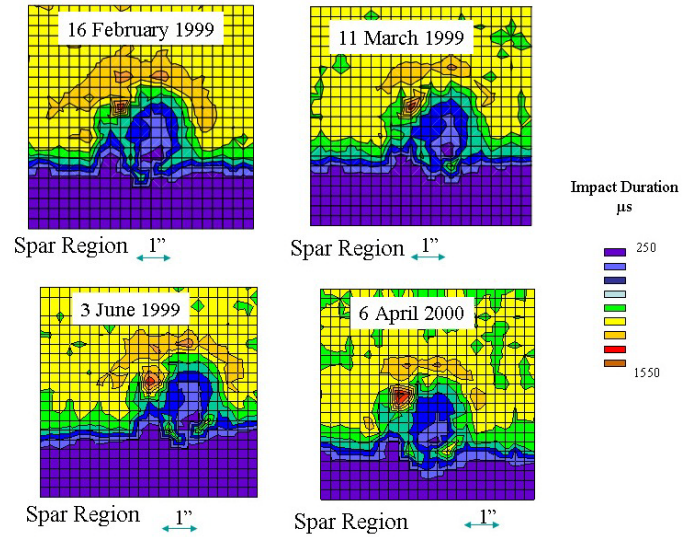


Computer Aided Tap Tester (CATT): repair and monitoring

Tap Test of Blackhawk UH-60 Rotor Blade Repair:
(Kevlar skin and honeycomb core)



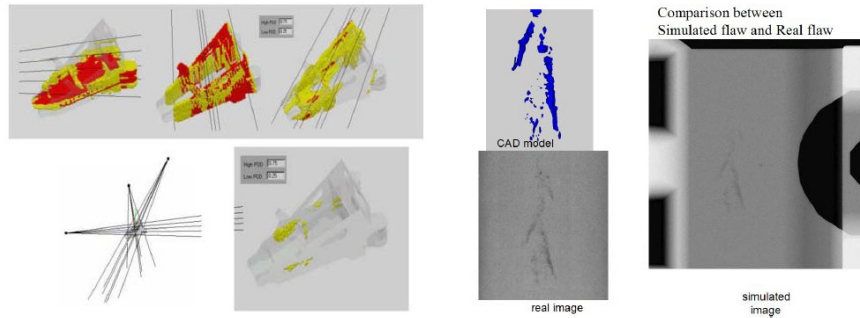
Repaired Region on a Blackhawk UH-60 Rotor Blade



Non Destructive Simulation Tools

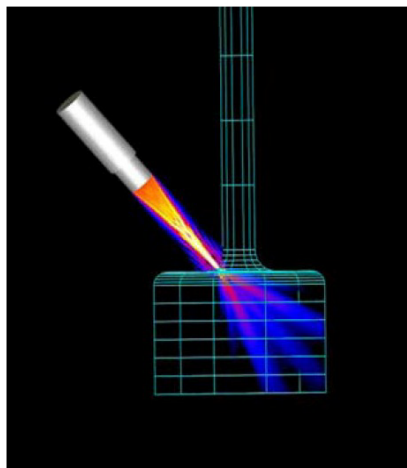
- X-ray Radiography
- Computed Tomography
- Ultrasonics
- Eddy Current

Codes Can Now Treat Quite Complex Geometries

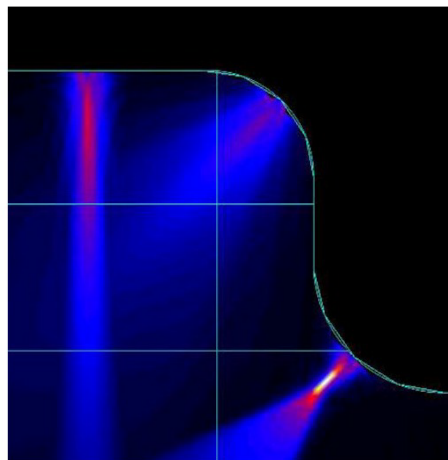


Ultrasonic Modeling

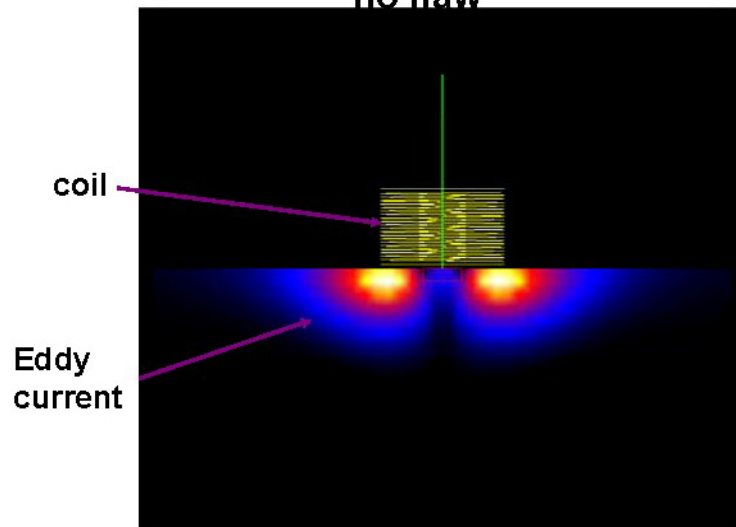
Curved Interface



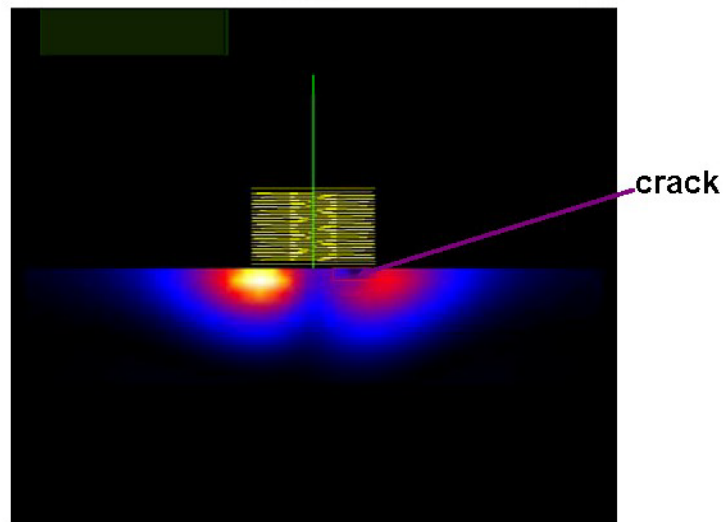
Curved interface different curvatures



Cross Section of Eddy Current no flaw



Cross Section of Eddy Current flaw



Outline

- Overview of the Center for NDE
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Inspection Issues – underwater pipes

from Extreme Radiography Workshop
Los Alamos and British Petroleum
October 2010

Principle focus on radiography issues of well head
in the Gulf of Mexico this summer

detector vendors
source vendors
modeling capabilities

Review of DOE activities
Overview of inspection issues from BP



Radiography Underwater

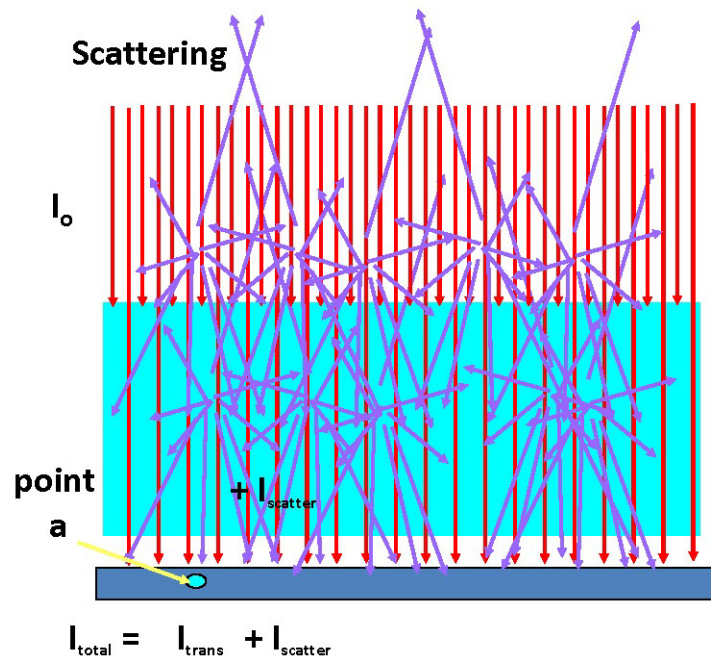
water adds significant scattering to the problem

scatter ratios of 10

need to reduce scattering

Sources and detectors at depth
pressure protection

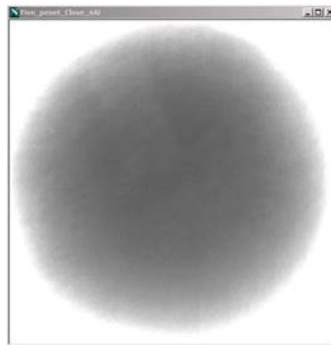
Interpretation of images
use of NDE models



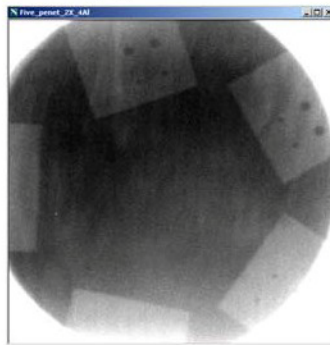
Effect of Scatter on Sensitivity

4" Al w/ 1% penetrameters inserted in between 1" Al layers

Film on contact



2X mag - Film 30"
away



Heavy use of Monte Carlo (MCNP)

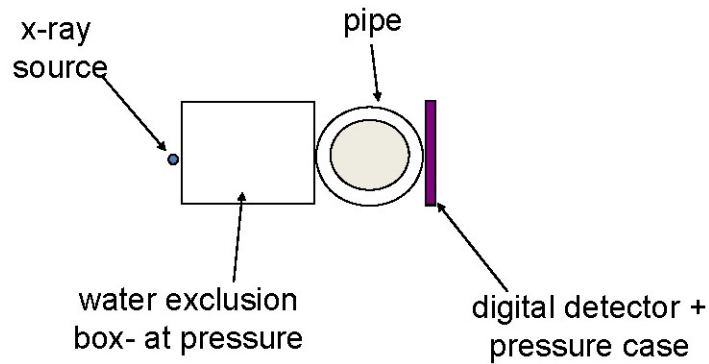
image interpretation

equipment design

sensitivity assessment



Top view – underwater radiography X-ray modeling result



Inspection Issues Discussed

Limited removal of insulation

UT/EC pigs require shut down

Radiography with no shut down
scattering an issue

45% pipe presently uninspectable

Inspection Sensitivity Goal

present

$3T \times 3T \times 10\%T$ t = wall thickness

Goal

$1T \times 1T \times 10\%T$ t = wall thickness



Inspection Issues Discussed, continued

Erosion wall thinning
insulation
high density concrete
silt covered
up 10,000' depths

Welds
stress cracking
porosity
material properties



Outline

- Overview of the Center for NDE
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quantitative NDE
structural Health Monitoring



Changes in NDE inspections

More complex geometry

New materials

Smaller defects

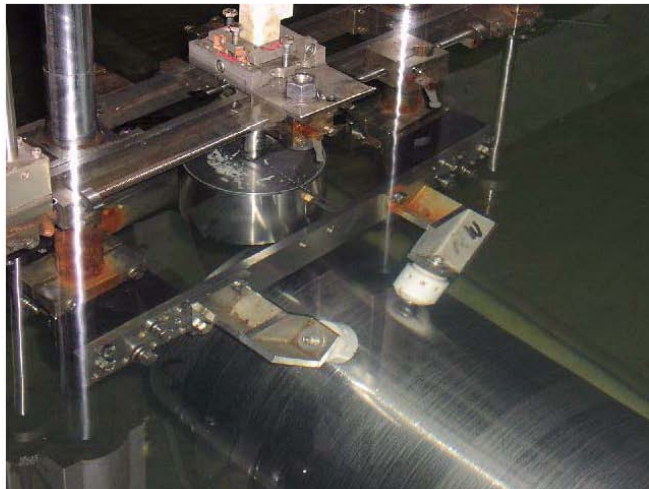
Application of quantitative models

Structural health monitoring



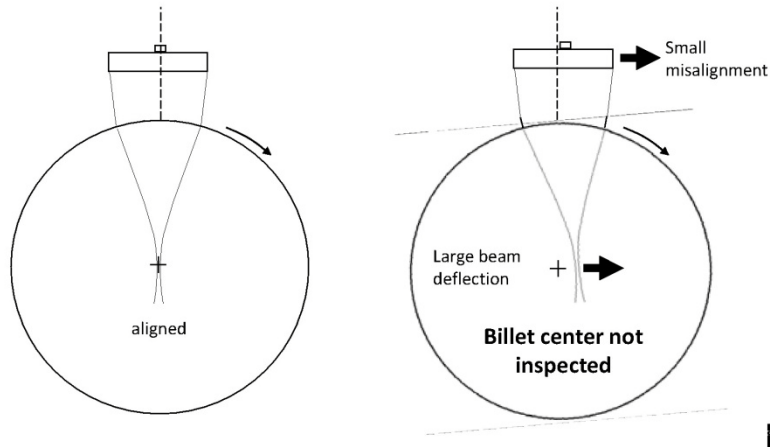
Industry Demonstration At West Penn Testing

April 2010



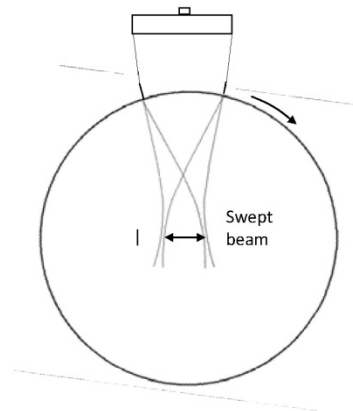
Multi-Zone Drawbacks

- Multiple transducers and electronics are costly
- Alignment procedures costly in time
- Inspection of billet center sensitive to misalignment



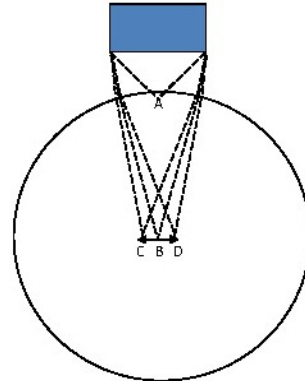
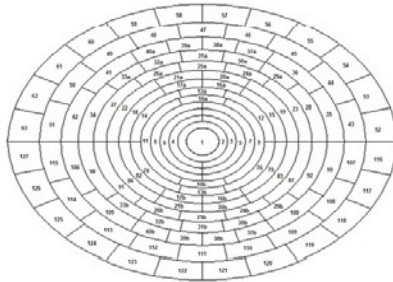
Phased Array Implementation

- Can uniform focus inspection be performed using a single phased array transducer?
- Can beam be electronically swept in angle to assure coverage of billet center?
- Can these things be done using currently available instrumentation?

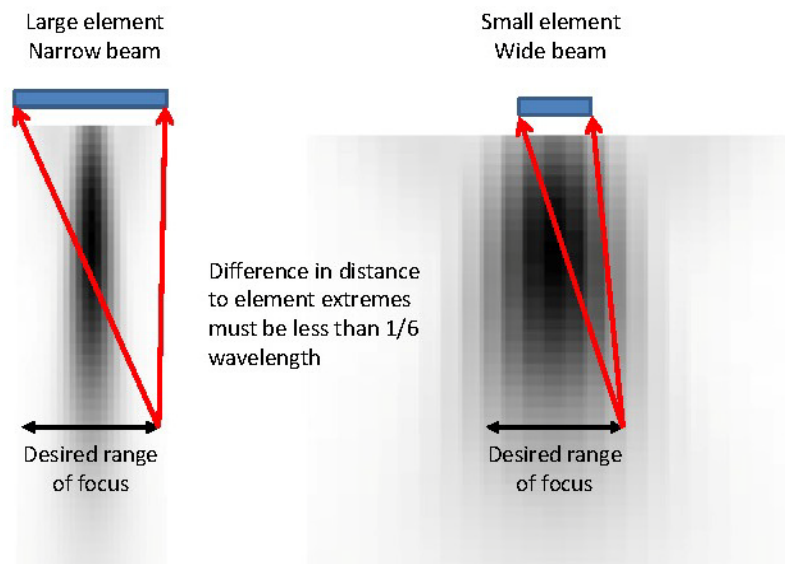


Transducer Element Layout

- Segmented annular array
- Ring boundaries are lines of constant phase to transducer center axis
- Segment rings to assure $<\lambda/6$ phase error to all focal points
 - All focal depths
 - All lateral sweep positions at billet center

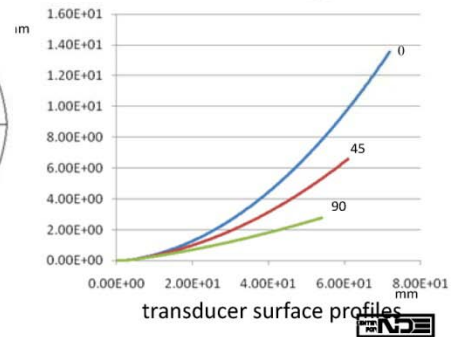
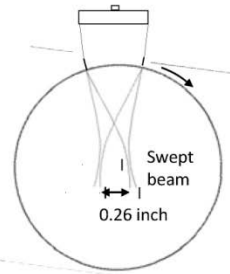
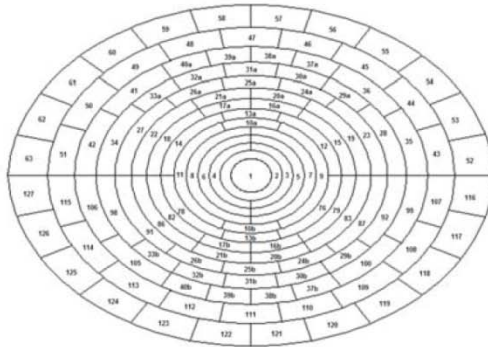
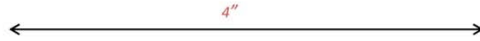


1/6 wavelength phase error criterion



Result

- 32 delay channel system: No
- 64 delay channel system: Yes
 - Can sweep 0.26 inch with $< \lambda/6$ phase error at all focal points

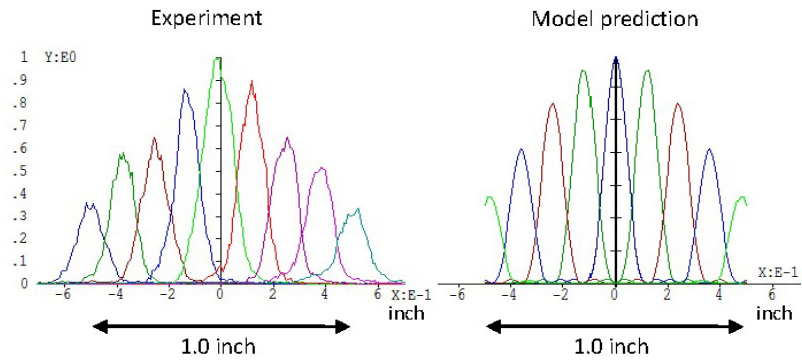


- 9 focal laws for sweeping beam loaded into Focus unit
- Focused transmitter scanned over back of chord block
- Reception response of each focal law recorded
- Scan covers 1.41 x .472 inch: beam swept over one inch



NDE

Measured Back Wall Beam Profiles

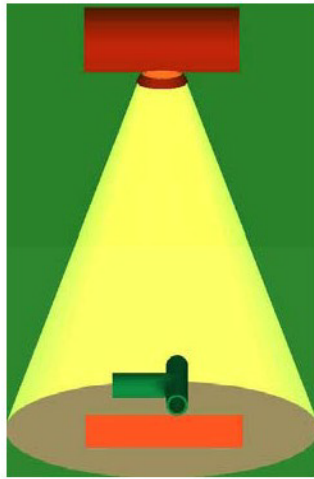


Result

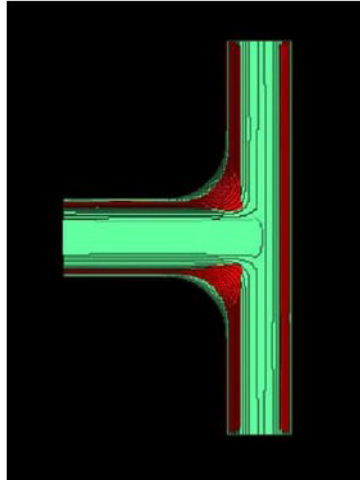
- Replaced 6 independent UT transducers
- Shorter set up time for alignment
- Addressed sensitivity to alignment
missed large defect reduced
- Application of NDE models to
design optimal transducer
predicted output

ENDE

Landing Gear Inspection Optimization



Setup Configuration



Detectability Map



- Coverage is a key issue for this part.

- Detectability for a 1 mm defect

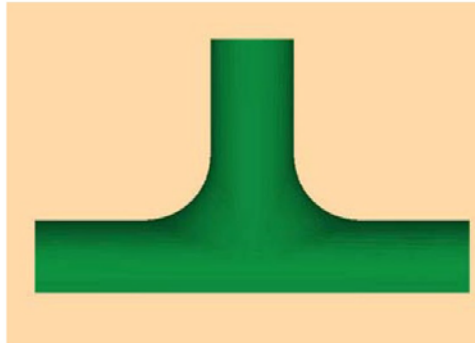
green high detectability
red low detectability

- Detectability criteria is
contrasts higher than 0.08 are
easily detected

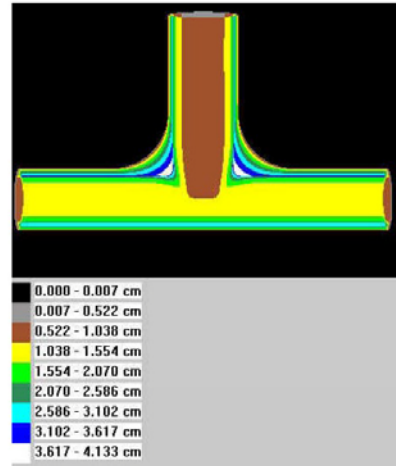
$$D_{\text{flaw}} - D_{\text{background}} = \text{contrast}$$



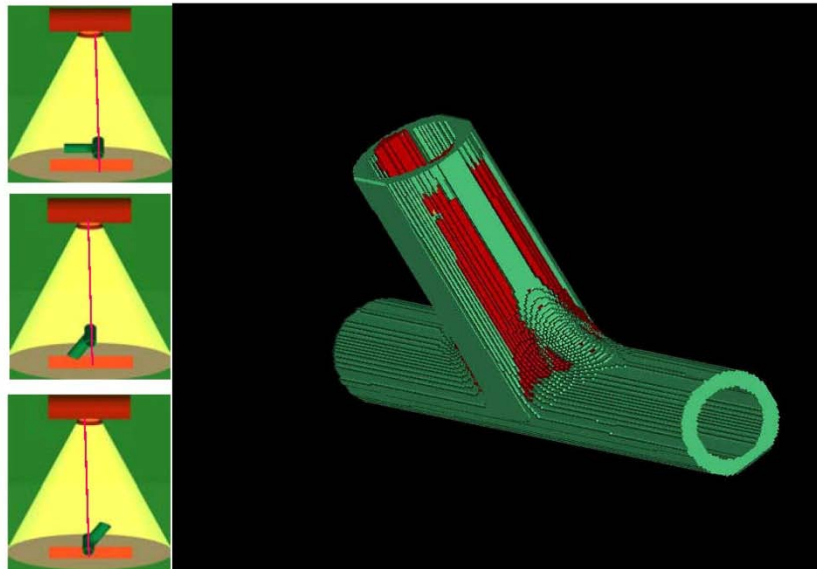
Coverage Optimization



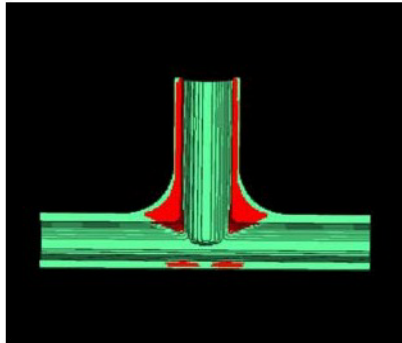
Cad Model



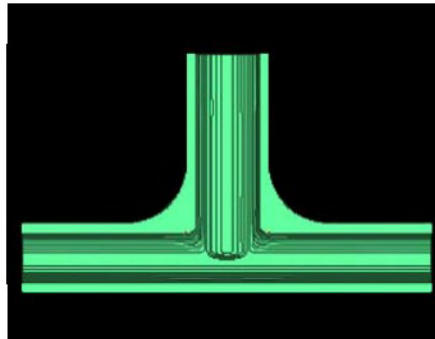
Projection Thickness Map



Effect of exposure Parameters



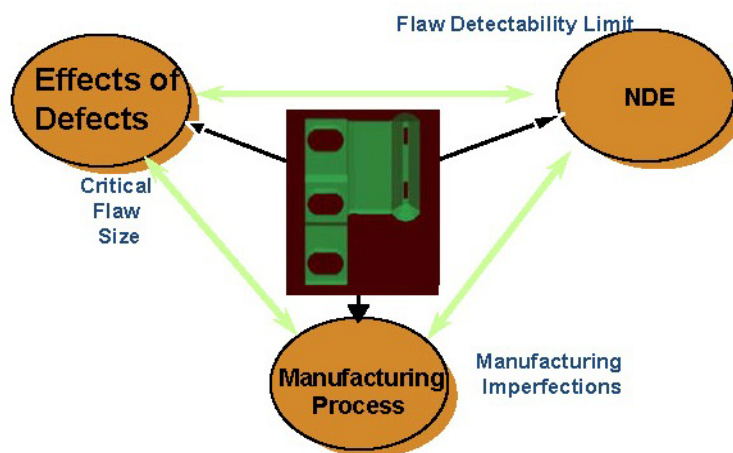
Cross Section of three views
0 120 and 240 degrees



Higher kVp to penetrate
thick areas



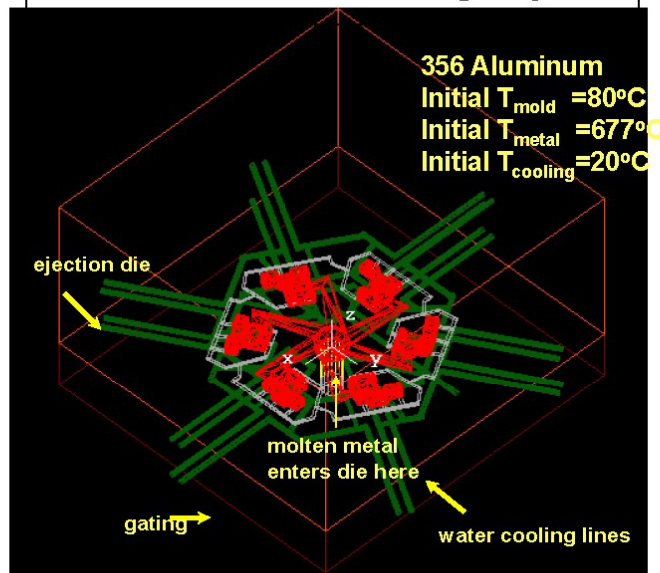
Overview of Accept/Reject Criteria





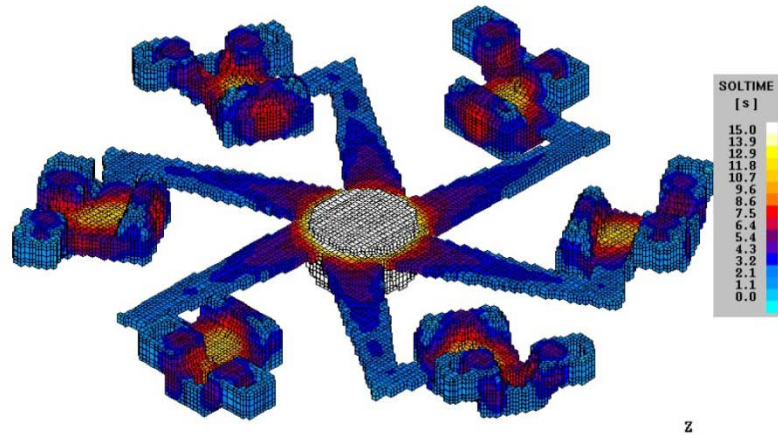
FNDE

Permanent Mold Tooling Layout:



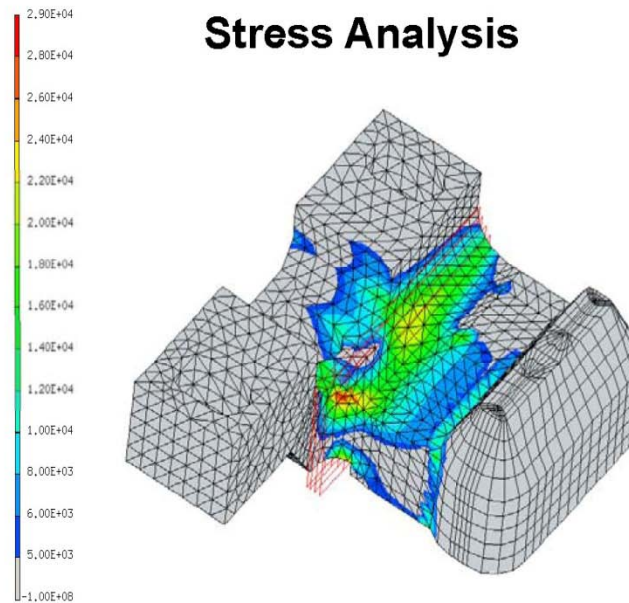
FNDE

Local solidification time (sec)

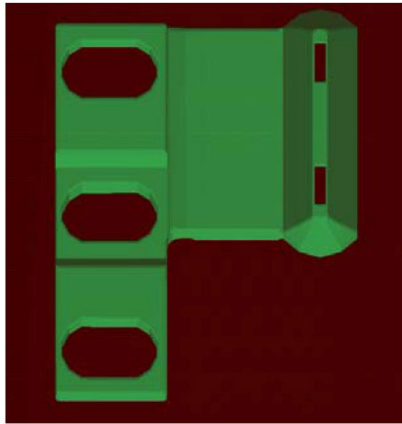


END

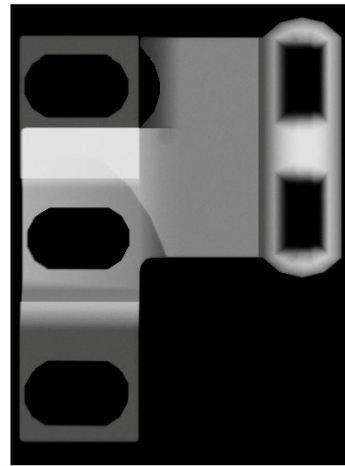
Stress Analysis



END



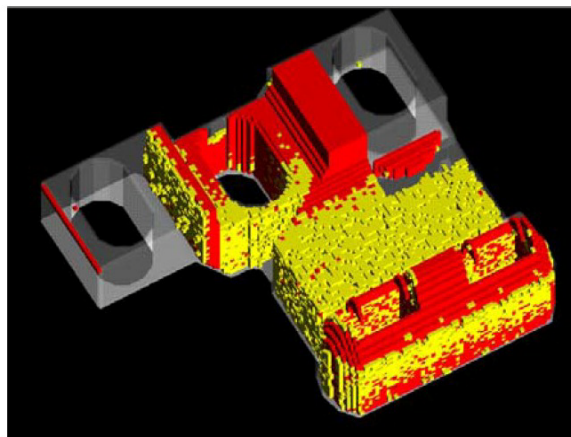
CAD model of
motor mount casting



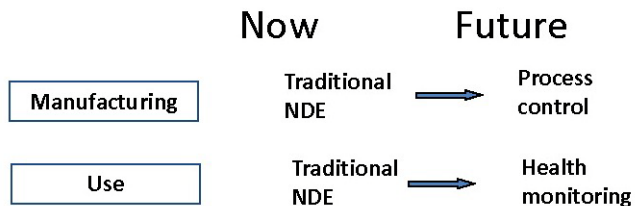
Simulate X-ray
with defect



3D POD Map of 0.4mm Flaw



Economic Forces Are Driving a Transition



KEY QUESTION:
How great will be transition be?



NASA Drivers for a Computational Simulation Assisted Estimate of POD

- Reduce validation cost
- Reduce time required for validation
- Validation of in-space inspections
- Rapid comparison of different methodologies for particular application – pretesting down select of methods
- Optimization of techniques for particular requirements
- Identification of critical inspection parameters
- Assessment of automated flaw detection methodologies
- Optimization of data reduction techniques
- Sanity check on technique claims

56

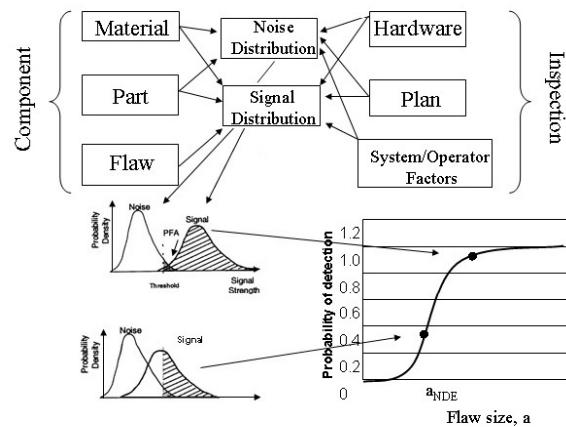


NASA Desired Products – Simulation Based POD Estimate

- Establish validated procedures for simulation based estimation of POD (Handbook)
 - Generalized flaw
 - Complex structure
- Validated simulations for widely applied techniques
- User friendly packages for POD estimation



• Full Model-Assisted Approach (FMA)



Condition-Based Maintenance (CBM)

- Current NDE very effective at assuring safety
- However, economic pressures encourage other options
 - Periodic inspections are costly and can increase down time during outages
- Continuous monitoring of condition seen as an attractive complement



Condition-Based Maintenance (CBM)

- Similar ideas are being developed in other industries under a variety of names
 - SHM
 - Material state awareness
 - Prognosis



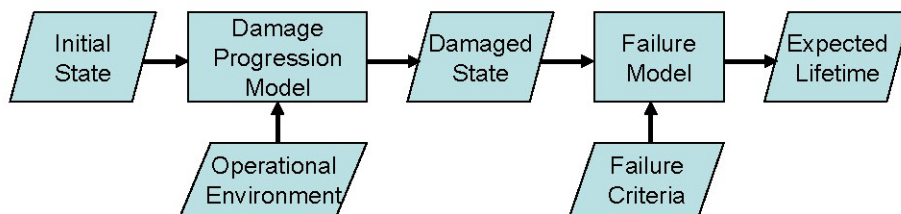
Terms and Strategies Still Being Defined

An Air Force View is That Structural Health Monitoring includes:

- Structural Models
- Loads and Flight Information
- Structural Damage Sensing (SDS)
- Reliability manager to integrate data from the above three components



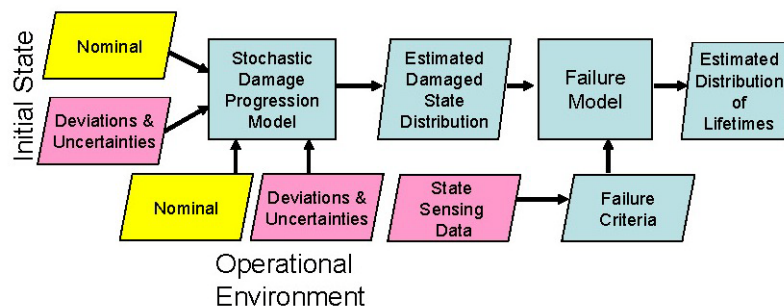
Ideal, Deterministic View of Life Prediction



- The information available is not sufficient to make a deterministic prediction of life
 - We do not know all of the inputs
- A rationale approach to managing uncertainty is required
- Must develop a stochastic strategy that includes various stages of noninvasive sensing and their uncertainties



Stochastic View of Life Prediction



- The prior contains our knowledge about the materials state that is expected to be present
 - In one way or the other, we often make such assumptions in a less formalized way
 - “If the defect were a crack, it would have the following size”
- We use the measurement results to determine which of those possible states are most consistent with the data
 - In essence, ruling out the portions of the prior distribution that are inconsistent with the observations
- The posterior is the sharpened distribution of states that emerges



Conclusions

- Significant progress in quantitative NDE
- Validated models
- Applications to increasingly complex inspection issues
- Moving towards engineering base for NDE
- Integration into design and fabrication
- Emergence of structures sustainability and structural damage sensing



Supporting Information for Working Group Discussion

Impact of Material Quality Control on Underwater Welding, Inspection and Reliability

Marcus Cridland, ABS

Review of Standards and Certification for Underwater Welding and Inspection

Rodger D. Holdsworth and Thomas J. Reynolds

Underwater Welding Consumables Development

Valter R. dos Santos, M. J. Monteiro, PUC-Rio, Rio de Janeiro, Brazil

Alexandre Q. Bracarense, UFMG, Minas Gerais, Brazil

Ezequiel C. P. Pessoa, IFET, Minas Gerais, Brazil

Diver/Welder Training and Qualification

W. Jack Couch, Oceaneering International, Inc.

Reliability of Underwater Wet Welding for Offshore Structures

Faustino Perez, Instituto Mexicano del Petroleo

Pingsha Dong, University of New Orleans

Stephen Liu, Colorado School of Mines

Opportunities for Improving Underwater Inspection, Repair and Reliability Analysis

David L. Olson, Zach S. Jones, A. Al Abdullah, Juan C. Madeni, and Stephen Liu,

Colorado School of Mines, Center for Welding, Joining and Coatings Research

The Role of Performance Demonstration Initiatives to Qualify NDT Methodologies and Inspectors for In-Service Inspections using Risk Based Inspections Structural Integrity Management

Lawrence Goldberg, Sea Test Services

Peter W. Marshall, Moonshine Hill Proprietary

RBI for Fatigue Life Extension of Fixed Platforms

Peter W. Marshall, Moonshine Hill Proprietary

Inspection Technologies for Offshore Facilities at Saudi Aramco

Faisal Al Abbas, Saudi Aramco

Impact of Material Quality Control on Underwater Welding, Inspection and Reliability

Marcus Cridland – ABS

Underwater Welding Presents Unique Challenges for Classification Societies

Evaluation of the adequacy of underwater welds for intended applications is complicated and requires appraisal of achievable weld properties against the category of structure and consequence/likelihood of failure, or in other words risk assessment. When speaking of weld properties consider the “achievable properties.” In the context of this paper achievable properties are not the properties achieved in the welding procedure qualification tests but the properties achieved during the onsite production welding. This by no means attempts to devalue the information obtained in the weld procedure qualification tests, the test information is vital to qualify essential weld parameters. However it should be recognized that an underlining problem is that contractors often meet very different conditions than they have experienced or qualified against in the test laboratories. In addition we are faced with the distinctiveness of each repair. Seemingly no single repair on a ship or offshore vessel replicates a previously accepted repair.

The purpose of the paper is to accompany the white paper, Impact of Material Quality Control on Underwater Welding, Inspection, and Reliability, and to discuss how onsite circumstances could differ from the qualification conditions and influence the quality of the production weld, with particular focus on the importance of metallurgical deviations.

In order to be able to identify how the onsite circumstances can influence the quality of the production weld it is necessary to distinguish between the underwater welding categories:

- Dry welding in a 1 atmosphere cofferdam;
- Dry welding in a hyperbaric chamber; and
- Underwater wet welding.

Dry Welding

Dry welding in a 1 atmosphere cofferdam appears at first glance to be straight forward, the procedure is qualified in air at 1 atmosphere and carried out in air at 1 atmosphere therefore why should there be any additional concerns regarding metallurgy.

Consider situations where dry welding is carried out below the waterline against a water-backing, for example during pitting repairs on ship bottom plating or the replacement of stiffeners against a side shell or other water barrier. With water-backed welding there is a tendency towards reduced elongation and toughness in the weld metal resulting from the relatively rapid quench, in addition there is also the possibility of entrapment of hydrogen. To minimize this tendency, coated low-hydrogen electrodes or low hydrogen welding processes are to be used. Preheating will also reduce the quench effect and remove moisture

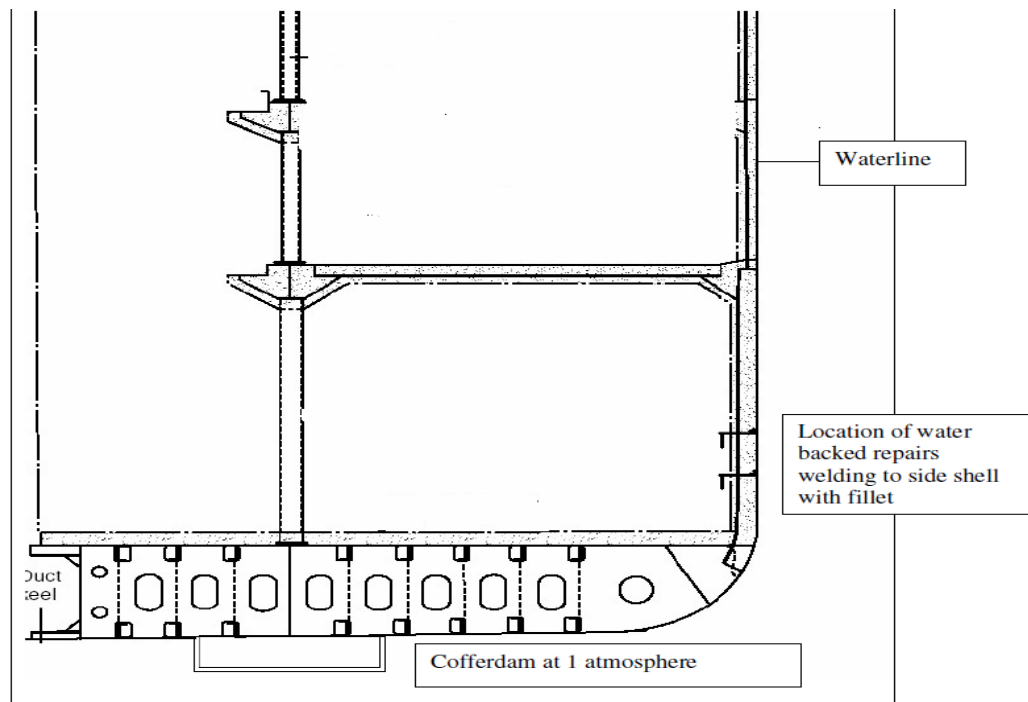


Figure 1. Schematic of weld repairs to ship afloat

The rapid chilling effect of the water-backing has to be incorporated in the qualification of the weld procedure and therefore qualification tests are carried out simulating the rapid cooling. Usual practice is to use a test tank containing agitated chilled water as the water-backing and to qualify the procedure to the material to be welded in production at the minimum thickness, thus simulating the most severe cooling rate.

Problems can develop when the material used in qualification does not fully represent the chemical composition or delivery condition, of the material to be welded. Even if the grade designation of the material used in qualification has the same grade designation of the material to be welded, there can be fluctuations in chemical limits, within the specification limits, that will result in a higher carbon equivalent (CE) than was qualified. It has been found that in such cases a satisfactory WPS during qualification can crack during production welding. This is particularly relevant when water-backed weld repairs are done to aging vessels. Steel production techniques have advanced. The steels rolled today achieve the required mechanical properties by thermal mechanical processes, and are readily weldable, have specified maximum CE (Table 1), and have leaner chemistries than the steels produced to the same grades 15 to 20 years ago, which had no CE limits. Meaning that qualification of a WPS on the steel grade of today is easier than qualification on the same steel grade of the past. This is well understood and efforts are made to obtain steel for qualification that matches the chemistry of the steel to be welded, unfortunately it is sometimes very difficult to obtain steel that has a sufficiently high CE to match the original steel.

Table 1. CE limits in current TMCP ship grade steels from current ABS Rules

Grade	Carbon Equivalent, Max. (%) ⁽¹⁾	
	$t \leq 50 \text{ mm (2.0 in.)}$	$50 \text{ mm (2.0 in.)} < t \leq 100 \text{ mm (4.0 in.)}$
AH 32, DH 32, EH 32, FH 32	0.36	0.38
AH 36, DH 36, EH 36, FH 36	0.38	0.40
AH 40, DH 40, EH 40, FH 40	0.40	0.42

In addition to matching the carbon equivalent the minimum plate thickness and weld size has to be taken into consideration. Procedures should be qualified to a maximum weld size and the minimum plate thickness against the water backing. The aim minimum thickness should be around 12mm, experience has demonstrated that any less than this increases the quenching effect and promotes the likelihood of cracking of the internal weld.

Also consideration needs to be given to the condition and geometry of the existing structure, for example:

- Welding over existing welds seams
- Welding proximity to existing seams
- Cutting through existing weld seams if inserting plate
- Complexity of 3D profile, for cofferdam design and sealing
- Location of internals
- Localized wastage of plate
- Cleaning and grinding
- Damage of coatings

Dry Cofferdam Welding in the Repair of Ships Afloat

It has become more common today, due to lack of available dry dock facilities, to propose repair of shell fractures and supporting structure on the underwater body of ships in the afloat condition.

Fractures are generally repaired in one of two ways, either by cropping and inserting the affected area or by gouging and welding. Both repair methods require the use of divers and some type of cofferdam to allow the repair to take place afloat. The cofferdam size depends upon the size of the affected area to be repaired. Appropriate and appropriately approved welding procedures and welder qualifications are essential. When it is proposed to conduct only one sided welding, the root pass is critical. If the root pass does not achieve proper penetration, then the weld may not be acceptable as a permanent repair. If water-backed welding is proposed then the qualification against water-backing is required.

The reason for the fracture or repair is to be determined, and past repair history of the vessel is to be examined, to see if similar fractures have occurred and how they were dealt with. If the fracture is a result of fatigue, then gouging and welding without modifying the structure (i.e., changing the reason for the fracture) will not always result in a permanent repair as the fracture could reoccur.

A step by step repair plan should be produced that covers all aspects of the repair including condition of the ship, NDT, materials, welding procedures and welding qualifications.

The Following Includes Elements of a Typical Repair Plan

Ship in a sagged or hogged condition. Generally the fractured area should be in compression. Whether to ensure a hog or a sag condition depends on the fracture location and orientation.

Drill stopping the ends of fractures.

Threshold for inserting versus gouge and re-weld. Influenced by the size of damaged area, as there are limitations on size of cofferdams, and vessel's previous repair history.

Repair Guidelines In general welding and repairs should be in accordance with applicable Rules, IACS Recommendation 47 Shipbuilding and Repair Quality Standard Part B, applicable IACS Guidelines for Surveys.

The repair plan should detail the sequence of the repair welding.

Removing and replacing internals.

Backing bars can be applied during repairs, but the backing bar should not be left in place for permanent repairs.

NDT pre-repair to locate ends of fractures.

NDT during repair, after gouging, to confirm fracture removal.

NDT of the root pass.

NDT post repair PT or MPI and UT from inside and outside.

There have been many repairs carried out in the shipping and offshore industry, and provided the repair is well planned, safe and successful repairs can be achieved.

Dry Welding in a Hyperbaric Chamber

Hyperbaric chamber welding is carried out at a pressure equal to the hydrostatic head at the depth of welding. The elevated pressure and the type of gas used in the chamber affects the weld quality in a number of ways and selection of gas combinations and weld processes has to be done carefully to suit the material to be welded at the depth to be welded.

The common chamber gas combinations below each have their specific traits and applications:

Air Nitrogen and Oxygen can only be used at low pressures near the splash zone, higher pressures are explosively dangerous and can cause porosity in the weld and Nitrogen absorption will reduce ductility.

Argon Has a low thermal conductivity which slows the weld cooling rate, but at high pressure has a narcotic effect.

Helium Helium and Oxygen is used at depths greater than 150 feet, it is not explosive and can be breathed by divers, but the high thermal conductivity increases the cooling rate.

The White Paper refers to interesting studies whereby chemical elements are lost or gained in the weld metal at different pressures. The graph is indicated below in Figure 2.

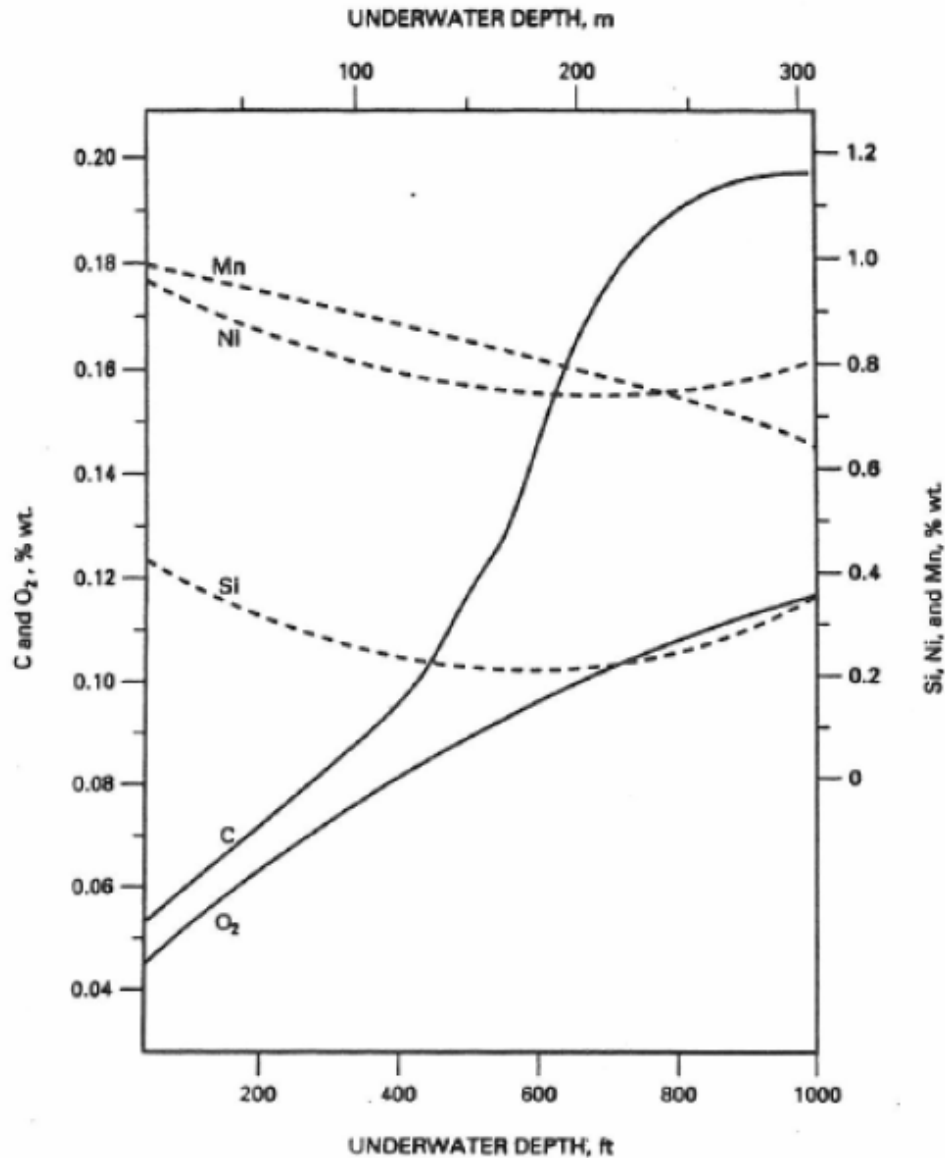


Figure 2 Chemical composition of various elements/gases in weld metal versus water depth (Reference 14 of white paper)

Of particular interest is the percentage increases in Carbon and Oxygen and reduction in Silicon and Manganese. The increase in Oxygen produces high porosity and loss of toughness and the Carbon pickup results in increased susceptibility to cracking. Coupled with this is the loss of Silicon and Manganese which decreases strength and hardenability. With such pronounced increases in Carbon and

Oxygen it becomes even more important to know the actual chemistry and delivery condition of the steel to be welded and to have a full understanding of the environment, and not rely upon material specification values. The qualification test pieces need to closely match the chemistry of the material to be welded, otherwise problems with loss of ductility and strength, and cracking can occur.

Underwater Wet Welding

Underwater wet welding as the term indicates is welding directly exposed to the wet environment. There is no need for an expensive chamber and the versatility and freedom makes wet welding an appealing process for repairs of underwater structures. The limitation of the wet welding process, is that the welds produced are usually poor quality when compared with dry habitat welds. This means that the application of wet welds is limited to low risk locations that would not compromise the structure. There has been many attempts and studies made to investigate and improve the quality of wet welds, but the process is sensitive to the environment, the joint type, base metal chemistry and physical properties, the fit-up and process instabilities. The white paper, Impact of Material Quality Control on Underwater Welding, Inspection, and Reliability, explores some of the challenges and adverse characteristics of wet welding. One particular prevalent attribute of underwater wet welding that is apparent, is that underwater wet welding it is not as well understood as dry welding and consequently to move forward industry needs to better comprehend the metallurgical reactions occurring in the wet welding process.

The Fundamental Obstacles

Quenching

The rapid quenching of the weld metal by the surrounding water does increase tensile strength but at a price, it also increases hardness beyond acceptable levels. Even with base metal CE of 0.40% the Vickers hardness at the fusion line will be in excess of 400. Furthermore high levels of martensite are produced in the coarse grained HAZ, which is susceptible to hydrogen cracking.

The ductility and elongation of the weld are reduced. Elongation values are expected to be at least 14% for wet welds.

Impact strength of the weld is reduced when compared with dry welds, in addition as depth increase impact values decrease.

Porosity can form from gas entrapment, supersaturation of dissolved gasses or gas-producing reactions, it increases with water depth, and if not controlled the mechanical properties of the weld will be reduced.

Residual stress resulting from rapid contraction leads to regions of high tensile stress which intern affects fracture behavior.

Hydrogen Embrittlement and Cracking

A large amount of hydrogen is present in the weld pool, resulting from dissociation of the water vapour in the weld arc. Hydrogen in the weld pool diffuses in to HAZ, which can cause embrittlement and cracks in steels with CE of 0.40% especially where a susceptible martensitic microstructure exists.

Tensile stress and residual stress will further promote cracking.

Cracks can grow and may result in catastrophic failure.

Poor Visibility

Another obvious hurdle is poor visibility. The quality of the weld relies heavily upon the welders skill. If the welder cannot see then it is likely the welder will not be able to produce a reasonable weld.

Wet Welding, Other Inherent Difficulties

Fit-up tolerances must be controlled. Wet welding does not close gaps well.

Position of welding can adversely affect the weld.

Arc is disrupted by bubbles created during welding (overhead position).

Bead shape defects can arise from the rapid cool.

Entrapment of slag can be increased because of the rapid cool and depth.

Weaving can result in interposes weld defects.

Micro Cracks can exist that require 400X magnification to be detected.

High levels of Oxygen 2000 ppm in the weld lead to element loss. Figure 2.

Carbon pickup.

Rapid quenching of weld stops results in hard spots and hydrogen cracking.

Corroded plate affecting joint fit-up and thickness variation.

Wet welding can produce stray currents, leading to corrosion.

Acceptable welding parameter ranges narrow, as pressure increases. Figure 3.

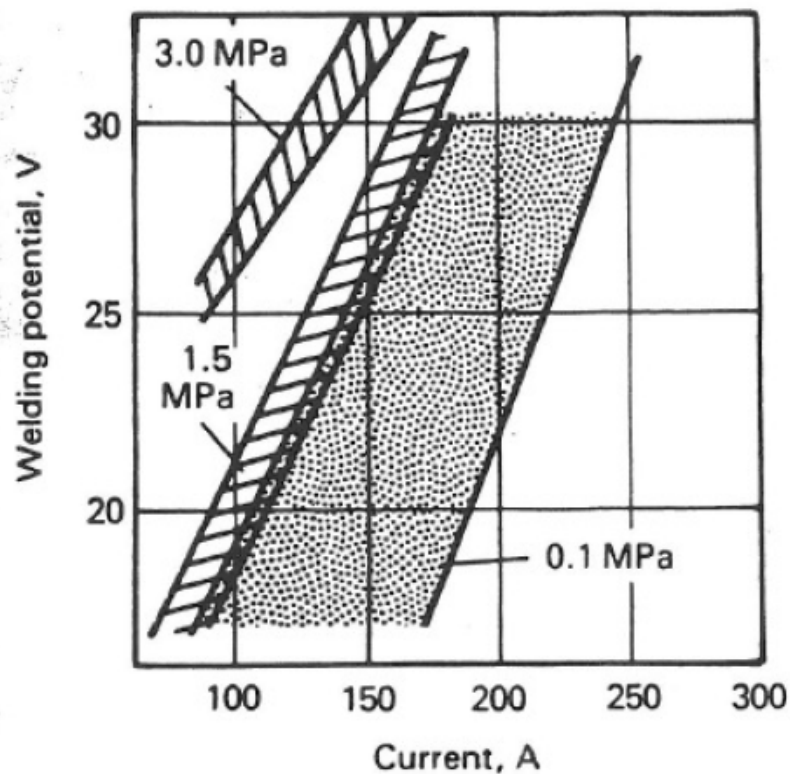


Figure 3. Acceptable Welding Parameter Regions for Various Pressures
(Reference 24 of white paper)

Much work has been done to try to overcome the obstacles presented above and effective measures have been taken to produce favorable microstructures, reduce the chance of hydrogen cracking, limit porosity, and reduce residual stresses. Measures discussed within the white paper include electrode selection and electrode coating, selecting weld parameters, designing low stress joints, using small weld deposits, applying high heat input procedures, use short arc lengths, and applying temper beads.

Recent work has also been done in trying to understand the metallurgical reactions in wet welding, the white paper discusses that in wet welding, there are three types of ferrite that may form: grain boundary ferrite, Widmanstatten or sideplate ferrite, and acicular ferrite.

Microstructures of wet welds containing grain boundary ferrite and/or Widmanstatten ferrite typically have poor mechanical properties.

Acicular ferrite is recognized as the micro structural constituent giving the highest resistance to cleavage fracture and it is discussed that a way to improve the metallurgical and mechanical properties of wet welds is by promoting a high percentage of acicular ferrite in the weld microstructure, by additions of titanium, zirconium and boron.

It is clear that to achieve satisfactory welds with underwater wet welding many additional factors need to be taken into account in producing a suitable WPS, the qualification of the WPS as with the dry welding needs to be suitable for the application, the joint and the environment in which it will be applied.

It is even more important with wet welding to be sure that the material used in qualification fully represents the chemical composition, mechanical properties and delivery condition of the material to be welded. As previously discussed in this paper, even if the grade designation of the material used in qualification has the same grade designation of the material to be welded there can be fluctuations in chemical limits, within the specification limits, that will result in a higher carbon equivalent (CE) than was qualified. This is very apparent when welding older steels with the same grade designation as modern steels.

The CE limit of 0.40% is not particularly high and many existing aging structures will have steel with CE percentages pushing this limit or even above it, and there seems little point to qualifying an unrepresentative procedure on lower CE steel and applying this to high CE steel.

Hopefully with research directed at trying to improve the mechanical properties of wet welds by improving their metallurgical properties, the industry will gain a better understanding of the metallurgical reactions occurring in wet welding.

There have been many reported success stories in applying wet welding to structural members however because of the questionable quality and quality consistency of wet welds, currently the industry still considers wet welds as temporary.

Review of Standards and Certification for Underwater Welding and Inspection

Rodger D. Holdsworth, Chevron

Thomas J. Reynolds, Global Divers & Contractors

1.0 ABSTRACT

This paper outlines the current standing of standards related to Underwater Welding; revisions to the recent 2010 edition of the AWS D3.6 Underwater Welding Code; and a discussion on Marine Industry needs related to Underwater Welding and Inspection.

Further developments on standards, specifications and codes for underwater welding and inspection were addressed in the 1994 International Workshop on Underwater Welding of Marine Structures. Sessions held at this workshop discussed effective consensus standard organization attributes of committees responsible for maintaining International Underwater Welding Standards and key elements that are generally included. Working Group discussions held at this workshop also captured the State-of-the-Art, at the time, in design, workmanship, technique, qualification, inspection, testing and quality assurance and also generated a number of questions for Committees to consider when developing future editions of Underwater Welding Standards.

Since 1994 both the State-of-the-Art of Underwater Welding and the content of Underwater Welding Standards has improved. This paper captures the improvements made, provides answers to many of the questions captured in the 1994 workshop and introduces new questions that Industry and Regulators have related to advances in processes, technology, consumables, materials, inspection and testing requirements and more.

Lastly, this paper includes provision to capture “Marine Industry Needs” to facilitate providing useful information to those responsible for updating and maintaining offshore Inspection and Testing and Underwater Welding Standards.

2.0 INTRODUCTION

The number and category’s Worldwide standards for Underwater Welding have remained relatively unchanged over the last 15 years with the exception of a new Specification for Wet Welding Electrodes for Shielded Metal Arc Welding currently being balloted by AWS.

Efforts to align requirements from one standard to another are ongoing but challenging considering the differences between Standards Organization requirements such as ISO, AWS and others. The AWS D3.6 has transitioned from a Specification to a Code standard for the 2010 edition and remains the leading International Underwater Welding performance standard to date with an active international membership.

Advances in standards include guidance and commentaries on best practice, safety, technique, design, sample Underwater Welding procedure and welder qualification forms and more. Though there have been significant improvements, there are a number of areas that require further development including Safety, Marine Certified Welding Inspector (MCWI) qualification requirements, Diver Welder training guidelines, Quality Control of Underwater Welding Processes, Ship Husbandry and other marine

application needs. There have also been a number of lessons learned over time that have sparked advances in design, equipment, methods, consumables, etc. that have yet to be addressed in current Underwater Welding Standards.

This paper is intended to outline the current status of Underwater Welding Standards and provide sufficient information that can be used by committees responsible for developing and maintaining Underwater Welding Standards.

3.0 UNDERWATER WELDING STANDARDS

3.1 ISO

ISO standards for Underwater Welding are developed and maintained by the ISO Technical Committee ISO/TC 44, *Welding and allied processes*. Current state of the art of underwater welding will require updating the below listed standards to include additional provisions for design, workmanship, technique, qualification, inspection, testing and quality assurance unique to underwater welding. It is recommended that TC-44 enlist a Work Group of qualified subject matter specialists to work in collaboration with the AWS D3b Subcommittee on Underwater Welding to align the requirements and maintain consensus in international Underwater Welding Standards.

3.1.1 15614-10-2005 Specification and qualification of welding procedures for metallic materials – Welding procedure test. ISO 15614 is made up of the following standards.

- Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys
- Part 2: Arc welding of aluminum and its alloys
- Part 3: Arc welding of cast iron
- Part 4: Finishing welding of aluminum castings
- Part 5: Arc welding of titanium, zirconium and their alloys
- Part 6: Arc welding of copper and its alloys
- Part 7: Overlay welding
- Part 8: Welding of tubes to tube-plate joints
- Part 9: Arc underwater hyperbaric wet welding
- Part 10: Hyperbaric dry welding
- Part 11: Electron and laser beam welding
- Part 12: Spot, seam and projection welding
- Part 13: Resistance butt and flash welding

The ISO 15614 Part 10 specifies how to qualify welding procedure specifications for welding in hyperbaric dry environments and the minimum testing requirements necessary for qualification of welding procedures for both mechanized and automated welding. The application of Part 10 also requires the following normative standards:

- ISO 4063, Welding and allied processes – Nomenclature of processes and reference numbers
- ISO 6947, Welds – Working positions – Definitions of angles of slope and rotation
- ISO 14175, Welding consumables – Shielding gases for arc welding and cutting
- ISO 15607:2003, Specification and qualification of welding procedures for metallic materials – General rules

- ISO 15609-1, Specification and qualification of welding procedures for metallic materials – Welding – procedure specification – Part 1: Arc welding
- ISO 15618-2, Qualification testing of welders for underwater welding – Part 2: Diver-welders and welding – operators for hyperbaric dry welding
- EN 288-9, Specification and approval of welding procedures for metallic materials – Part 9: Welding – procedure test for pipeline welding on land and offshore site butt welding of transmission pipelines

3.1.2 15618.2 – 2001 Qualification testing of welders for underwater welding – Part 1: Diver-welders for hyperbaric wet welding.

The ISO 15618-1 standard was prepared by the European Committee for Standardization (CEN) in collaboration with Technical Committee ISO/TC 44, *Welding and allied processes* and Subcommittee SC 11, *Approval requirements for welding and allied processes personnel*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement) to establish the requirements for hyperbaric wet welding. The ISO 15618-1 standard requires the following Normative standards:

- EN 288-1
Specification and approval of welding procedures for metallic materials – Part 1: General rules for fusion welding
- EN 288-2
Specification and approval of welding procedures for metallic materials – Part 2: Welding procedure specification for arc welding
- EN 499
Welding consumables – Covered electrodes for manual metal arc welding of non alloy and fine grain steels – Classification
- EN 571-1
Non destructive testing – Penetrant testing – Part 1: General principles
- EN 910
Destructive tests on welds in metallic materials – Bend tests
- EN 970
Non-destructive examination of fusion welds – Visual examination
- EN 1290
Non-destructive examination of welds – Magnetic particles examination of welds
- EN 1320
Destructive tests on welds in metallic materials – Fracture test
- EN 1321
Destructive tests on welds in metallic materials – Macroscopic and microscopic examination of welds
- EN 1435
Non-destructive examination of welds – Radiographic examination of welded joints
- EN 1714
Non destructive examination of welds – Ultrasonic examination of welded joints

- EN ISO 4063
Welding and allied processes – Nomenclature of processes and reference numbers (ISO 4063:1998)
- prEN ISO 5817
Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections (ISO/DIS 5817:2000)
- EN ISO 6520-1
Welding and allied processes – Classification of geometric imperfections in metallic materials – Part 1: Fusion welding (ISO 6520:1998)
- EN ISO 6947
Welds – Working positions – Definitions of angles of slope and rotation (ISO 6947:1993)
- CR ISO 15608
Welding – Guidelines for a metallic material grouping system (ISO/TR 15608:2000)
- ISO 857-1
Welding and allied processes – Vocabulary – Part 1: Metal welding processes

In addition to the above listed Normative standards the ISO 15618-1 standard provides general guidelines for Underwater Wet Welding including Essential Variables for Approval Testing, Range of Approval, Examination and Testing, and Acceptance Requirements for Test Pieces.

3.1.3 15618.2 – 2001 Qualification testing of welders for underwater welding – Part 2: Diver-welders and welding operators for hyperbaric dry welding

The ISO 15618-2 standard was prepared by the Technical Committee CEN/TC 121 "Welding," the secretariat of which is held by DS, in collaboration with Technical Committee ISO/TC 44 "Welding and allied processes" to establish the requirements for hyperbaric dry welding. The ISO 15618-2 standard requires the following Normative standards:

- EN 499
Welding consumables – Covered electrodes for manual metal arc welding of non alloy and fine grain steels – Classification
- EN 571-1
Non destructive testing – Penetrant testing – Part 1: General principles
- EN 910
Destructive tests on welds in metallic materials – Bend tests
- EN 970
Non-destructive examination of fusion welds – Visual examination
- EN 1290
Non-destructive examination of welds – Magnetic particles examination of welds
- EN 1320
Destructive tests on welds in metallic materials – Fracture test
- EN 1321
Destructive tests on welds in metallic materials – Macroscopic and microscopic examination of welds

- EN 1418
Welding personnel – Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials
- EN 1435
Non-destructive examination of welds – Radiographic examination of welded joints
- EN 1600
Welding consumables – Covered electrodes for manual metal arc welding of stainless and heat resisting steels – Classification
- EN 1714
Non destructive examination of welds – Ultrasonic examination of welded joints
- EN ISO 4063
Welding and allied processes – Nomenclature of processes and reference numbers (ISO 4063:1998)
- prEN ISO 5817
Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections (ISO/DIS 5817:2000)
- EN ISO 6520-1
Welding and allied processes – Classification of geometric imperfections in metallic materials – Part 1: Fusion welding (ISO 6520:1998)
- EN ISO 6947
Welds – Working positions – Definitions of angles of slope and rotation (ISO 6947:1993)
- CR ISO 15608
Welding – Guidelines for a metallic material grouping system (ISO/TR 15608:2000)
- ISO 857-1
Welding and allied processes – Vocabulary – Part 1: Metal welding processes
- ISO 3581
Covered electrodes for Manual arc welding of stainless and other similar high alloy steels – Code of symbols for identification

In addition to the above listed Normative standards the ISO 15618-2 standard provides general guidelines for Underwater Dry Welding including Essential Variables for Approval Testing, Range of Approval, Examination and Testing, and Acceptance Requirements for Test Pieces.

3.2 AWS

3.2.1 AWS 3.6 Underwater Welding Code, 2010 Edition

The D3.6 Underwater Welding Code was prepared by the D3b Subcommittee on Underwater Welding, in collaboration with the AWS D3 Committee on Marine Construction. The first edition of the standard was published in 1983 as a Specification, with subsequent editions issued in 1989, 1993 and 1999.

The 2010 edition, the AWS D3.6 has transitioned from a Specification to a Code Standard to facilitate elevating it as a recognized and adopted consensus standard by both marine industries and governing authorities worldwide as industry accepted practice for Underwater Welding Operations. AWS defines a Code as: A code is intended to be a mandatory document. It includes a set of conditions and requirements relating to a specific subject. A code describes industry-accepted procedures by which it can be determined that the requirements have been met. It is written to make it suitable for adoption by

governmental entities, trade groups, insurance companies, and other authorities as a part of a law or regulation or cited as a normative reference in other standards.

... whereas an AWS Specification is defined as:

A specification details, using the prescriptive shall, the essential technical requirements for a material, product, system, or service. It specifies the procedures, methods, qualifications, or equipment by which it can be determined that the requirements have been met. A specification is mandatory when cited as a normative reference by a mandatory document or agreed to be mandatory by the concerned individuals or agencies, such as when used for procurement purposes.

Significant updates have been incorporated in the 2010 AWS D3.6 Code edition including:

1. Overall changes to Code Language aligned with International criteria (e.g. metric units, international terms / definitions, ISO Normative References vs AWS, ANSI, ASTM and more)
2. The Class C designation for welds that are not load bearing has been dropped from the D3.6M:1999 edition, Clause 9 and related references have been deleted.
3. Arc voltage is no longer an essential variable for the qualification of dry SMAW WPSs (Table 5.1).
4. The maximum depth qualified for dry welding has been increased to the qualification test depth plus 20 m (66 ft) (Table 5.3).
5. Welders qualified using PG(3G or 3F) or PF(3G or 3F) are no longer qualified for horizontal position (H) production welding (Table 5.5).
6. Heat Affect Zone (HAZ) Charpy Impact (CVN) testing is no longer a requirement for wet welding procedure qualification for Class B welds (Tables 8.1 and 8.2).
7. Updates to all sections design, workmanship, technique, qualification, inspection, testing, quality assurance and commentary / guidance.

3.2.2 AWS A5.35/A5.35M Specification for Wet Welding Electrodes for Shielded Metal Arc Welding.

The A5.35/A5.35M Specification for Wet Welding Electrodes for Shielded Metal Arc Welding was prepared by the D3b Subcommittee on Underwater Welding, in collaboration as a Subcommittee to the AWS A5 Committee on Filler Metals and Allied Materials. The specification is the first edition for classification of electrodes developed for shielded metal arc welding underwater, in the wet, with no mechanical barrier between the water and the welding arc. The specification covers for ferritic, austenitic stainless steel, and non-ferrous filler material, including any auxiliary coatings applied over the electrode covering.

The A5.35/A5.35M Specification represents a significant leap forward in the formal classification of electrodes including application of auxiliary coatings. Prior to the introduction of this standard there were no formal means to certify that specialty electrodes used in wet welding operations were in accordance with formal requirements for classifying electrodes used for this purpose. The integrity of wet welding electrodes was often scrutinized and in some cases considered a “black art”.

The Specification includes provision for classification, acceptance, certification, rounding off procedure, auxiliary coating integrity, tests, retesting, additional requirements for weld tests, method of manufacture, electrode identification, electrode lot identification and marking of packages. The

Specification also includes a guide to correlate the electrode classifications with their intended applications.

3.2.3 Welding Handbook – Volume 4, Chapter 10 – Underwater Welding and Cutting, 2010

This revised chapter addresses preparation and planning points for underwater welding operations. In this section, welder/diver support and communication techniques are reviewed. Further, the fundamentals of underwater welding are reviewed for the six welding methods addressed in AWS D3.6M:2010. A discussion of weld classes is made by qualifying welding procedures using various welding processes followed with a discussion concerning metallurgical considerations. The consequences of hydrogen pickup as well as methods to mitigate hydrogen buildup are reviewed.

Wet welding case histories are presented using various filler metals, depths, environmental conditions and welding techniques. Wet and dry welding mechanical and metallurgical properties are also discussed and compared. Finally safety aspects of underwater welding are discussed as well. This chapter is an ideal starting point for engineers that will be involved with the planning and execution of underwater welding activities.

3.3 Military

3.3.1 S0300-BB-MAN-010 U.S. Navy Underwater Cutting and Welding Manual

The S0300-BB-MAN-010 U.S. Navy Underwater Cutting and Welding Manual was prepared by the U.S. Department of the Navy, Naval Sea Systems Command for military underwater cutting and welding applications. It is written for the U.S. Navy diver who specializes in ship salvage and harbor clearance operations. Although this manual is not a procedural guide for certifying welding used in pre-planned underwater ship husbandry applications it does provide long established insight to safety, personnel qualifications, technology and processes used in underwater cutting and welding operations.

3.3.2 S9086-CH-STM-010/074V1R5 Navel Ship Technical Manual, Chapter 074 – Volume 1, Welding and Allied Processes

This document also was prepared by the U.S. Department of the Navy, Naval Sea Systems Command for use by the military when performing underwater welding on naval vessels. Section 074-6.9 *Underwater Welding* defines the different modes of underwater welding and safety requirements. This section further states the requirements for wet and dry chamber hyperbaric welding procedures and maintenance of welding performance qualification personnel.

Inspection, welding, workmanship and third party monitoring and certification procedures are detailed for the user.

3.3.3 Association of Diving Contractors International (ADCI) Consensus Standards for Commercial Diving and Underwater Operations, 4.31 Welding and Burning, Fifth Edition – 2004 (Sixth Edition undergoing public comment period and expected publication is in 2011). The 2004 Edition of this section is very general and addresses several safety aspects of underwater welding.

3.3.4 ASME Section XI, IWA 4660 (Formally Code Case N-516)

ASME addresses underwater repair welding following In service inspection and repairs/maintenance to operating nuclear facilities. IWA 4660 set forth the guideline for qualifying welding procedures and

welders for performance. IWA addresses essential variables specific to underwater welding and then defers to ASME IX for all other variables and requirements.

3.3.5 American Society for Nondestructive Testing – Recommended Practice No. SNT-TC-1A

This recommended practice specifies the requirement for the qualification and certification of personnel in Nondestructive Testing. It only addresses the testing methods being carried out topside. It has been adopted by many diving companies that carry out underwater nondestructive testing. In the qualification and certification guidelines, it addresses Level I and Level II inspectors and their roles and responsibilities.

3.3.6 Certification Scheme for Welding and Inspection Personnel (CSWIP-DIV-7-95-Part 1)

This certification scheme is managed by TWI Certification Ltd and was formed in 1993. TWI Certification Ltd is accredited by the UK Accreditation Service in accordance with EN ISO 17024 “Criteria for certification bodies operating certification of personnel”.

“Requirements for the Certification of Underwater (Diver) Inspectors,” CSWIP-DIV-7-95-Part 1 is similar to SNT-TC-1A with the exception that it specifically addresses diver inspectors. CSWIP has a similar inspector qualification and certification criteria as SNT-TC-1A however they are defined as either a 3.1U Underwater Inspector (SNT-TC-1A Level I) or a 3.2U Underwater Inspector (SNT-TC-1A) except they are diving personnel specific.

3.4 Class Society

Class Society’s typically have internal process instructions for qualification of welding procedures and welders that follow the requirements of AWS D3.6 or other Underwater Welding Standards that apply.

3.4.1 Det Norske Veritas (DNV)

DNV is an independent organization that issues and provides revisions to their standards. DNV receives input from user groups through Joint Industry Projects and workshops that assist in the revision process.

3.4.1.2 DNV-OS-F101 Submarine Pipeline Systems 2007

Appendix C of this standard addresses the criteria for all welding on pipeline applications such as: applications, equipment, tools, personnel, consumables, procedures, examination, testing, Post Weld Heat Treatment, materials and process specific requirements.

Section I of this Appendix, “Hyperbaric Dry Welding,” addresses the following criteria:

- I 100 General Description of application
- I 200 Qualification and testing of welding personnel for hyperbaric dry welding. The subsection addresses the requirements for the Hyperbaric welding coordinator; welder for hyperbaric welding; Training program; Test welding; Qualification testing of welders; Retesting
- I 300 Welding processes for hyperbaric dry welding addressing allowable welding processes
- I 400 Welding consumables
- I 500 Shielding and backing gases
- I 600 Welding equipment and systems
- I 700 Welding Procedures
- I 800 Qualification welding

- I 900 Qualification of welding procedures
- I 1000 Examination and testing
- I 1100 Production Welding requirements

The DNV OS-F101 standard (Appendix C, Section I) make reference to one ISO standard and that is regard to welder performance qualification. The standard is ISO 15618-2, Qualification testing of welders for underwater welding- Part 2: Diver-welders and welding operators for hyperbaric dry welding.

3.4.1.2 DNV-RP-F113 Pipeline Subsea Repair 2007

This document addresses subsea mechanized hyperbaric dry welding by remote operation for fillet or butt welding without personnel required in attendance in the habitat. The recommended practice addressed the following areas:

- Pipeline design basis
- Pipeline exposures
- Installation and attachment to the pipeline
- Welding
- Design
- Testing
- Documentation

3.4.2 Bureau Veritas (BV)

3.4.2.1 Guidance Note 198, Underwater Welding – January 1986, General Information and Recommendations

This document details the requirements for welding procedure qualification and welder performance qualification. It states the criteria for welding inspector qualification, addresses the need for confirmation welds and following up inspection after the work is completed. The next revision, Rev. 1, is pending.

3.4.3 American Bureau of Shipping (ABS)

ABS has no intention of issuing an underwater guidance and recommended practice. ABS refers to AWS D3.6M (current edition) for welding procedure qualifications.

4.0 MARINE INDUSTRY UNDERWATER WELDING AND INSPECTION NEEDS

While standards for underwater welding have advanced, so to have technologies, materials, consumables, design and related work requirements for all facets of underwater construction. Marine Industries are diverse, each made up of distinct characteristics, qualities, or elements unique to the enterprises they serve. The following sections outline both the advances and needs of a variety of industries that apply Underwater Welding and Inspection.

4.1 Common

4.1.1 More guidelines are needed on design for underwater repairs and techniques used in various Marine applications. It is recommended that the AWS D3.6 Underwater Welding Code expand guidelines/commentary.

4.1.2 Need to Develop Marine Certified Welding Inspector (CWI) guidelines to improve the quality of CWI performance on underwater welding and inspection projects. Need to further develop testing criteria and requirements for Marine CWI's.

4.1.3 Need to develop Training / Qualification requirements for underwater welders, inspectors and Marine CWI and define typical industry performance expectations.

4.1.4 Need to expand inspection requirements of current Underwater Welding Standards to include provisions for emerging technology such as Alternating Current Field Measurement (ACFM).

4.1.5 Need to expand provisions current Underwater Welding Standards to include new applications such as Underwater Friction Stud Welding.

4.1.6 Address new training and qualification requirements implemented by the US DOT (Operator Qualification).

4.2 Offshore Oil and Gas – Same as 4.1 Common, no additional needs communicated during the course of the workshop

4.3 Ship Husbandry – Same as 4.1 Common, no additional needs communicated during the course of the workshop

4.3 Nuclear – Need for continued collaboration between regulatory and industry standards related to Underwater Welding in Nuclear Power Plants. Current state of the art submitted below by Jim O'Sullivan, Procon1, LLC, St. Louis, Missouri, September, 2010.

Underwater welding has been implemented in nuclear plants since the 1980's. In 1987, the first major wet underwater repair of a nuclear reactor internal component – a stainless steel steam dryer at PPL's Susquehanna Steam Electric Station – was implemented using the guidance of AWS D3.6. This method of repair significantly reduced the amount of radiation experienced by the welders compared to performing the repairs in a dry environment. The success of this repair gained significant interest, and resulted in numerous similar wet underwater welded repairs of steam dryers for Boiling Water Reactors throughout the world.

Another wet underwater welding "first" occurred at Susquehanna a couple of years later, when the first in-vessel wet welded repair was performed by application of a weld overlay on a damaged stainless steel feedwater nozzle – within 8 feet of the extremely highly-irradiated reactor fuel.

In the late 1980's the ASME Section XI committee began writing provisions for the ASME Section XI Boiler and Pressure Vessel Code to perform underwater welded repairs to nuclear power plant components. These requirements were based on the requirements of AWS D3.6 merged with the

requirements of ASME Section IX, and were first published by ASME as Code Case N-516. The rules were subsequently incorporated into Section XI as an approved repair method. Both the Code Case and the Code revision have been accepted by the U.S. Nuclear regulatory Commission for general application at nuclear power plants throughout the United States, with restriction that implementation on irradiated materials requires prior specific authorization.

Successful wet underwater welded repairs have been performed on Boiling Water Reactor (BWR) torus sections, which are an older design comprised of rolled carbon steel plate and girders, and which act as water-filled suppression pools for condensing reactor steam. In another case, stainless steel Residual Heat Removal (RHR) piping supports within a suppression pool were reinforced using wet underwater welding techniques when it was determined that the original design was discrepant under certain loading conditions. Additional repairs have been approved by the NRC for underwater welded repair of carbon steel liner plates and supports in the newer cylindrical-shaped suppression pools of BWR's. Such repairs may now be performed without prior specific NRC approval.

More recently, wet underwater welding has been used for attaching stainless steel instrument support brackets to Upper Guide Structures (UGS) within Boiling Water reactors. In another situation, wet underwater welding was used for attaching anti-rotation locking devices to the stainless steel reactor core barrel. And the NRC has also approved use of wet underwater welding for application of partial weld overlays to repair cracked stainless steel core spray piping within reactor vessels. The NRC has also accepted proposals by the Electric Power Research Institute (EPRI) for performing wet underwater welding on irradiated stainless steels using certain specified qualification testing techniques. The latest efforts within the ASME Code Committee involve development of a Code Case for application by the remote automatic ambient temperature underwater laser beam welding (LBW) application of Inconel weld inlays and overlays on the interior of reactor nozzles to mitigate development or progression of stress corrosion cracking (WRSCC) in Pressurized Water Reactors (PWR's). This Code Case is presently undergoing review within the ASME Section XI committees, and is expected to be approved sometime in 2011.

4.4 Ports, Harbors, Rivers and Lakes – Need to expand provisions of current Underwater Welding Standards unique to Ship Husbandry, Ports, Bridges, Locks and Dams.

5.0 SUMMARY

At the 1994 Underwater Welding Workshop emphasis was primarily on improving requirements for design, workmanship, technique, qualification, inspection, testing, quality assurance and introducing a wet electrode classification specification. Since the 1994 Workshop, Underwater Welding Standards have addressed the majority of concerns addressed at that time. The 2010 Workshop showed a shift in concerns with emphasis more on updating and expanding sections of existing standards such as inspection, testing, weld processes, etc.

In 1994 participants communicated interest in developing aids to help end users such as Procedure and Welder Qualification Forms, Commentary providing useful guidelines and better understanding, etc.

This objective was achieved but the forms need to be kept “evergreen” and therefore updated on a continual basis.

There was a need to develop and maintain a specification for the classification of wet welding electrodes. This objective has been completed with the introduction of the A5.35/A5.35M Specification for Wet Welding Electrodes for Shielded Metal Arc Welding currently being balloted by AWS. Publication is anticipated in 2011.

The need to align with other International Underwater Welding Standards was recognized. The ISO TC44 Committee and the AWS D3b Subcommittee on Underwater Welding have clearly established since 1994 that there is strong interest in maintaining alignment vs introducing double standards related to underwater welding. The challenge is bringing together qualified members of the International community as a working group under ISO TC44 to work in cooperation with the AWS D3b Subcommittee to update and maintain current ISO Underwater Welding Standards. This objective will require continued dialog between ISO TC44 and the AWS D3b Subcommittee in addition to unification of efforts to establish a TC44 working group.

The 2010 Workshop on Standards concluded with increased emphasis on:

1. Developing and maintaining Marine CWI qualifications.
2. Establishing diver welder and inspector training criteria.
3. Expanding the provisions of current Underwater Welding Standards to include other Marine Industries.
4. Continuing to work with other Standard Organizations to collaborate and maintain alignment in developing and maintaining Underwater Welding Standards.
5. Work to maintain and update the A5.35/A5.35M Specification for Wet Welding Electrodes for Shielded Metal Arc Welding to include provisions for range of qualification by depth, etc. and improvements in state of the art.

Underwater Welding Consumables Development

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1. Introduction

The development of consumables for underwater welding historically followed the growing of offshore oil and gas production. In fact, before the 1970s a few technical documents were produced. In the period between the 1970s and the 1990s some remarkable screening studies and new coatings formulations were performed such as the reported by Stalker (1977), Nóbrega (1981), Gooch (1983a and 1983b), Ibarra (1989) and West (1990). These studies were presented and discussed during the 1994 Workshop and allowed the development of others.

As reported, the development strategy for wet welding generally adopted worldwide in these two decades was to initially evaluate the atmospheric welding commercially available electrodes and secondly propose new coatings formulations based on the screening studies.

After the workshop in 1994, where underwater welding and in particular the development of consumables for this application was extensively discussed, much development took place, focusing on the formulation of the electrodes.

This paper describes some findings of the team who worked on the 1994 workshop and discusses what was developed following ideas and proposals by this team. Major developments occurred mainly in the direction of achieving electrodes capable of producing underwater welds in Class A.

The conclusions address that much progress have been effectively made during the last years but much work still have to be done. The list of needs to be developed or further improvements is presented.

2. Review of the extensive consumables evaluation period (from the 1960s to the 1st Workshop on Underwater Welding – 1994)

During the 1st Workshop on Underwater Welding in 1994, extensive studies regarding the tentative to use commercially available coated electrodes for underwater welding were discussed and presented. These studies allowed the development of the new formulations mainly founded in the rutile base formulation.

Stalker (1977) tested 17 (seventeen) commercially available ferritic electrodes (cellulosic, rutile, oxidizing, acid iron oxide and basic), including 1 (one) commercial electrode already used for wet welding, and 13 (thirteen) austenitic electrodes (rutile and basic). For the ferritic electrodes types the results indicated that only one, with a coating based on iron oxide, has good resistance to hydrogen cracking even under severe conditions. They also concluded that only alternative to reduce hydrogen cracking is the use of austenitic electrodes, despite all their deposits contained bands of hard martensite along the fusion boundaries. Hydrogen cracks were observed in API 5LX 65 steel of CE = 0.36% even when welding with these two selected types of electrode at moderate restraint levels. The main conclusion was that further work is required to develop an iron oxide coated electrode with improved

handling characteristics. Its operational performance in all positions and at greater depths should be assessed.

Nóbrega (1981) tested 22 (twenty-two) commercially ferritic electrodes (cellulosic, rutile, oxidizing, acid and basic), including 2 (two) commercial wet welding electrode, 6 (six) austenitic electrodes (rutile and basic) and 10 (ten) Ni-based (rutile and basic). In this work it was concluded that for the range of ferritic electrodes, only rutile and oxidizing types are recommended for underwater wet welding. Rutile electrodes presented high diffusible hydrogen content, however they only must be recommended to the welding of low carbon equivalent steels. On the other side, the lower diffusible hydrogen content of oxidizing electrodes make them the most recommended for wet welding provided that good running characteristics have been assured. In the study it was found that all austenitic weld metal presented solidification cracks and concluded that new electrodes, specifics for wet welding, matching low susceptibility of hydrogen cracking and good running characteristics should be developed.

Gooch (1983) following the same line, tested 12 (twelve) commercially available ferritic electrodes (cellulosic, rutile, oxidizing, acid and basic), including 2 (two) commercial wet welding electrodes, 8 (eight) austenitic electrodes (rutile and basic) and 6 (six) Ni-based (rutile and basic). In the results they observed that defects such as porosity and lack of fusion were lower for the rutile electrodes. These electrodes also presented excellent operational characteristics and could deposit beads with good profile. Despite the good results, rutile ferritic electrodes produced welds with severe cracking in the HAZ and weld metal. On the other side the occurrence of hydrogen cracks was almost entirely avoided with ferritic oxidizing and Ni-base electrodes. However both types presented poor arc stability leading to the formation of flaws in the weld metal, such as porosity and lack of fusion. Additionally, Ni-base electrodes showed susceptibility to solidification cracking.

West et al. (1990) evaluated commercial electrodes for underwater wet welding. They carried out tests with 8 (eight) commercial electrodes, 6 (six) mild steel ferritic rutile type and 2 (two) austenitic type. The 2 (two) mild steel electrodes allowed AWS D3.6 class B welding procedures qualification for maximum 0,17% C and 0,35% C.E. steels. According to the results, wet welding can be applied in non structural ship repairs or in temporary structural repairs to be rewelded or replaced in the next scheduled drydocking. Several all-weld metal tensile tests results showed elongation from 6,0% to 9,3%. High hardness zones just beneath the capping passes were successfully treated by the temper bead technique to values accepted by class A. Nevertheless its application requires high skill welders and good visibility. The two austenitic electrodes did not presented good performance. Hot cracks type predominantly occurred in the root pass.

With the results of these works it was concluded that the behavior of wet welding joints is limited by the weld metal mechanical properties. No commercially available consumable could be considered as optimum and developments on coating formulation showed to be necessary.

Based on the studies referenced above, the best performance electrodes were identified as belonging to two groups: One group is the related to rutile based coatings which main properties are the good arc stability and other running characteristics. Considering mechanical properties, the rutile type electrodes presented the best results. In the other group, due to the oxidizing behavior in the welding pool, the electrodes produce welds with considerable lower diffusible hydrogen content. As a consequence, smaller risk of cold cracking is expected when using this kind of electrodes.

Another important aspect to be considered is the electrode operational weldability. In the case of wet welding, this aspect is extremely relevant due the adverse environmental situations that the diver-welder or welder-diver faces. In practice, the use of rutile type electrodes makes the operation easier for the welder, which enables the production of weld beads with better appearance and, therefore, influences the welding productivity. Considering the limitations in the diving time imposed to the diver-welders working in non saturated regime, productivity is particularly important in underwater conditions. Generally the rutile electrodes produce weld beads with higher mechanical strength compared to other electrodes (Liu et al. 1994b, Ibarra et al. 1991). On the other hand, rutile electrodes produce deposit weld metal with high diffusible hydrogen content.

The use of oxidizing electrodes implies a much lower risk of hydrogen cracking, both in the HAZ and in the weld metal. This feature gives to the oxidizing electrodes greater flexibility regarding the specification of the steel to be welded (Nóbrega 1981). However, these electrodes present some limitations and disadvantages of operational nature. These include difficulty of slag removal and difficulty of manipulation by the diver-welder.

A more detailed description of the rutile and oxidizing electrodes properties is presented as follows:

	Ferritic rutile	Ferritic oxidizing
Operational weldability	Excellent in general considering slag removal, appearance regularity, stability	Poor in general considering slag removal, appearance, regularity, etc.
Weld metal chemical composition	Increasing depth increases oxygen and carbon. Decreases manganese and silicon	Practically insensitive to depth. High oxygen and low manganese, silicon and carbon
Diffusible hydrogen	High (< 90ml/100g). Decreases with increasing pressure (mechanism is not well understood)	Medium (< 20ml/100g)
Porosity	Increases markedly with depth	Increases moderately with depth for shallow waters (<30m)
Microstructure of the weld metal columnar region	Similar to welds in air. Acicular ferrite can be significantly present. The trend is the decreases of its amount with depth	Practically insensitive to depth. Predominantly pro-eutectoid ferrite. Difficult to form acicular ferrite
Non metallic inclusions	Similar to welds in air. Amount increases with depth following the oxygen content changes	High amount. Practically insensitive to depth
Hardness	Decreases with increasing pressure following microstructural and chemical composition changes	Practically insensitive to depth
Mechanical strength	Class E 70XX is commonly achieved. Decreases with depth according to microstructural and mainly to porosity changes	Low strength deposits. Decreases with depth according to porosity changes. The main possible strengthening mechanism is the grain refinement by alloying elements
Ductility	Low elongation (< 15%) in the tensile test. Decreases with depth according mainly to porosity changes	Possible to achieve good elongation (around 20%)
Toughness	Commonly meet the requirements of the main standards or codes. Decreases with depth according mainly to porosity changes	Commonly meet the requirements of the main standards or codes. Decreases with depth according mainly to porosity changes

	Ferritic rutile	Ferritic oxidizing
Root cracks	Lower cracking susceptibility in lap joints and butt joints with backing comparing to oxidizing electrodes	Susceptibility increased probably due to the lower strength, toughness of the ferritic columnar grains and high amount of inclusions
HAZ hydrogen cracking	High cracking susceptibility for C > 0,15% and C.E. > 0,38%. Risk of occurrence decreases with increasing depth	Low cracking susceptibility for structural steels in general
WM hydrogen cracking	High cracking susceptibility in general	Low cracking susceptibility in general

3. Summary of Working Group Discussion (1994)

In 1994 the International Workshop on Underwater Welding of Marine Structures, held in Louisiana, presented an important contribution featuring the state of the art in underwater welding. The main conclusions related to wet welding consumables are reproduced below as well as the recommended themes for research and development.

Main conclusions:

With regards to base metal hardenability and HAZ cracking:

1. *Considering the steels that are currently in service in marine structures such as offshore platforms, CEIIW is adequate for the prediction of cracking susceptibility. Steels whose compositions fall into the application range of Pcm do not usually present weldability problem.*
2. *To better define weldability using CEIIW, the following guideline is recommended. For steels that have carbon equivalent less than 0.40 wt. pct., HAZ cracking is generally not observed. For steels between 0.40 and 0.46 wt. pct., precaution steps must be taken to decrease HAZ hardness and hydrogen control. Examples of such steps include multiple temper bead technique, postweld heat treatment and electrodes with higher oxygen potential. It should also be pointed out that success in application of these techniques to your practice is dependent on the identification of the optimal processing parameters for the local conditions.*

With regards to weld metal and consumables:

1. *Wet welds that satisfy AWS D3.6 Specification Type B Classification are readily achievable for depths less than 200 ft. and for steels with carbon equivalent less than 0.40 wt. pct. For depths less than 100 ft., presently available consumables are capable of producing consistent results. Between 100 and 200 ft., variations in weld behavior (chemical composition, electrode operability, porosity, etc.) are sometimes observed.*
2. *Between 200 and 325 ft. water depth, repeatability in producing welds that meet AWS D3.6 Type B acceptance criteria becomes difficult.*

With regards to future development:

Working Group recognizes that if the aim is to develop suitable and acceptable solutions for underwater welding in a predictable future, a number of preliminary conditions must be fulfilled:

- The need to depart from traditional approaches and to “break circle.”*
- The need to recognize that consumables most probably will have to be differentiated according to depth, possibly according to root, fill and/or capping functions.*
- In view of the highly challenging problems that are faced, all possible, even uncommon, designs and incident technologies at hand should be integrated in the development process*
- In view of the multiplicity of factors involved in the design formulations, development and evaluation processes, only a comprehensive, multi-disciplinary and systematic, scientifically-oriented approach is likely to lead to real significant progress*

Research and Development Needs

The Working Group identified and prioritized the following Research and Development needs to further Underwater Wet Welding applications in Structural Marine Fabrication:

- 1. Steels with carbon equivalent less than 0.40 wt. Pct.:
 - a) For depths less than 100 ft Type A welds (instead of the currently accepted Type B welds) should be targeted by reducing porosity and by improving ductility and impact toughness.*
 - b) For depths between 100 and 200 ft., Type B+ welds (instead of the currently accepted Type B welds) should be targeted by reducing porosity and by improving ductility and impact toughness.*
 - c) For depths between 200 and 325 ft., Type B welds (instead of the currently accepted Type B- welds) should be targeted by reducing porosity and by improving ductility and impact toughness.**
- 2. Steels with carbon equivalent between 0.40 and 0.46 wt. pct.:
There is a need for more detailed investigation with respect to a) porosity, b) inclusions, c) cracking, d) alloying element segregation, and e) hydrogen control in the weld metal.*
- 3. The use of electrodes with high oxygen potential has shown promising results in underwater wet welding and should be further investigated for optimal effect in balancing porosity with inclusions and hydrogen control.*
- 4. Consumables should be developed for welding the new TMCP steels, in particular, to produce weld metals with toughness that matches those of the base metals.*
- 5. Priority in further consumable develop should be focused on C-Mn-Si and C-Mn-Si(Low Alloy) systems with micro-alloying elements such as titanium and boron.*
- 6. The rutile-cellulosic (E6013 Type) and rutile (E7014 Type) slags are capable of delivering quality underwater wet welds. Further improvements of these systems, expected to result in high quality consumables which will achieve the weld quality proposed earlier, should be targeted. Flexibility in design could be achieved by using coated tubular cored electrodes.*

7. *The use of FCAW (flux cored arc welding) has great potential in underwater wet welding. Developmental work in the design of consumables, wire feeder and power design, using a systems approach, is strongly recommended.*

4. The recent developments from 1994 till now

Research and development projects targeting reduction of porosity and improvement of ductility and impact toughness were carried out after 1994. New consumable formulations focused on C-Mn-Si and C-Mn-Si (Low Alloy) systems with micro-alloying elements such as titanium and boron based on rutile coatings were developed by Colorado School of Mines welding research group.

Sanchez-Osio, Liu and Ibarra (1995), reported the effect of calcium carbonate additions into the flux coating of E6013 covered steel electrodes on weld metal porosity for 10m water depth. Porosity decreased by 1.5 pct. with increasing calcium carbonate content from 9 to 12 wt. pct. However, high CaCO_3 additions resulted in arc instability and higher porosity (Figure 4.1). Porosity level obtained with 12 pct. CaCO_3 was approximately 1 pct. It was also reported that additions of titanium and boron to the rutile coating produced a microstructure containing up to 60% acicular ferrite at depth of 33 ft (10m).

Rowe, Liu and Reynolds (2002) developed 60 different coating formulations and welds were made at various depths to 300ft (91m). They added Fe-Mn, Fe-Ti, Fe-B and Fe-Si-rare-earth-metal (REM) alloy to the electrode coating. Addition of manganese failed to increase the weld metal manganese content owing to the oxidizing environment. When manganese was added with titanium, it was possible to control the manganese content of the weld metal. Appropriate levels of Ti –B additions produced microstructures containing 60 – 90% acicular ferrite at depths to 300ft (91m). The ferroalloy additions were also found to influence porosity. Increasing additions of manganese reduced porosity, whereas excessive levels of titanium and boron increased porosity, Figure 4.2. All weld metal tensile tests results showed elongation lower than 7 % for rare earth metal, titanium-boron, and iron-manganese additions, lower than 10% for titanium-boron and ferro-manganese additions and from 3.6 to 18.6 % for ferro-manganese additions alone.

Perez et al (2003) added nickel to the flux coating of a rutile base electrode and it promoted an increase in toughness. Optimum value found was close to 2% of Nickel addition. Perez (2007) also reported that wet welds deposited at 50m water depth using rutile base covering electrode with low carbon content in the steel rods and “deoxidizers” additions to the flux coating exhibited 0.33 pct. porosity, which is an important reduction of porosity for this water depth.

Pessoa et al (2007) added exothermic such as (CaC_2) and aluminum (Al) additions in tubular covered rutile base electrodes and studied the influence of these ingredients on weld metal composition and porosity. Aluminum additions reduced porosity, increased heat input, and promoted acicular ferrite formation. At high concentrations, greater than 20% addition in the internal fluxes, aluminum also protected the transfer of alloying elements such as manganese and silicon, as shown in Figure 4.3. Calcium carbide additions reduced porosity, increased weld metal carbon content, produced short and more stable arc, and helped to protect the transfer of important alloying elements. The optimal amount of aluminum and calcium carbide to control porosity and microstructure found was close to 20 and 10%, respectively.

Aiming the understanding of porosity formation mechanisms in rutile electrodes, Pessoa, Bracarense and Liu (2008) related porosity variation along weld beads to short-circuit transfer mode and carbon oxidation during droplet formation. Andrade et al. (2010) tested commercial E6013 grade electrodes with core rods with two different carbon content (E2 – 0.002 wt. pct. and E6 – 0.6 wt. pct.). Electrodes with higher carbon content produced higher weld metal porosity. It was directly related with the increase of the number of short circuiting events in metal transfer and carbon oxidation in the droplet. The addition of Ferro-manganese and aluminum to the insulating layer of covered E6013 grade electrodes increased the weld metal manganese content and reduced porosity.

Kim (2003) tested four differed electrode formulation with variations in aluminum additions, iron powder, titanium, calcium and potassium. The results found were high impact value (from 44 to 55 J/cm²), tensile strength from 511 to 545 MPa and maximum elongation of 9%.

Murzin and Russo (1994) explored the effects of slag and gas forming components, fluorides, metal powders to the electrode covering on the hydrogen content of underwater wet welds. Additions of calcium fluoride reduced the hydrogen content of the weld metal. An increase of the amount of slag phase on the surface on the welded component reduced the cooling rate of the HAZ metal. Exothermic mixtures were also added to the insulating layer improving the thermal shielding of the weld pool.

Gonzales et al, (2007) and Fischer et al (2009) reported the development and manufacturing procedure to waterproof electrodes without the use of varnish layer. Acicular ferrite as high as 80% was measured in the columnar region of the weld metal.

Targeting class A welds, low welding depths developments by reducing diffusible hydrogen and porosity and by improving ductility and impact toughness were focused by some researchers. High oxidizing potential electrodes were used as a basis.

Pope and Liu (1996) investigated the addition of hematite to the coating of a rutile base electrode. Electrodes with hematite additions produced diffusible hydrogen contents of 40 to 50 mL/100g whereas 90 to 100 mL/100 g was obtained with rutile electrodes, as shown in Figure 4.4. The authors concluded that the hydrogen content of wet welds is influenced to a greater extent by the slag composition than by the oxygen content of the weld pool. Medeiros and Liu (1998) reported diffusible hydrogen levels as low as 13 mL/100 g using iron oxide type consumables. Some results from Medeiros and Liu are shown in Figure 4.5. An electrochemical model for the transfer of hydrogen to the weld metal was proposed. The reduction of weld metal hydrogen content was attributed to a reduction in the solubility of water vapour in the slag with increasing iron oxide content in the covering.

It is interesting to note that both, Pope and Liu (1996) and Medeiros and Liu (1998) reduced diffusible hydrogen by increasing the basicity of an acid slag toward a more neutral value. A disadvantage of iron oxide type electrodes is that the impact toughness properties of the weld metal are usually inferior to those of weld metal deposited using rutile type electrodes. Pope et al (1995) investigated additions of nickel to iron oxide type consumables to increase strength and toughness. An increase from 0 to 3% of the nickel content in the weld metal increased the Charpy impact toughness, at 0°C, from 19 to 43 J (14 to 32 ft lb). This result (43 J) is comparable to the toughness of typical rutile type deposits. The effect of nickel additions on toughness is shown in Figure 4.6. Pope et al. (1995a) tested iron oxide electrodes with nickel additions at depths to 66 ft (20 m). Chemical composition remained constant with depth, but porosity increased with depth. The increase in porosity led to a reduction in strength and toughness with

increasing depth. With further development, iron oxide type electrodes with nickel additions may become a lower hydrogen alternative to rutile type electrodes at certain depths.

Taking into account the expected continuous growing of the world offshore oil and gas production it is expected that the need for underwater inspection and maintenance interventions would also increase. Considering the expected trend to employ floating productions units the maximum depth target for the majority of welding interventions will be limited to 20 meters, a research and development project was started in 2007 in Brazil. This project named “Consumíveis para Soldagem Molhada” (CSM) has the main objective of developing an oxy-rutile electrode for wet welding up to 20m depth, combining low weld pool hydrogen absorption with the recognized good operational properties of rutile type electrodes. Commercial wet welding electrodes were also evaluated. All the welds were performed in laboratory by a mechanized gravity system.

The CSM project has been developed according to the following steps:

1. Evaluation commercial welding electrodes named as A (oxidizing type) and B, C, D, E (rutile type);
2. Development of an oxy-rutile electrode;
 - a. Fabrication and welding tests at 0.5m depth of 8 batches of electrodes (series R), aiming the lowest possible diffusible hydrogen;
 - b. Fabrication and welding tests up to 20m depth of 20 batches of electrodes (series F, M and P) aiming the improvement of mechanical properties and operational features.

Preliminary results of this project have already been published (Bracarense et al. 2008 and Santos et al. 2010). Diffusible hydrogen results for commercials and an experimental oxy-rutile electrode are presented in Figure 4.7. The microstructural aspects for commercial electrodes are shown in Figures 4.8 to 4.10 and Table 4.1. Results related to mechanical behavior and chemical composition for commercial electrodes are shown in Tables 4.2 and 4.3. The low elongation values for rutile type electrodes can be explained by the occurrence of transversal hydrogen microcracks in the weld metal as shown in Figure 4.11.

Some important features of selected experimental electrodes from joints welded at 10m simulated depth are presented Table 4.4. The comparison of toughness and porosity between an experimental (F2) and commercials electrodes as a function of depth is shown in Figures 4.12 to 4.15. The results of weld metal cracking susceptibility are illustrated in 4.16 and summarized in Figures 4.17 to 4.19. The occurrence of a few millimeters root cracks in the weld metal of fillet welds have been observed for oxy-rutile electrodes (Figure 4.19) consistently with Santos et al. (1992). Susceptibility of hydrogen cracking in the HAZ has been evaluated and the main results are shown in table 4.4. Figure 4.20 illustrates the distribution of hydrogen cracks in the HAZ of a CTS specimen welded with a typical rutile type electrode.

From the partial results of the CSM project it was concluded that:

- oxy-rutile electrodes present a great potential for the application in shallow waters (up to 20m) preventing hydrogen cracking, reducing porosity and enhancing ductility.
- the weld metal ductility, measured by elongation and bending angle, mostly exceeded the requirement of class A.

5. Considerations regarding the qualification of wet welding procedures for floating production units

Procedures qualification of underwater welding for structural applications is commonly done using “Specification for Underwater Welding” AWS D3.6M: 1999 (American Welding Society, 1999). According to this specification the quality of wet welds is classified as class A and class B. The difficulty to achieve class A in wet welding rises from the fact that the requirements are similar to those required in the atmospheric welding. Welds classified as class B are accepted as limited structural quality welds, the requirements are less stringent than those required for class A and easier to achieve in wet welding up to 20m to 30m.

The following requirements are critical to achieve the qualification of wet welding procedures in the class A:

- a) no cracks in weld metal (WM) or heat affected zone (HAZ).
- b) elongation in the all weld metal tensile test (14%, 16%, 18% or 20%, depending on the specified yield strength of base metal and specimen geometry).
- c) hardness $\leq 325\text{HV}$ (HAZ and WM).
- d) bending angle: 180° for 2T or 2-2/3T depending on the yield strength of the base metal.

The requirements “a” and “b” are strongly dependent on the weld metal microstructure, the porosity and diffusible hydrogen. So, the coating formulation plays an important role on this process. It is generally recognized that low ductility is the characteristic of wet welds that mostly hinders the application of this technique in ship structures, as pointed out by the Ship Structure Committee (SSC-370: 1993). However, some literature results (Nobrega 1981) have exceeded the elongation specification for class A in the case of some oxidizing electrodes, suggesting the possibility of good reproducibility and dependence of the hydrogen content. Diffusible hydrogen contents in the range of the 10ml/100g to 20ml/100g have been reported (Stalker et al.1975, Gooch 1983, Nobrega 1981, Medeiros 1997). Its influence on the presence of weld metal microcracks was pointed out (Liu et al. 1994b, Pope 1995, Bracarense et al. 2008, Santos et al. 2010).

The requirement “c,” maximum hardness in the HAZ, is directly related to the chemical composition of the base metal and the cooling rate. This in turn depends on the welding energy. Cooling rates in welding are usually expressed by the cooling time between 800°C and 500°C (Δt_{8-5}). Typical values for Δt_{8-5} in wet welding vary from 0.8 s to 6.0 s with energies welding 1kJ/mm to 3.5 kJ / mm (Kinugawa et al 1982). Other authors (Stalker et al. 1975 and Nóbrega 1981) also reported values between 2s and 3s. In a conservative analysis, Figure 5.1 presents the results of simulations of the HAZ maximum hardness as a function of the base metal chemical composition, assuming Δt_{8-5} ($\Delta t_{800-500}$) for 2s and 3s. The limit values for C and Mn are representative of typical low strength ship steels chemical composition specifications and were taken from ASTM A131 “Standard Specification for Structural Steel for Ships.” According to Figure 5.1 to broaden the range of approval for class A and B it is necessary move up and to the right the dashed lines. To achieve this feature, it is necessary to make modification in the welding procedure. One modification could be to reduce cooling rate by an increasing heat input, e.g. increasing the diameter of the electrode and hence the welding current. Other modification could be to perform a post-welding localized heat treatment to promote tempering of the martensite in HAZ.

The requirement “d,” 180° bending, is supposed to be achieved if the requirements “a,” “b” and “c” are successful achieved by increasing the ductility of the weld metal, reducing the HAZ hardness and reduced the incidence of cracks.

Since both the carbon content and the carbon equivalent are key variables in the qualification of welding procedures, it is recommended for future studies to develop new welding procedures to ensure acceptable hardness levels for the entire range of the ship steels chemical composition.

The high cooling rate resulting from the cooling action of water during the weld creates some microstructural features in the heat affected zone (HAZ) of the base metal which represent important barriers for wet weld qualification. High hardness in the HAZ and the high amount of diffusible hydrogen may lead to the formation of hydrogen cracks (cold cracks) even in the weld metal (Ozaki et al. 1997). The increase in porosity with depth also contributes considerably to the decrease of ductility and is the main factor which leads to failure in all weld tensile test required for class A (Suga and Hasui 1986, Bracarense 2008, Pessoa 2006).

6. Conclusions

The recent trends for the concepts of offshore production units indicate extensive use of floating production units (ships and semi-submersibles platforms). As a consequence it is expected that most interventions for wet welding structural repairs in the future will be limited to less than 20m. Deeper water interventions are supposed to be performed in the dry environment (hyperbaric welding).

The suggestions for research and development themes, raised in the International Workshop on Underwater Welding of Marine Structures – 1994, have mostly been met. The main propositions have been developed as thesis and academic studies as well as in the form of applied research projects supported by the industry or services companies. From the published results produced since that time, focusing on the development of consumables for wet welding, some conclusions can be drawn:

1. Most of the research and developments have concentrated in “shielded metal arc welding process” mainly in covered electrode development.
2. Rutile type and oxidizing type electrodes have been mostly selected as basis for new consumables developments.
3. Improvements in the quality of wet welds have been searched both by minor additions to conventional coatings formulations and to new concepts changing more significantly the nature and the amounts of compounds employed.
4. Wet welds “class A” remain still no consistently achievable, even in shallow waters, although significant advances in this direction seemed to be done. The following specifications are pointed out as the main obstacles to be overcome.
 - a) no cracks in weld metal (WM) or heat affected zone (HAZ).
 - b) elongation in the all weld metal tensile test (14%, 16%, 18% or 20%, depending on the specified base metal yield strength and specimen geometry).
 - c) hardness $\leq 325\text{HV}$ (HAZ and WM)
 - d) bending angle: 180° for 2T or 2-2/3T depending on the yield strength of the base metal
5. Reduce diffusible hydrogen is mandatory to consistently increase ductility (elongation and bending angle), reducing porosity and cracking susceptibility.
6. Aiming Class A, neither rutile type nor oxidizing type electrodes have been isolated successfully used as a basis for new consumables. Hybrid electrodes (oxy-rutile) have presented promising results

7. Research needs on wet welding consumables development

Priority 1: Reach class A and improve class B weld properties

Developments should target shallow waters (< 60 ft) prioritizing SMAW process. Ship steels (C_{max}: 0,2%, C.E._{max}: 0,4%) should be employed as base metal. Two routes are suggested to guide future research programs: development of new consumables and improvement of welding techniques.

New consumables should be developed based on oxidizing or rutile type electrodes. If the development is based on oxidizing type, titanium oxides and/or other compounds and alloying elements should be added to improve operational features and mechanical strength. On the other hand, if the development is based on rutile type, iron oxides and/or other compounds should be added to reduce diffusible hydrogen. The use of specific consumables for different depths and/or different parts of the same weld joint (such as: root pass, filling and finishing) can be considered.

The following critical requirements for developments based on oxidizing electrodes are suggested:

- 1) keep diffusion hydrogen lower than 20 ml/100g
- 2) keep porosity less than 0,5%
- 3) minimum 18 % elongation in the all weld metal tensile test
- 4) reduce susceptibility of weld metal root cracks

The following critical requirements for developments based on rutile electrodes are suggested:

- 1) keep diffusion hydrogen lower than 50ml/100g
- 2) keep porosity less than 1%
- 3) minimum 18 % elongation in the all weld metal tensile test
- 4) reduce susceptibility of weld metal and HAZ hydrogen cracking

The development route dealing with welding techniques should focus the reduction of HAZ hardness. Overcoming the difficulties of applying multiple or single temper bead can be considered. Special attention should be taken to the development of localized post weld tempering techniques. Heating using termite consumables seems to be the most promising method.

Priority 2: Development or improvements of welding processes and techniques

- 1) FCAW: optimize welding system (power source and wire feed system) and develop new formulations.
- 2) develop the application of friction welding to crack repairs
- 3) development of mechanical devices or automated systems to improve welders performance.
- 4) development of waterproof electrodes by polymers addition in the covering.

Basic fundamental research should focus the better understanding of the physics and chemistry phenomena in metal-slag interaction.

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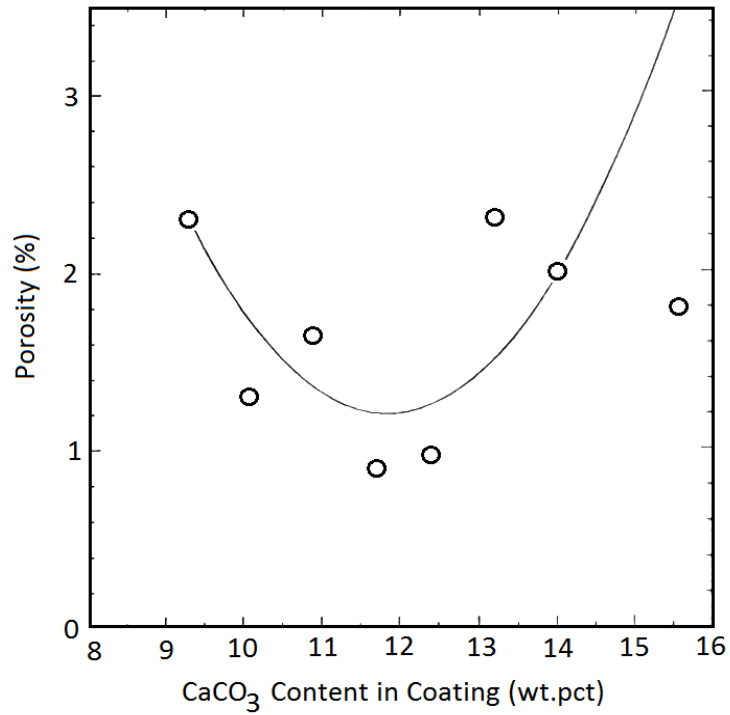


Figure 4.1 Weld metal porosity variation as a function of calcium carbonate additions to the flux coating of e6013 steel electrodes [Sanchez-Osio and Liu]

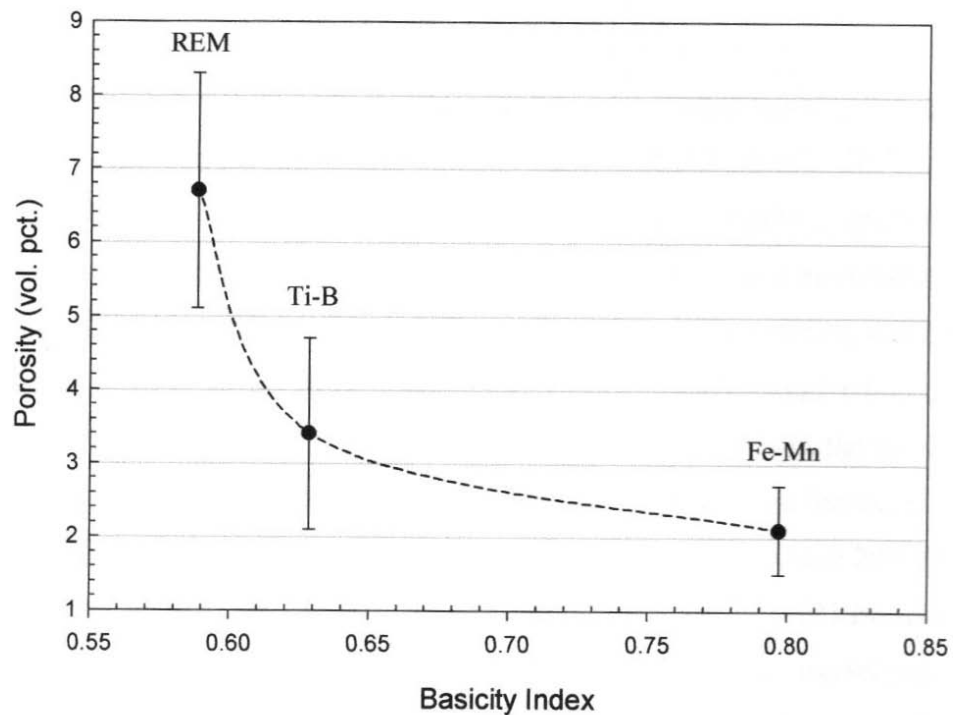


Figure 4.2 Weld metal porosity as a function of slag basicity index [Rowe et al]

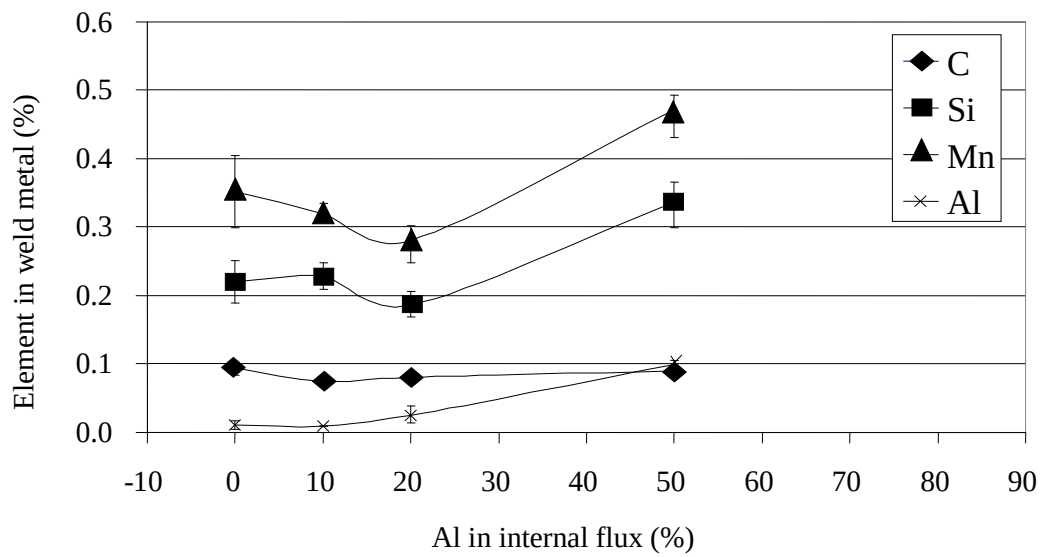


Figure 4.3 Underwater weld metal carbon, silicon, manganese and aluminum content as a function of aluminum addition in the internal flux [Pessoa et al, 2007]

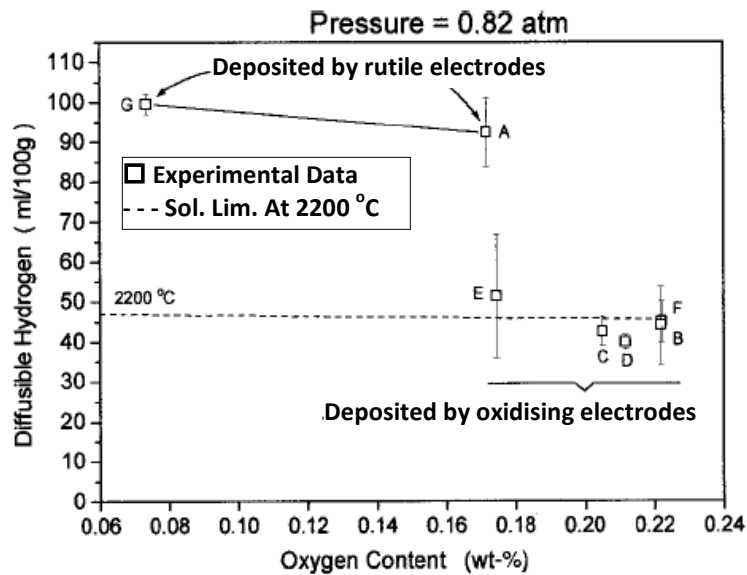


Figure 4.4 Effect of hematite additions on diffusible hydrogen content for rutile base electrodes [Pope and Liu, 1996]

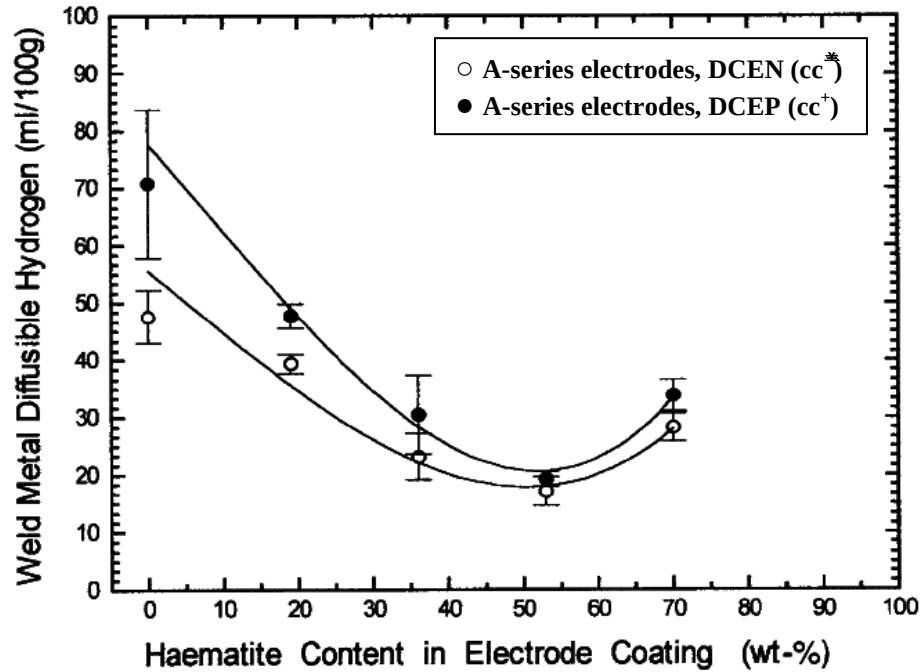


Figure 4.5 Diffusible hydrogen in underwater wet welds as function of hematite content of electrode coating [Medeiros and Liu, 1998]

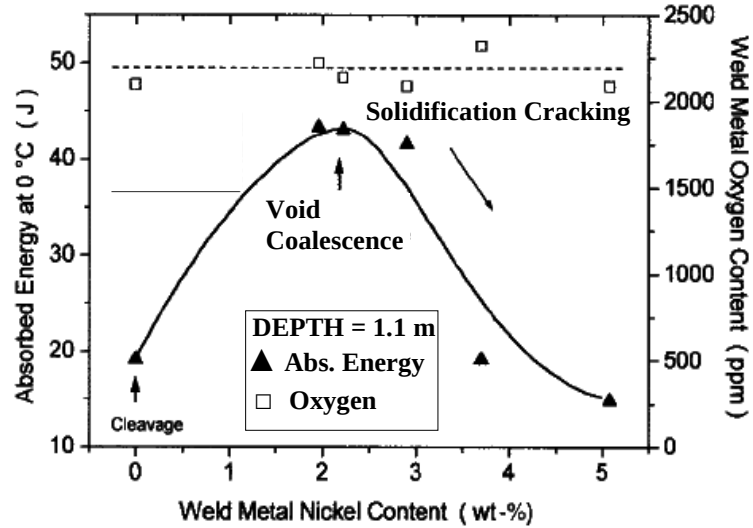


Figure 4.6 Effect of nickel additions on toughness of underwater wet welds produced using oxidizing electrodes [Pope et al, 1995]

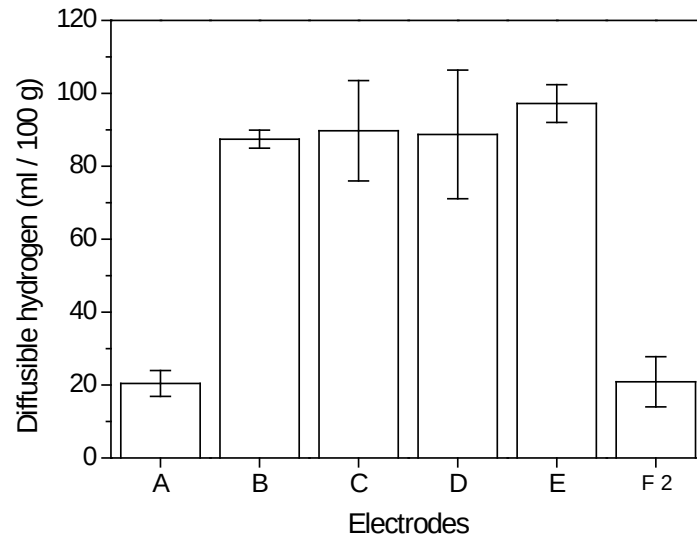


Figure. 4.7 Diffusible hydrogen content for commercial electrodes tested at 0.5 m depth – average of at least 3 results. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode (Santos V. R. et. al. 2010)

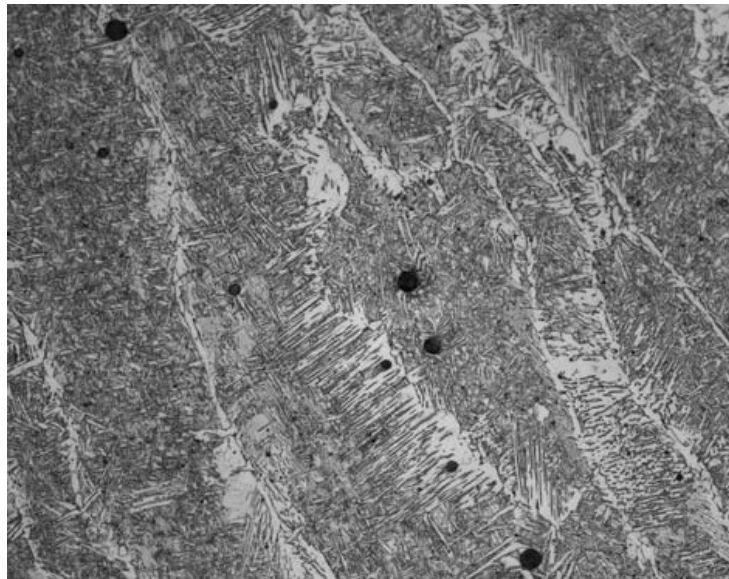


Figure 4.8 Typical microstructure of the weld metal columnar region for rutile type electrodes, showing acicular ferrite, proeutectoid ferrite and side plate ferrite

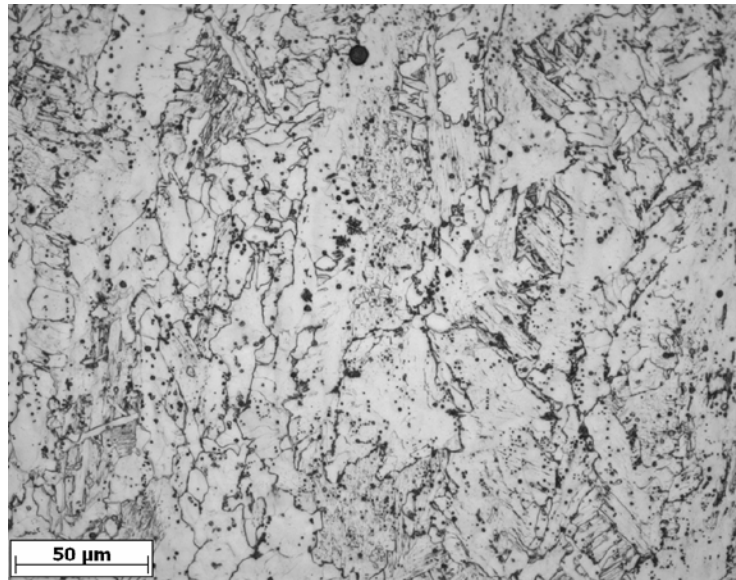


Figure 4.9 Typical microstructure of the weld metal columnar region for oxidizing type electrodes. Proeutectoid ferrite is the predominant microconstituent.

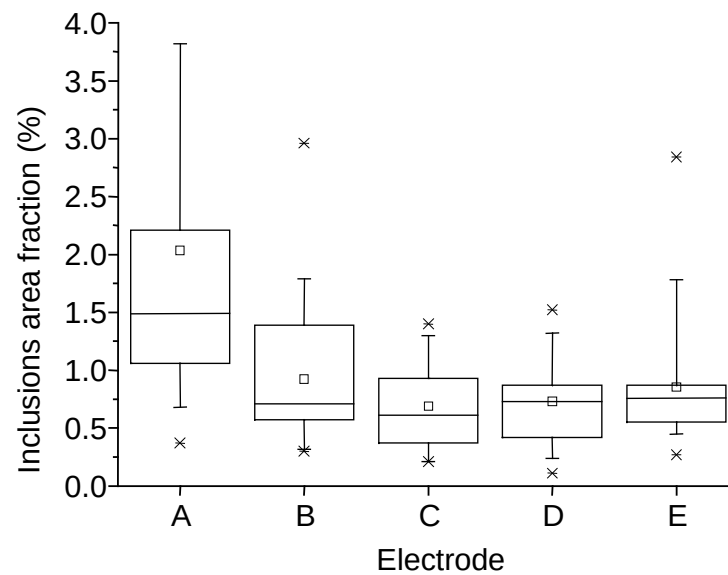


Figure 4.10 Area fraction of non metallic inclusions in weld metal. Welding depth: 0.5 m. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes.(Bracarense, A. Q. et al. 2008)

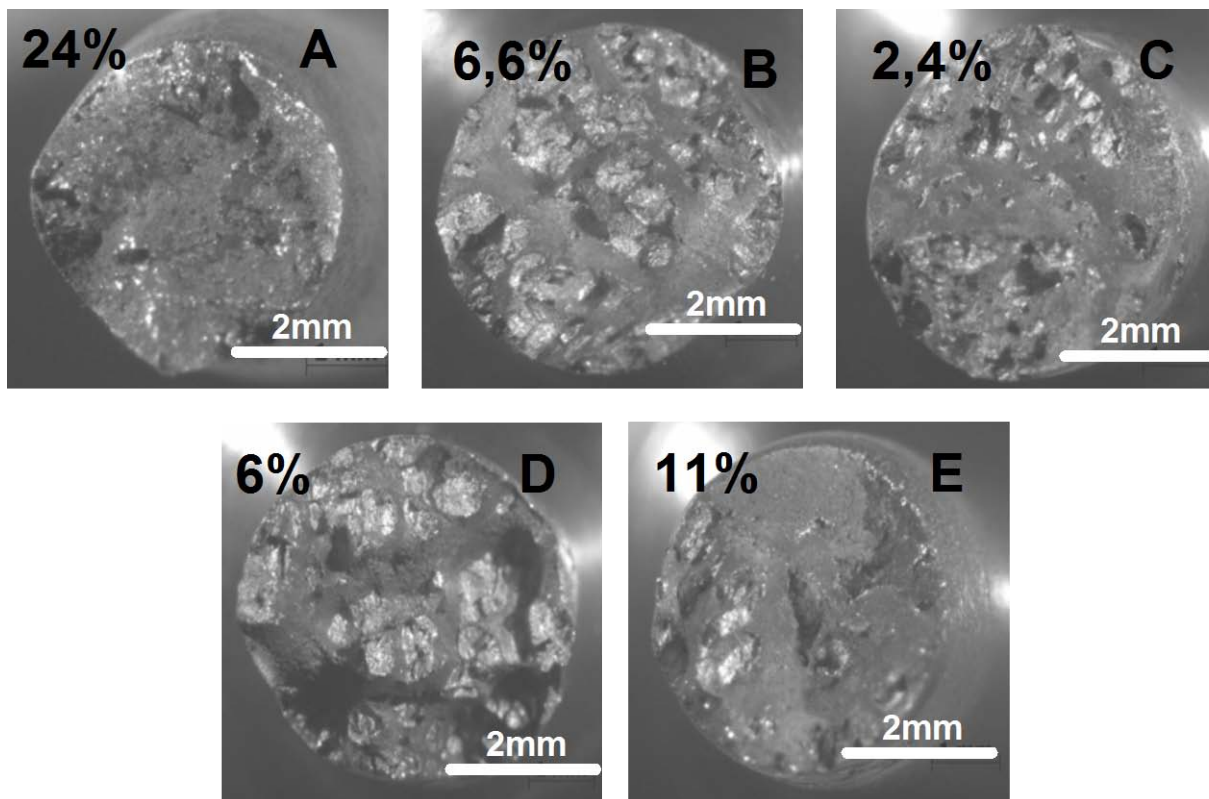


Figure 4.11 Fracture surfaces of specimens after tensile tests. Elongation results (%) are shown. Welding depth: 0,5m. Transverse hydrogen cracks appear as bright areas. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes.

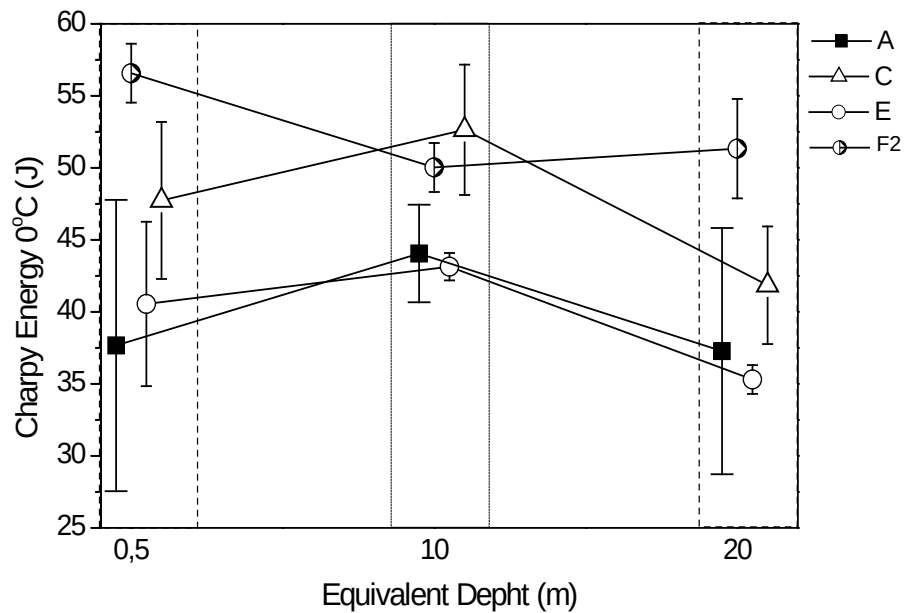


Figure 4.12 Influence of depth on the toughness of the weld metal. A: commercial oxidizing type electrode; C and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode (Santos V. R. et. al. 2010)

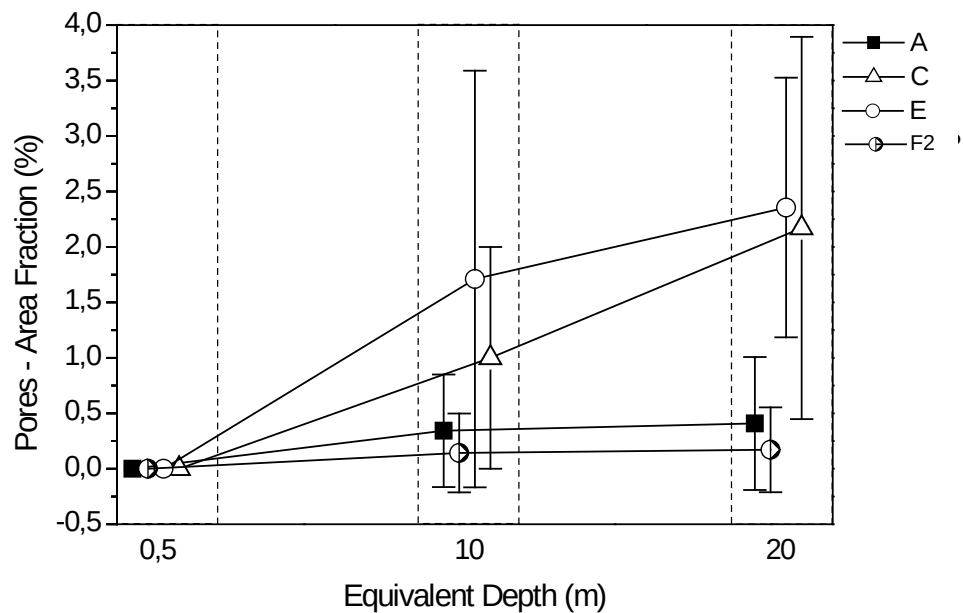


Figure 4.13 Influence of water depth on the porosity A: commercial oxidizing type electrode; C and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode (Santos V. R. et. al. 2010)

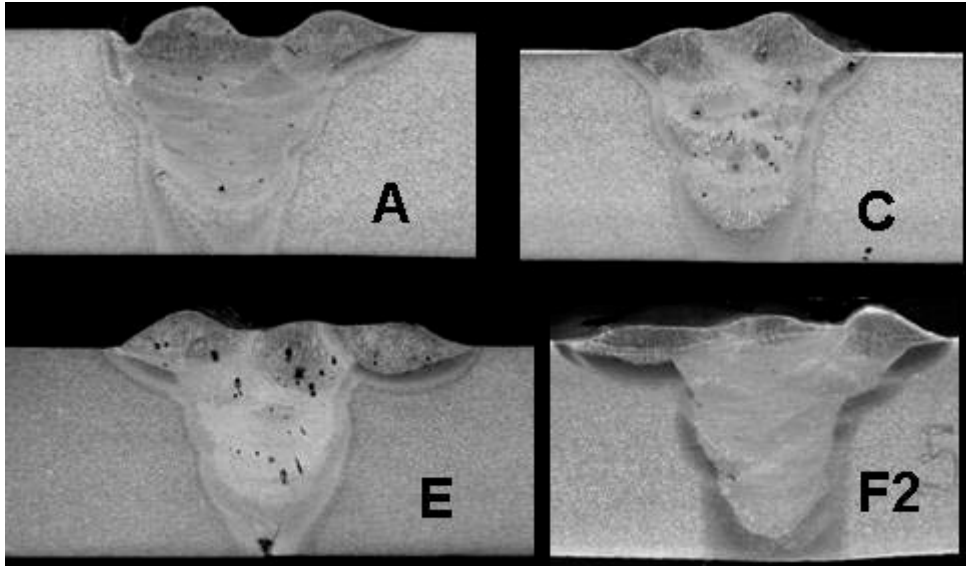


Figure 4.14 Representative macrographs illustrating the porosity level resulted in 20 m equivalent welding depth. A: commercial oxidizing type electrode; C and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode (Santos V. R. et. al. 2010)

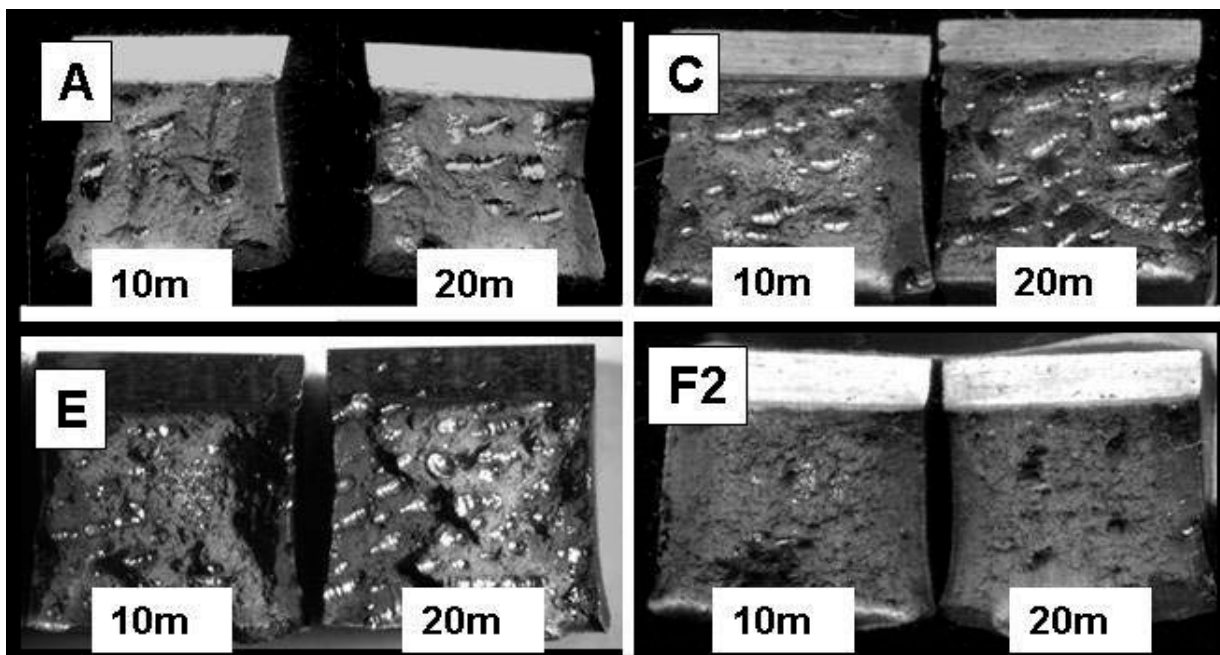


Figure 4.15 Fracture surfaces of Charpy specimens illustrating the influence of water depth on the porosity. A: commercial oxidizing type electrode; C and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode. Equivalent welding depth: 10 and 20 m

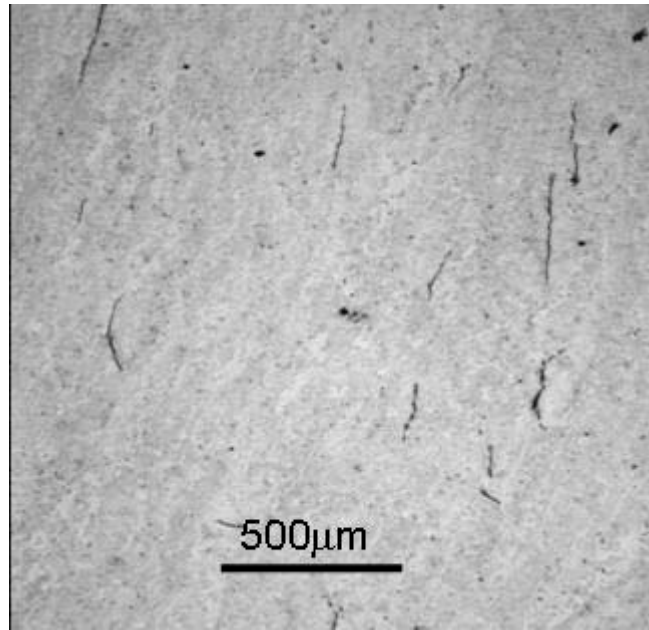


Figure 4.16 Transversal hydrogen micro-cracks in weld metal. Longitudinal section of CTS specimen welded at 0.5 depth. Electrode E (Diffusible hydrogen = 90 ml/100g). Plate thickness: 12.5 mm.

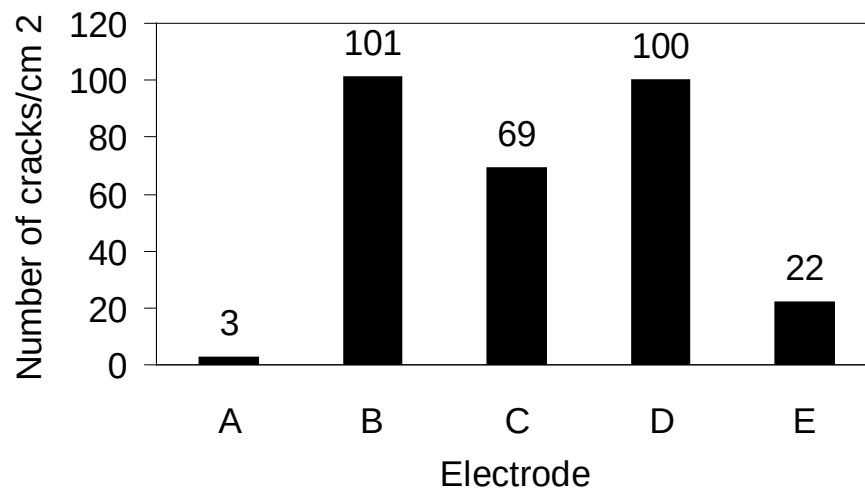


Figure 4.17 Quantitative crack evaluation in weld metal by manual counting in longitudinal sections of groove welds. Welding depth: 0.5 m. Average of counting of number of cracks on three (1cm x 1cm) samples. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes.

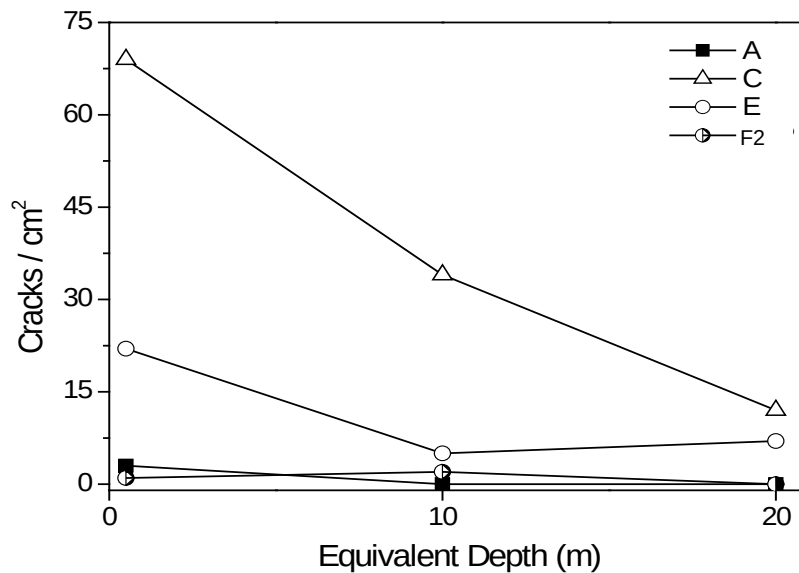


Figure 4.18 – Influence of water depth on incidence of hydrogen cracks in the weld metal. Selected results for number of cracks per unit area in longitudinal sections of groove welds. A: commercial oxidizing type electrode; C and E: commercial rutile type electrodes; F2: oxy-rutile experimental electrode. (Santos V. R. et. al. 2010)

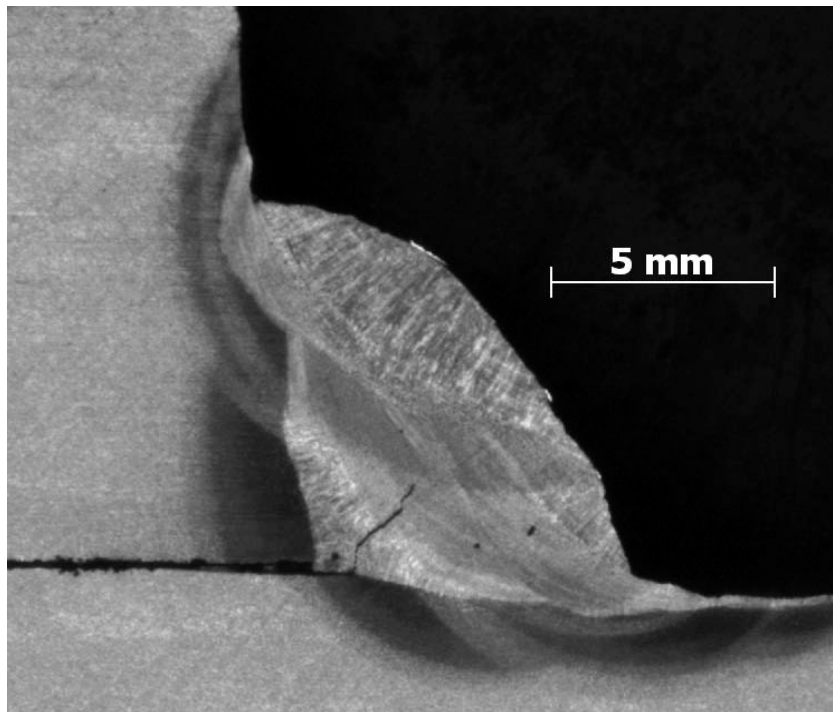


Figure 4.19 Root crack in shear strength test specimen. Oxi-rutile electrode P4. Base Metal: ASTM A131 AH 36. Plate thickness: 16 mm. Welding depth: 10m.

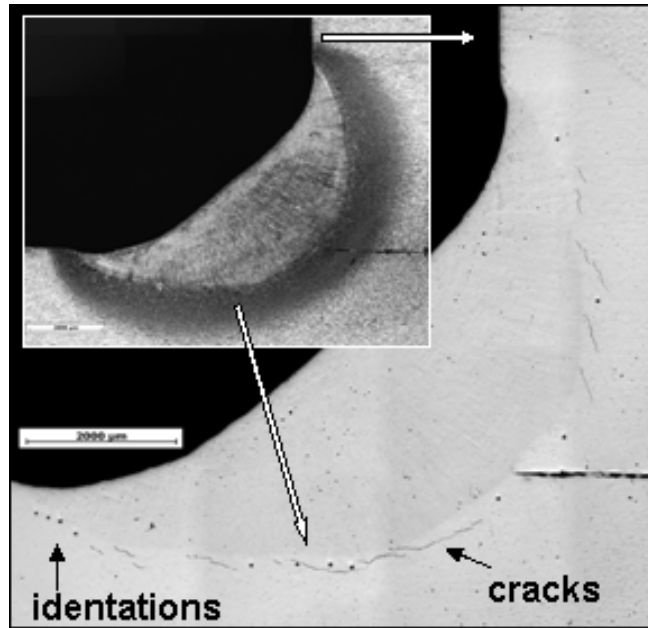


Figure 4.20 Distribution of hydrogen cracks in the HAZ of CTS specimen. Base metal: 0.21%C and 1.05%Mn. Equivalent welding depth: 20m. Commercial rutile type electrode E. Diffusible hydrogen: 90ml/100g. Top – left image: nital 2%. Background image: after re-polishing. (Santos V. R. et. al. 2010).

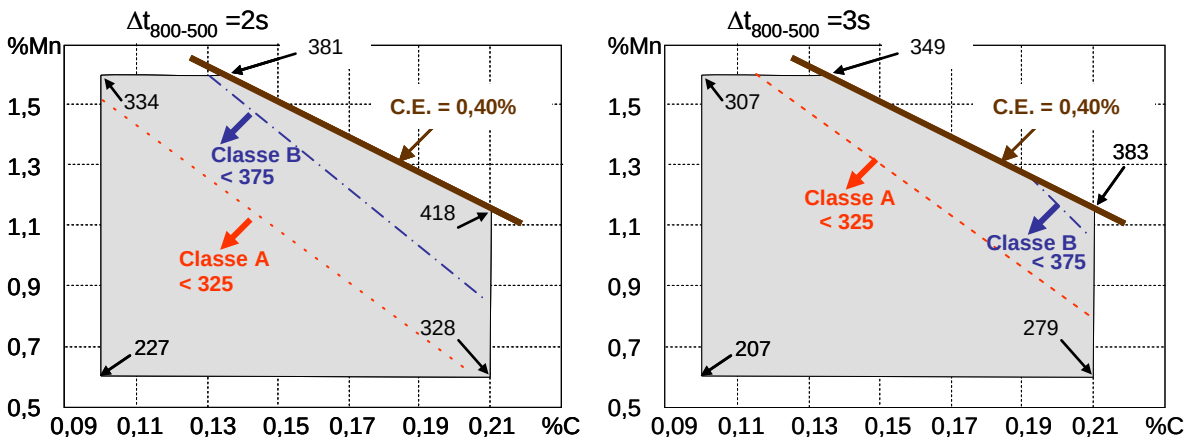


Figure 5.1 Ship Steels ASTM A 131. Maximum HAZ Vickers hardness estimated theoretically as a function of carbon and manganese contents for $\Delta t_{8-5} = 2s$ and $\Delta t_{8-5} = 3s$. Dashed lines limit the composition of steels which potentially would meet the maximum hardness requirements 375max or 325max for classes A and B respectively.

Table 4.1 Quantitative results of weld metal microstructure in multipass V groove welded joint. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes. Welding depth: 0.5 m. (Bracarense, A. Q.et. al. 2008).

Electrode	CR%	CGR%	FGR%	AF%	PF%	FSP%	FGS (μm)
A	15.3	11.3	73.3	1.0	49.0	50.0	4.02
B	35.0	19.0	46.0	40.6	33.2	26.2	3.85
C	35.0	21.0	44.0	37.4	29.4	33.2	3.92
D	21.0	26.5	52.5	42.2	8.4	49.4	3.08
E	24.0	20.0	56.0	4.6	45.0	50.4	3.85

CR: Columnar region; CGR: Coarse grain region; FGR: Fine grain region;
AF: Acicular ferrite; PF: Proeutectoid ferrite; FSP: Ferrite second phase;
FGS: ferritic grain size in the FGR

Table 4.2 Weld metal chemical composition (weight %). A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes. Welding depth: 0.5 m. (Bracarense, A. Q. et al. 2008).

Electrode	Mn	Si	Ti	P	S	O	C	Ni	Mo
A	0.033	0.010	0.000	0.015	0.007	0.261	0.055	2.020	0.000
B	0.501	0.309	0.018	0.020	0.012	0.083	0.087	0.055	0.000
C	0.513	0.384	0.015	0.014	0.009	0.092	0.070	0.069	0.000
D	0.609	0.370	0.013	0.025	0.008	0.079	0.075	0.036	0.440
E	0.343	0.199	0.011	0.026	0.007	0.110	0.090	0.026	0.000

Table 4.3 Weld metal mechanical properties from multipass V groove welded joint. A: commercial oxidizing type electrode; B, C, D and E: commercial rutile type electrodes. Welding depth: 0.5 m. (Bracarense, A. Q.et. al. 2008).

Electrode	Hardness (HV1) ^a	Y.S. (MPa) ^b	T.S. (MPa) ^b	Elong. (%) ^b	Reduction of area (%) ^b	Rupture stress (MPa) ^c	Charpy V 0°C (J) ^d
A	183.5	379	456	24.0	45.0	469	33.6
B	201.9	325	522	6.6	6.0	617	37.6
C	200.2	354	464	2.4	17.0	640	47.7
D	220.6	362	513	6.0	4.1	> 631 ^e	40.5
E	183.0	375	515	11.0	15.4	603	39.2

- a Average of 30 indentations
- b All weld metal tension test with 1 (one) test for electrodes A, B, C and E and 2 (two) tests for electrode D
- c Transverse tension test, average of 2 (two) tests for electrodes B, C and E and only 1 (one) test for electrodes A and D
- d Average of 3 tests
- e Rupture occurred in weld metal

Table 4.4 Partial results of project CSM in October 2010

Properties**	Selected experimental electrodes*		
	F2	F7	M4
Diff. Hydrogen. (ml/100g)***	15 / 30 / 20 18	14 / 15 / 19	****
WM Porosity (%)	0,14	0,13	****
WM Yield strength (MPa)	398	399 / 399	407 / 417
WM Tensile strength (MPa)	462	464 / 461	482 / 479
WM Elongation (%)	19	13,8 / 18,4	20,0 / 18,8
WM. Area reduction (%)	28,6	24,3 / 26,0	45,2 / 34,4
WM Charpy V 0°C (J)	51 / 51 / 48	61 / 56 / 58	54 / 48 / 54
WM Hardness (HV5)	172	****	190
Bending angle (°) 2T lateral bending	180 / 180 180 /180 / 70	65 / 70 / 70 / 180 180 /180 / 180	180 / 180 / 180 180

* F2, F7 and M4 correspond to three development stages presenting the best results

** Exception for diffusible hydrogen, properties were taken from tests in multiple bead welds deposited in V groove at simulated 10m water depth. Welds were made in laboratory by a mechanized gravity system inside a hyperbaric simulator

*** Diffusible hydrogen at 0,5m water depth

**** Results not available in October 2010

Table 4.5 – Cracking susceptibility evaluation in CTS tests

Electrode	Base metal	Depth (m)	CIP
E (commercial)	A	0.5	0.89
E (commercial)	A	10	0.76
E (commercial)	A	20	0.67
E (commercial)	B	0.5	0.26
E (commercial)	B	10	0.07
F7 (experimental)	A	10	0.0
R6 (experimental)	A	10	0.0

Base metal A (wt%): C : 0.212, Mn: 1.053, C.E.: 0.392

Base metal B (wt%): C : 0.159, Mn: 0.969, C.E.: 0.326

Diffusible Hydrogen (ml/100g) – E: 90, F7: 20, E6: 30

CIP: Crack Incidence Parameter (total cracks length / fusion line length)

Diver/Welder Training and Qualification

W. Jack Couch, Oceaneering International, Inc.

Divers and welders use a unique combination of two skilled trades. To understand the best way to access this combination of skills, looking at both the welding and commercial diving professions is required.

If you search the internet for welder training, there are thousands of hits, with almost every city and town having some type of welder training. A typical curriculum is shown below for a basic stick welder training program:

Subject	Clock Hours
Occupational Orientation and Safety	60
Basic Blueprint, Metallurgy and Weld Symbols	75
Welding Inspection and Testing	60
Electrical Fundamentals	45
Oxyfuel Systems	60
Cutting Processes – CAC/PAC	45
SMAW - Basic Beads	60
SMAW - Fillet Weld	105
SMAW - V-Groove BU/GOUGE	<u>105</u>
Total Clock Hours	615

There are also a number of night classes and OJT (on job training) opportunities, for welder helpers for those who cannot attend full time training. Welding instructors are usually quite skilled at the instruction they provide. Career length for welders depends on the type of welding being performed. Some welding projects require good physical fitness, while others can only require good vision and a steady hand. At production welding facilities, welders with 20, 30, and even 40 years of experience are not uncommon. Tack welders at a non structural manufacturer will be near the minimum wage, while duplex stainless pipe welders will likely be at the top of the pay scale.

Working welders have multiple welding processes that they may be required to master. SMAW (shielded metal arc welding) is normally the starting process for training welders, but many employers require (FCAW, flux core arc welding), GMAW (gas metal arc welding) and GTAW (gas tungsten arc welding) to earn top dollar in the welding industry.



GTAW welder training

An internet search for commercial diver training provides a fairly limited number of schools available. Each normally requires a full time training commitment of between 8 to 32 weeks. Curriculum from a typical commercial dive program is shown below:

Subject	Clock Hours
Orientation, Safety, and Industry Terminology	15
Diving Physics	30
Diving Physiology	18
Air Decompression	30
Dive Medicine	60
Chamber Operations	60
Seamanship and Rigging	90
Logs, Records, and Standards	15
Environmental Hazards	15
Diving Equipment	78
Marine Engines and Compressors Lab	16
Topside Welding and Oxy-Acetylene Cutting Lab	60
Underwater Work Lab	90
Underwater Cutting and Welding Lab	30
Mixed Gas Diving	30
Operations Planning	20
Industrial and Offshore Safety	<u>15</u>
Total Clock Hours	672

Companies providing commercial diving services are usually prevented from hiring employees who have not graduated from a commercial diving school, and most client companies will not allow a dive team member on the work site without the required commercial diving school training. Very few options are available for alternative training in the commercial dive business, with the exception of the US Navy and Chino prison dive school. Diving schools are challenged to keep the classes full, diving instructors tend to have a high turnover, and the dive school graduates often accumulate a good amount of debt by the end of training. Diving is physically challenging and requires a yearly diving physical. It is the

exceptional individual who dives for 30 years, with most moving to supervisor positions or other roles after about 10 years of diving experience. Shallow water inland divers tend to be on the low end of the pay scale while offshore deep diving offers the top pay scale.



From the challenges of the above two skill sets, we need to add a whole new level of complexity when the two are combined.. The first challenge is to pick an individual with one of the above skill sets and teach him the second skill set. Arguments will go on forever debating, is it easier to teach a welder to dive, or a diver to weld. There are numerous success and failure stories from either choice. Depending on the narrator, both can be quite convincing.

Assuming your choice is to take a welder and make him a diver, the obvious first hurdle is the completion of a commercial dive course, followed by either wet welder training and certification, or dry habitat welder training and certification. The obvious advantages are that a skilled welder will obviously learn the wet welding or dry habitat welding much faster than someone who is not a skilled welder. They will understand fabrication, fit-up tolerances, and welding equipment in general and easily adapt to the changes in the equipment. On the negative side, some find the decompression chambers, tight fitting helmets, mask and confined welding habitats bring on claustrophobic attacks, and others find living on offshore vessels, working 12 hour shifts and long spells away from their families more than they can handle. If the welder adapts well to the diver training, and the underwater welding work in general, it can still leave the challenge of safely adding this individual to a dive team. Much of the work involved in underwater welding projects can be heavy construction in low visibility conditions. An inexperienced diver will not be able to safely perform some of the tasks that lead up to the welding work. Common sense must be used to avoid placing the diver/welder trainee in a diving situation where you would not use any other inexperienced diver.



The final option of taking a diver and teaching him to weld seems straight forward with plenty of available methods and courses to teach welding. Yet there are companies that will take a diver with no welder training and start training him or her to weld underwater. This usually ends up with little usable skill in welding and the diver boasting “I can weld underwater but not on the surface.” Divers are the only ones capable of reaching the underwater worksite and 15 minutes of instructions on how to identify and close the master wing valve will have them putting subsea tree expert on their resumes. Two hours of melting things in the tank will also have them putting underwater welder on their resumes. All too often divers are given just enough instruction to take care of the immediate dive, which may work for some construction task, but provides a poorly trained diver/welder. If the diver is provided a week of underwater wet welder training, without previous surface welder training, you will end up with a poorly trained individual who can perform limited welding underwater with supervision, but completely lack proper safety, equipment knowledge, and essential variable understanding.

A welder to become a diver requires a commitment of 20 weeks by most standards, which produces a skilled welder and a trainee diver, yet the diving industry sometime feels they can train a skilled diver to become an underwater welder in a few hours or a few days. The industry must change its thinking. Training a diver to best industry practices for surface welding and testing the diver to these standards prior to ever beginning underwater welder training is recommended. Even then, all must understand that a diver trained to weld will initially yield a skilled diver and trainee welder.



Adequate skills in commercial diving and welding often are just the beginning for a good diver/welder, with additional training needed in proper fit-up techniques, training and testing in various welding processes used in dry habitat welding and NDT training and testing.

In conclusion, you can achieve your goal of highly skilled diver/welders by starting with a welder or diver either way. It's the short cuts in the training that will ultimately de-rail either process. Commercial diver training performed at a proper certified training school is usually well done, while in-house or a few day type welder training class tend to provide poor results, with a regular welding school providing the best trained welder.

Reliability of Underwater Wet Welding for Offshore Structures

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Pingsha Dong, University of New Orleans
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INTRODUCTION

It is well known that fixed and floating offshore platforms are subjected to environmental loads associated to hurricanes and storms. Under these conditions platforms can result with different type of damages or even completely collapsed. The degree of expected damage depends on factors such as: magnitude of the loads, age of the structure, location relative to the path of the hurricane or storm, type of structure, and prior structural condition.

Aging structures designed with the first specifications are prone to fail or result with severe damages under extreme loads. Additionally fatigue cracking, corrosion, and mechanical damages reduced the load carrying capacity of the structures. Therefore, these structures need to be assessed with current specifications. As a result of structural assessments, repairs, reinforcements or both are likely to be required to comply with current specifications.

Also, incidents developed during daily activities on these structures and surrounding vessel operations can result in damages to the structures. Some of the incidents associated with offshore operations are dropped objects, vessel collisions, anchor drag, fire and explosion. Resulted damages can be classified as dents, cracks, fractures, deformations, deflections, abrasion, wear, cuts, accumulation of mud and soil erosion.

Depending on the degree and type of damage there are several repair and reinforcement techniques used by the industry to comply with the specification requirements. However, only a few of these alternatives produce good quality repairs.

Underwater welding is a repair and strengthening option for underwater structural components. Reliable repairs and reinforcements can be achieved using appropriate designs and complying with specification requirements.

HISTORICAL PERFORMANCE OF OFFSHORE STRUCTURES

Over the years the offshore infrastructure has experienced the effects of hurricanes. According to the findings associated with the passage of hurricanes, actions have been taken to study and understand the effects of these events. Without available recommended practices for the design of fixed offshore platforms, platforms were designed, fabricated and installed since 1948. In the period from 1948 to 1969 30 platforms were destroyed by hurricanes. After hurricane Camille in 1969 the 1st edition of the API RP 2A for the design of fixed offshore platforms was issued. From 1974 to 1985 8 platforms were destroyed by 3 hurricanes. In 1992 hurricane Andrew destroyed 75 platforms (including caissons). In 2005 hurricane Katrina and Rita destroyed 45 and 74 offshore platforms, respectively. Even with more stringent design codes (21st edition API RP 2A) hurricanes Ike and Gustav in 2008 destroyed 59 and 1 platforms, respectively [1].

From 1948 to 2008 a total number of 307 platforms and caissons have been destroyed by hurricanes in the Gulf of Mexico, as shown in Figure 1.

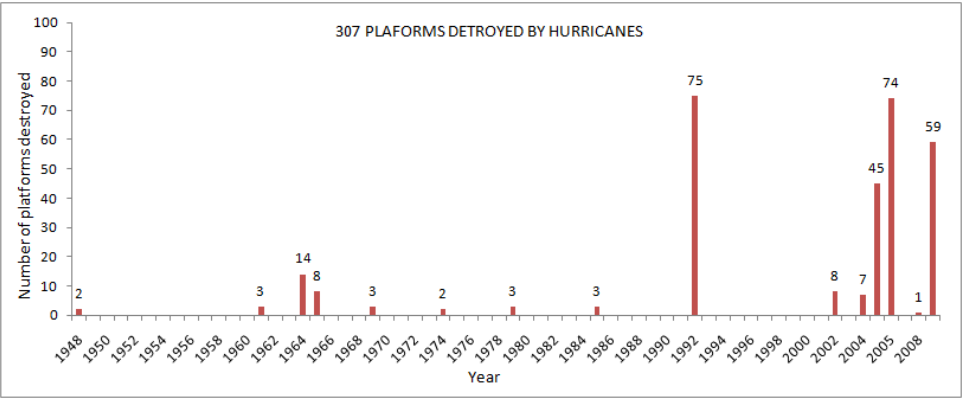


Figure 1. Platforms destroyed by hurricanes since 1948

It is clear that hurricanes are stronger and more frequent than ever before.

Platforms destroyed by Gustav and Ike

Recently, hurricanes Gustav and Ike in the fall 2008 affected approximately 3000 platforms in the Gulf of Mexico. Out of these affected platforms 60 were destroyed. Most of these (59) platforms were destroyed by Hurricane Ike and one destroyed by hurricane Gustav.

There are several factors that could be involved in the 60 platforms destroyed, some of which are: age, location with respect to the hurricane path, prior structural condition, type of structure, deck height, obstructed area in decks, orientation of the structure

Approximately 5% of the platforms installed in the 1970s were collapsed by hurricanes Ike and Gustav, see Figure 2. Note also in this Figure that even platforms designed recently (post 2000) have also failed [1].

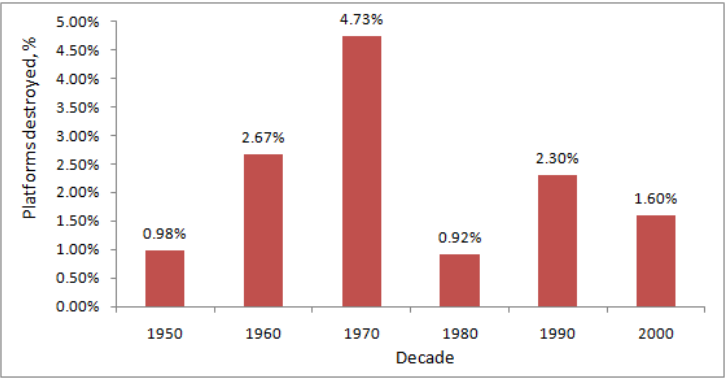


Figure 2. Percentage of destroyed with respect to exposed platforms by hurricanes Ike and Gustav versus installation decade

Platforms destroyed according to the structure type in descending number are as follows: 4-pile, tripods, caissons, and 8-pile structures, Figure 3.

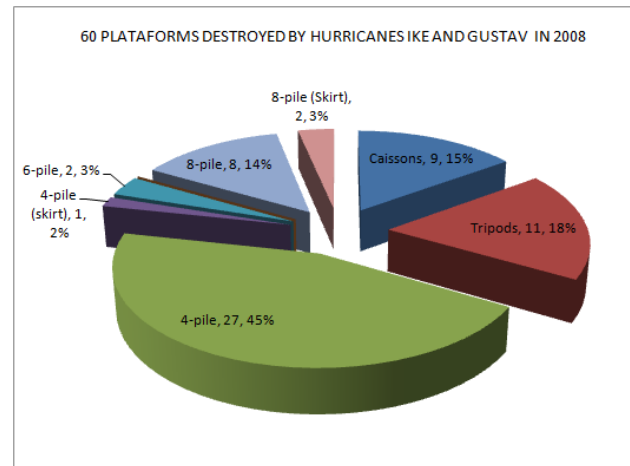


Figure 3. Type of structure, platforms destroyed and percentage

Based on its structural robustness, typical structures can be classified in descending order as follows: type 12-pile, 8-pile, 6-pile, 4-pile, tripods and caissons. According to this classification the number of destroyed structures should have followed the reverse order, in other words, the largest number of failures should have corresponded to caissons, followed by tripods, 4-pile structures, and so on.

The deck elevation is another aspect that contributes to the failure. Platforms with low deck elevation can see wave-in-deck with the possibility of experiencing destruction or substantial damage. Talking about wave-in-deck, a factor to be considered is the density of equipment, piping, enclosures, and appurtenances obstructing to the wave passage. Wave-in-deck could generate large horizontal load whose associated moment results in large tension and compression load on the columns and piles. Overloaded columns under compression loads can buckle and columns under tension loads could fail at the welded joints (pile-column).

Thus, caissons with empty decks could withstand hurricane better than more robust structures (e.g. 8-pile structure) with congested decks.

Structural damages

It is important to review the type of damages in offshore platforms caused by hurricanes because some of them could be good candidates for underwater welding repair. Also, the location of the damages in the structure should be known in order to identify the water depths where repairs may be required.

General damages in the structures resulted from the passage of hurricanes Gustav and Ike in Gulf of Mexico platforms are as follows [1]: pancake leg damage, 21 cases have been observed since hurricane Lili in 2002, bent deck beams, buckle braces, cracked welded joints, cracked legs.

Considering that the main structural components of fixed offshore platforms are legs or columns, braces, welded joints, and decks; the damages found in these components are the following [1]:

- a) Legs – buckles, cracks, tears, dents, holes, broken crown shim, and pancake
- b) Braces – buckles, dents, holes, cracks, tears, out of plane bowing, and severed
- c) Joints – cracks, punch-through of brace, pull out of brace leaving a hole on the chord, buckle nodes
- d) Deck – bent wide flange beams, bent deck columns, bents stairways and landings

For non-structural components

- e) Conductor Trays – cracks at joints, conductor torn loose from guide, tray drops and jams between conductors
- f) Appurtenances - miscellaneous damages o missing components

Additionally, seven platforms were leaning after the hurricanes passage due to damages on the legs, piles or both.

UNDERWATER REPAIR TECHNIQUES

There are several techniques available for the underwater repair of the type of damages previously mentioned; a careful selection of the repair technique has to be made for a successful repair.

Among the mitigating measures are drilling holes at the ends of cracks to stop its propagation. Removal of fatigue cracks by grinding off the cracked metal could increase the fatigue life of the component. Controlled grinding in “U” shapes arrests crack propagation, but the stress increases due to the reduced thickness of the cross-section. After the crack restarts it tends to propagate at faster rates.

Typical repair techniques include stress grouted clamp, hyperbaric welding and underwater wet welding.

- Stress grouted clamps have been used in many repairs because there is no need of tight tolerances, although poor fabrication control could result in poor fitting with grout leaks.
- Hyperbaric welding could offer good weld quality; however, this repair technique requires the design, construction and installation of a hyperbaric chamber to create a dry environment. Such hyperbaric chambers could become very complicate to build, install and seal in congested tubular connections.
- Underwater wet welding has been recognized to have the advantage of requiring simple equipment and welds are straight forward applied by qualified diver/welders.

AWS D3.6 M: 1999 REQUIREMENTS

According to the AWS D3.6:M1999 Specification [2], underwater welds can be classified as Class A, Class B, Class C or Class O. Class A welds are considered to have equivalent quality as welds deposited at surface (in a dry atmosphere). Class B wet welds are intended for less critical applications where larger discontinuities can be tolerated. Class C underwater welds are intended for non load-bearing applications. In order to produce quality underwater welds this specification has several requirements, such as:

- Welding Procedure specification
- Qualified welders
- Visual examination
- Radiographic examination
- Mechanical Testing
- All weld metal tension tests
- Bend tests
- Macro etched inspection
- Charpy V-notch tests

Weld quality required by the welding specification depends on the weld class selected for a particular application. This paper focuses basically on underwater welds intended for load bearing applications.

S-N curves of underwater wet welds are required for fatigue assessments. However, these curves should be representative of the used welding procedure specification, type of filler metal and water depth.

IMPROVEMENTS IN UNDERWATER WET WELDING

During the past years efforts have been made by different institutions and companies to improve wet welding. Improvements have been achieved in understanding the welding phenomena and improving the wet weld quality. Among the achievements are the following:

- Adding titanium and boron to commercial rutile flux coating promoted the formation of acicular ferrite. Wet welds deposited at 33 ft of water depth exhibited up 60 percent of acicular ferrite [5].
- Wet welds deposited with rutile grade electrodes with additions of ferro-manganese, ferro-titanium and ferro-boron exhibited acicular ferrite with approximately 90% and 60% at 100 ft and 300 ft, respectively [9, 10].
- Hydrogen assisted cracking in the heat affected zone and weld metal deteriorates the integrity of wet welds, therefore, consumable electrodes that produce low diffusible hydrogen in the weld metal are desirable. Very low values (18-20 ml/100 g) of diffusible hydrogen have been reported with high amounts of oxidizing agent (hematite) in the flux coating [8, 17].
- Toughness improvements of wet welds by nickel additions to the flux coating of SMAW electrodes have been reported [7, 11].
- Three commercial electrodes (E7018, E6013 and E7024) were tested for wet welding applications at three water depths (50, 100 and 150 m). Amongst the electrodes tested the E6013 electrode grade has been identified as the best for wet welding applications [13-16].
- Flux covered tubular electrodes with exothermic additions (aluminum and calcium carbide) have been tested for wet welding, the main findings are an increased recovery of alloying elements and reduced porosity in the weld metal [19].
- Porosity reduction has been successfully achieved; low titanium and low boron addition to rutile flux coating reported an approximately linear porosity variation from 0.6% (at 70 ft) to 2.8% (at 300 ft) [10]. Rutile electrodes with ultra-low carbon steel rods have reported porosity values under 1% at 50 m [18].

- Studying the mechanisms of porosity formation in wet welds has contributed to a better understanding of the wet welding phenomena and the implementation of mitigating measures. Porosity may be formed by molecular hydrogen [3,4] or carbon monoxide [5, 18, 20].

In order to have reliable AWS D.36:M Class A or B underwater wet welds for the repair or strengthening of damaged structures it is necessary to integrate the improvements up to date achieved. Isolated improvements may not be enough to consistently deposit reliable wet welds.

UNDERWATER WELD FITNESS FOR SERVICE

Fitness-for-service (FFS), also often referred to as Engineering Critical Assessment (ECA) offers a powerful for defining weld integrity and its fitness for continued service or repair/replacement using well-established quantitative fracture mechanics principles. For underwater wet-welding based repairs, FFS methodologies can be used to establish fitness for purpose based wet weld quality definition or weld defect acceptance criteria. These also include fitness for service assessment of complex structures such as underwater welds in tubular structures and plate structures. A few recent examples are described below to illustrate such an approach based on recent developments in other industries taking advantage of some of the state of the art fracture mechanics analysis methods over the last decade.

Weld Discontinuity Acceptance Criteria

As discussed in previous sections in this white paper, underwater wet welding tends to introduce various forms of defects or discontinuities in the form of surface and sub-surface pores, micro-cracks, inclusions, etc. Recent developments [21-22] have shown that conventional weld quality definition can be excessively conservative and difficult to achieve. One major finding is that it is the distribution of discontinuities that are more important than sizes of individual discontinuity features.

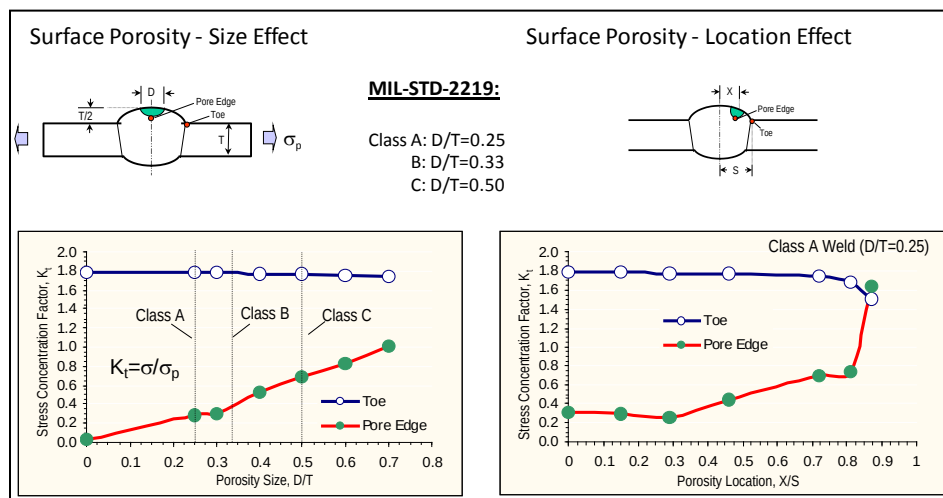


Figure 4. Effect of pore size and pore location on stress concentration factor K_t

As shown in Figures 4 and 5 for assessing porosity at surface and sub-surface in fusion welds on its effects on stress concentration with respect to some of the existing weld discontinuity acceptance criteria,

e.g., MIL-STD-2219, maintained by AWS D17. By means of a polygonal element method which is capable of modeling a surface or sub-surface discontinuity embedded in a single polygonal element, the stress concentration at the surface discontinuity can be readily compared with that at either weld root or weld toe. The left of Figure 4 shows that the stress concentration at a surface pore increases with the size of the pore. At $D/T \sim 0.25$ for Class A weld, the actual stress concentration at the pore does not have any noticeable influence on the stress concentration at weld toe, nor does it cause any concern due to much lower magnitude than that at weld toe. The weld toe position continues to dominate the structural integrity of the joint. However, the location of such a pore relative to weld toe is more important than its size, as shown on the right of Figure 4.

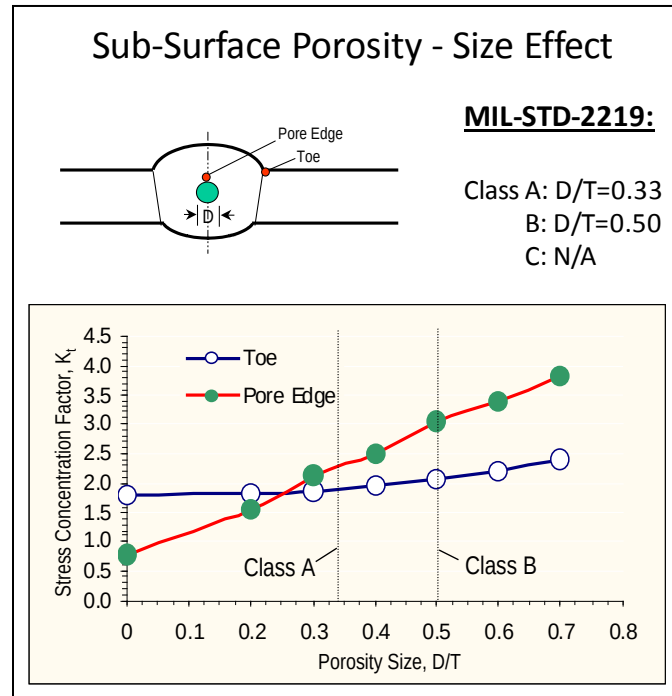


Figure 5. Effect of subsurface porosity size on stress concentration factor K_t

For a sub-surface defect shown in Figure 5, it is interesting note that stress concentration factor increases as pore size increases and surpasses the stress concentration factor at weld toe at about $D/T \sim 0.25$, smaller than that required by Class A weld acceptance criterion ($D/T=0.33$), see Figure 5 on the left.

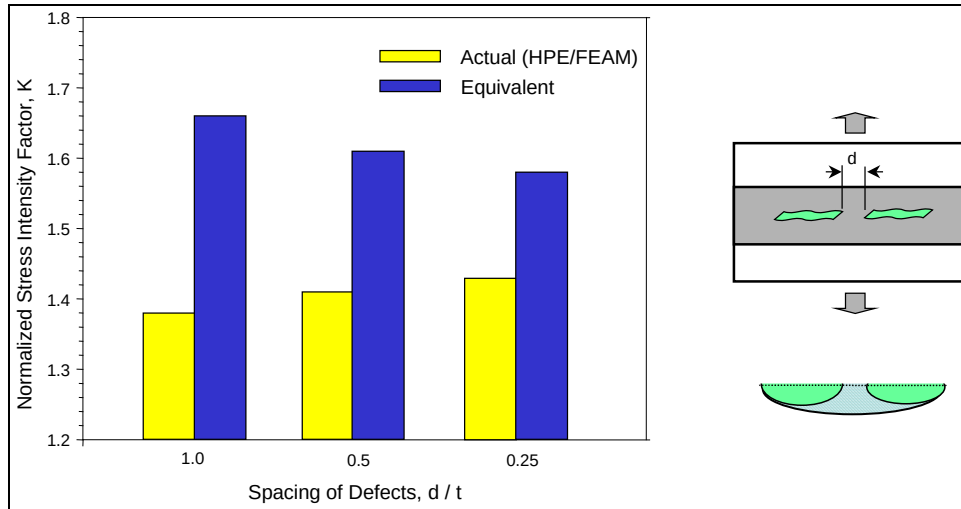


Figure 6. Effect of defect spacing on the stress intensity factor

Most of the existing weld discontinuity criteria such as those illustrated in Figures 4 and 5 are empirically based and tend to be overly conservative for most cases. These criteria can severely penalize underwater wet welds. Figure 6 summarizes a recent evaluation on defect spacing requirement in ASME Div 2 design code. The code stipulates that if two co-linear or -planar defects next to each other with a spacing d . A combined crack size plus the spacing d should be used to determine the acceptance of such a weld. A finite element alternating method is used here to assess the actual stress intensity factor K to compute the actual stress intensity factors for both the equivalent crack and two individual cracks. The results are summarized in Figure 6. As the defect spacing (d) increases, the conservatism using an equivalent crack rapidly increases, comparing with the actual maximum stress intensity factor calculated at individual crack locations. The resulting benefits for using the latter is enormous for qualifying underwater wet welds without sacrificing structural integrity.

Residual Stress Effects

Underwater wet welding can significantly increase residual stresses due accelerated cooling. All FFS or ECA procedures require consideration of residual stresses in fatigue and fracture driving force calculations. For underwater welding, a superficially obvious choice seems to assume yield magnitude residual stress uniformly distributed in a weld area. However, improved understanding in residual stress development mechanisms over the last decade [23-25] has shown that such seemingly conservative assumption is not applicable for weldments subjected to high convective cooling, such as the case in underwater welding. As shown in Figure 7, the transverse residual stresses due to “high convection cooling” are rather benign (actually rather beneficial), contrasting to that corresponding to “low convection cooling” simulating ambient air conditions. Note that it is the transverse stress component that directly contributes to fracture driving, e.g., K in performing FFS assessment. For the case of “high convection cooling,” weld metal upon deposit cools much faster on the surface than in the plate, resulting compressive residual stress near surface and tension near mid-plate thickness. A more comprehensive study is certainly needed under various underwater repair welding conditions in order to establish recommended practices in residual stress distributions for performing FFS assessment for underwater repairs.

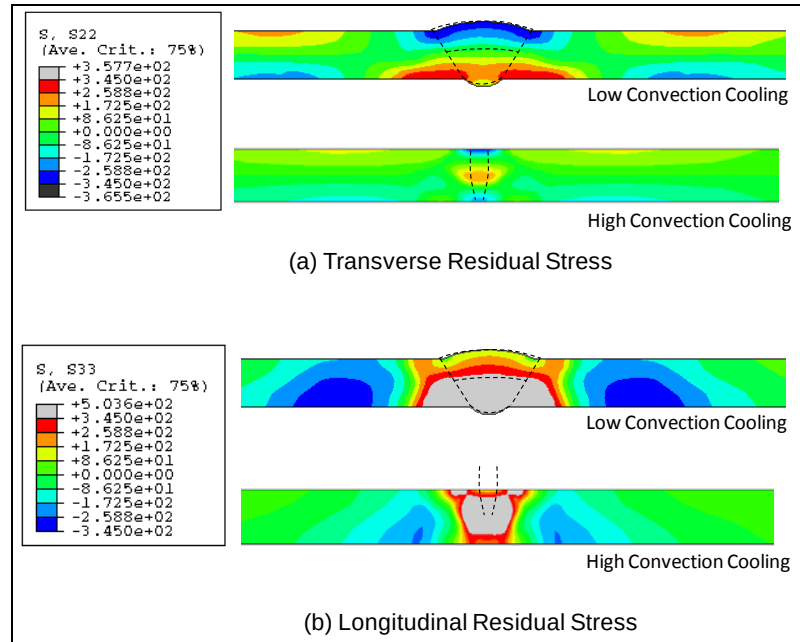


Figure 7. Effect of convection cooling on residual stress

Rapid K Solution Procedures for Offshore Structures

One major hurdle in performing FFS of offshore structures is the complexity of joint geometries that make fracture mechanics based K solutions much more difficult, contrasting to geometric simplicity in dealing pressure vessel and piping components on which K solutions are well established in FFS Codes and Standards, e.g., API 579-RP/ASME-FFS and BS 7910. For tubular joints and plate joints in fixed and floating structures, a brute force finite element based computation is often needed due to lack of handbook based solutions. Thanks to recent developments, particularly the so called mesh-insensitive structure stress method, which is a traction-based stress analysis method. A rapid engineering estimation of K solution now becomes possible once the traction stresses are calculated using the structural stress method. As an example, a FPSO side shell connection is evaluated using both the new method [26] and the conventional surface extrapolation based hot spot stress methods, the consistency in stress concentration factor calculations (normalized by unit side shell pressure) can be clearly seen in Figure 8, labeled as “the new structural stress method,” while the hot spot stress methods using two surface extrapolation schemes show significant variability.

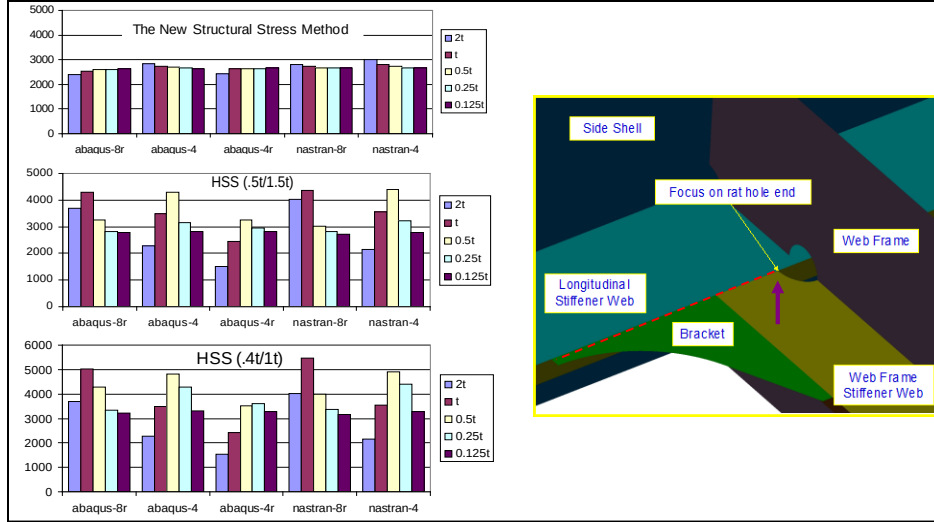


Figure 8. Comparison of stresses calculated with the new structural stress method and the traditional hot spot stress method

With the traction stresses calculated, the stress intensity factors at any given location can be calculated using existing K solutions expressed in terms of membrane and bending components of traction stresses [see 27], as described in Figure 9.

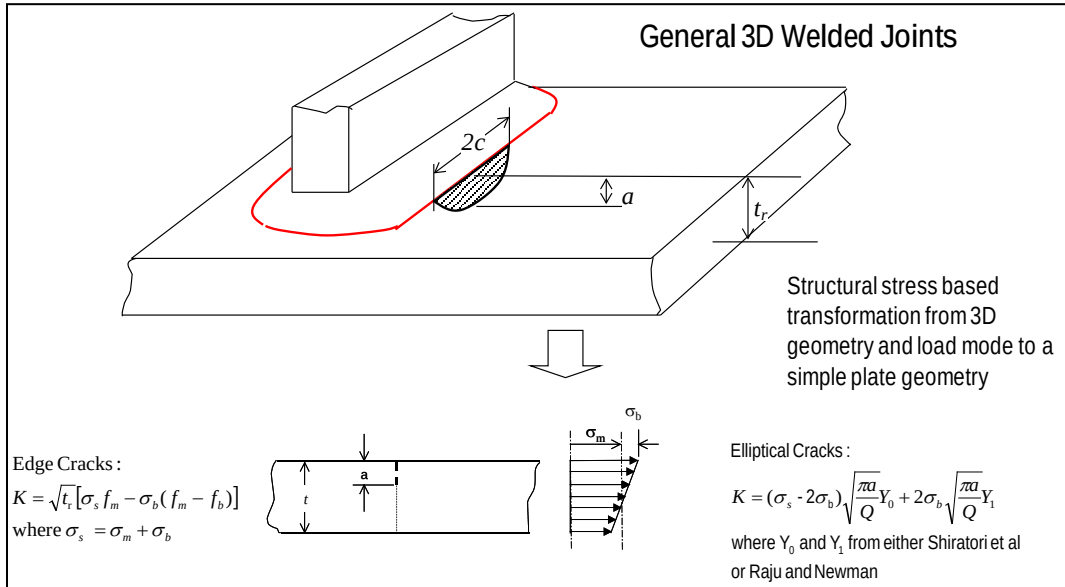


Figure 9. Illustration of general 3D welded joints

The validity of such a K solution scheme has been validated using existing weight function based K solutions, e.g., as shown in Figure 10.

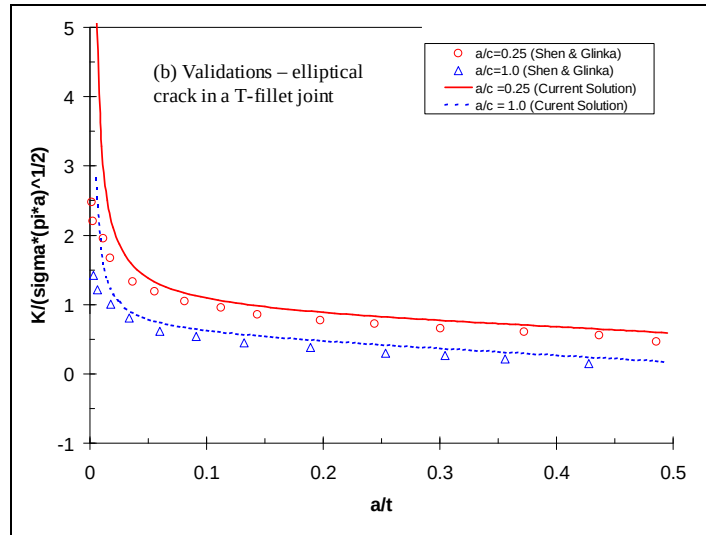


Figure 10. Stress intensity factor as a function of a/t

For tubular joints, the effectiveness of the traction stress analysis is illustrated in Figure 11 [27]. The corresponding K solution can then be readily obtained using the equations given in Figure 9.

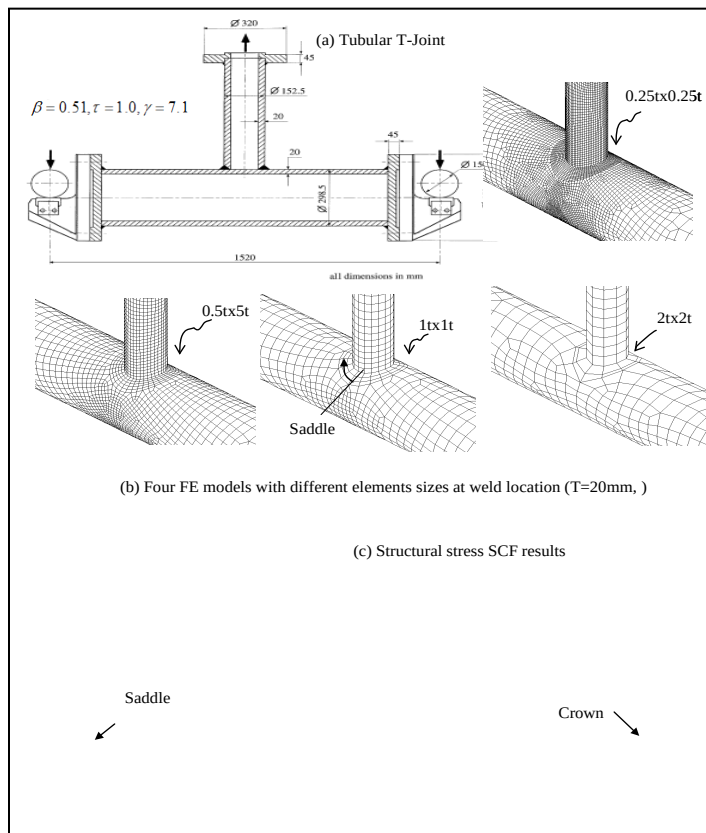


Figure 11. SCF calculation for a tubular T-Joint using Traction Stress Method

RELIABILITY OF UNDERWATER WELDS

It is important to mention that the global structural integrity of an offshore structure depends on the performance of each of the structural components, such as: columns, braces, joints, piles, and so on. However, depending on the structural arrangement and robustness the failure of a single component could or could not change significantly the global reliability of the structure.

Structural robustness is defined as the ability of the structure to tolerate damage. For example for two types of structures, e.g. 8-pile and 3-pile, designed under the same design codes, the 8-pile structure has more robustness than the 3-pile structure. Therefore, more damages could be tolerated by the 8-pile structure, while the same damages could be the reason for the failure of the 3-pile structure. Damages alone need to be severe enough to cause the failure of a robust structure. Structural failure occurs as a result of two or more combining factors, damages affecting the structural integrity plus loads greater or equal than the design loads. Hurricane overloading alone can cause the failure of a structure.

Fatigue is a deterioration process due to operational wave loads, and is the most common cause of failure of welded connections. This type of damage is manifested by cracks, which have three stages: initiation, propagation and accelerated growth. A weld is said to fail under cyclic or fatigue loading when the depth of the crack equals a critical value, usually taken as the thickness of the component. Change of material properties in the heat affected zone (HAZ), stress concentration due to geometrical changes, residual stresses and cyclic loading are the main causes of fatigue failure of welded connections.

Weld reliability will be considered in this paper as the condition in which the weld complies with its designed function during a determined service life period without failure.

Weld reliability based on the strength approach

In a welded connection the strength of the filler metal is equal or greater than the strength of the base metal; therefore, the weakest link would be the base metal. However, considering that underwater welds (wet welds) have more defects than surface welds one could state that the filler metal could be the weakest link in the welded connection. Consequently, the design of an underwater wet welded connection should consider that the total strength of the welded connection shall be equal or greater than the load.

$$S_w \geq L \quad (1)$$

where S_w is the strength of the weld and L is the load.

If the design complies with this basic principle underwater welds should be reliable. The degree of reliability of a welded connection depends on how greater or smaller S_w is compared to L . Strength and loads are in fact uncertain and can be modeled as random variables with probability density functions $f_{S_w}(s)$, and $f_L(l)$, respectively, (in this case both random variables are supposed to be statistically independent). Then, the probability of failure of a welded connection can be expressed as:

$$P_f = P(S_w \leq L) = P(S_w - L \leq 0) = \int_{L > S_w} f_{S_w}(s) f_L(l) ds dl \quad (2)$$

Solving the integral in Equation 2 requires in general the use of numerical methods. The simplest case is when both strength and load are normally distributed random variables. In this case the probability of failure can be calculated analytically as:

$$P_f = \Phi(-\beta) \quad (3)$$

where β is known as the reliability index and Φ is the standard normal distribution function, the reliability index can be calculated with the following equation

$$\beta = \frac{\mu_{S_w} - \mu_L}{\sqrt{\sigma_{S_w}^2 + \sigma_L^2}} \quad (4)$$

where μ_{S_w} and μ_L represent mean value and σ_{S_w} and σ_L the standard deviation of the strength and load, respectively.

Known the mean and standard deviation of the strength and the load, the reliability of a given welded connection can be calculated with Equation 4.

The relationship between the reliability index and the probability of failure is shown in Figure 12. As the reliability index decreases the probability of failure increases.

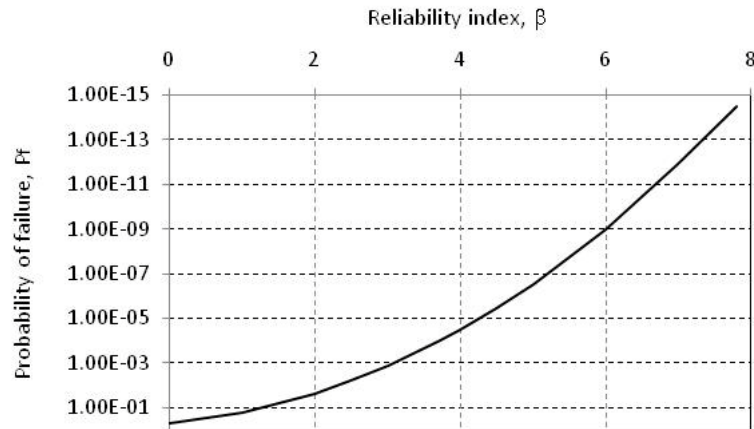


Figure 12. Relationship between the probability of failure and the reliability index

In general strength and load are not normal variables; therefore Equation 3 is not strictly valid. However, a numerical method (FORM, *First Order Reliability Method*) that transforms the original variables in equivalent normal deviates, and also linearizes the equation of failure. In this way, Equations 3 or 4 can be used as a good approximation of the probability of failure or reliability index.

By using Equation 4 one can determine approximately the reliability index for underwater welds. The calculated reliability index is compared with the acceptable minimum reliability level. If the reliability index is smaller than the acceptable minimum reliability index, then an action shall be taken. The reliability index is increased by increasing the size of the weld or reducing the load.

Fatigue Damage

Fatigue is the commonest degradation process in welded connections of offshore structures caused by cyclic loading. Fatigue is manifested as cracks that develop typically at hot spots at the weld toe in the heat affected zone or in the weld metal. One or more cracks can initiate and propagate through the wall thickness. In this paper, fatigue failure is considered to occur when the crack depth reaches the wall thickness (through thickness crack) of the structural element where the crack grows.

Three stages are identified in the growth of fatigue cracks, see Figure 13, stages are:

Stage I. Microscopic features or defects at the surface of the material such as pores, cracks, undercuts, and slag inclusions combined with mean stress and the environment lead to the initiation of a crack. Certain period of time or number of cycles are needed to initiate a crack from a microscopic to a macroscopic size. At the end of this stage, cracks can be detected and sized.

Stage II. It is a region of stable crack propagation typically with an increasing growth rate. In this stage, superficial features have low influence in the crack growth. An additional period of time or number of cycles is required to grow a fatigue crack until it reaches a critical size.

Stage III. Due to the crack size reached in stage II the mean stress increases, resulting in very rapid crack propagation. This stage is a small fraction of the total fatigue life. The crack penetrates the thickness of the structural component.

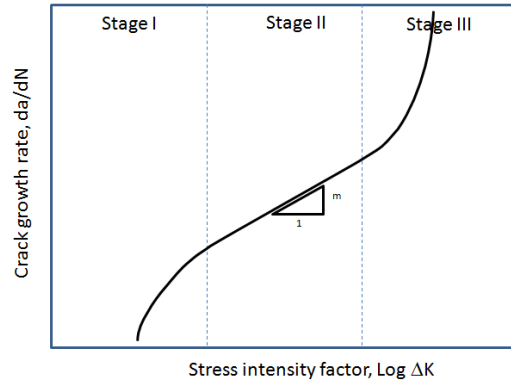


Figure 13. Stages in the propagation of fatigue cracks

Fatigue damage D can be expressed as Miner's rule.

$$D = \sum_i \frac{n_i}{N_i} \quad (5)$$

where n_i is the number of loading cycles associated with a given stress range i and N_i is the endurance number of cycles at the stress range i . Failure of a welded connection is when $D \geq 1$.

On the other hand, the Paris & Erdogan equation is typical used to assess crack growth as a function of the number of stress cycles, based on fracture mechanics

$$\frac{da}{dN} = C(\Delta K)^m \quad (6)$$

where a is the crack size, N number of stress cycles, C and m are material dependent variables and ΔK is the stress intensity factor range, which according to Newman and Raju approximation is

$$\Delta K = S \cdot Y(a, X) \cdot \sqrt{\pi a} \quad (7)$$

where S is the stress range, $Y(a, X)$ is the geometrical correction factor as a function of the crack size.

The stress intensity factor takes into account the material thickness, environment and stress ratio.

Part of the scatter in fatigue crack growth rate data was attributed to poor experimental fatigue testing. However, various researches after studying this problem concluded that the scatter in the fatigue crack growth rate data is due to material in-homogeneities.

The crack depth as a function of the number of cycles can be calculated with Equation 6. For example, Figure 14 presents three curves of crack size versus number of cycles. These curves were obtained for 2024-T3 aluminum alloy; curve b was calculated with the Paris equation using deterministic values for the material parameters. Assuming C and m as random variables different curves were obtained following a path in the region denoted by curve-a to curve-c, these curves resemble the crack growth versus number of cycles curves obtained with experimental tests for the 2024-T3 aluminum alloy. The use of deterministic values could lead to under- or over-estimates in the number of stress cycles required to reach a given crack size.

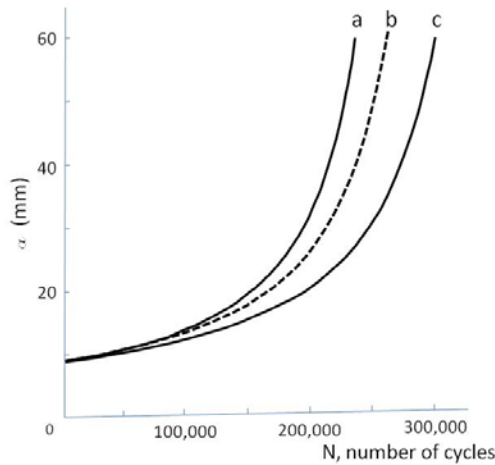


Figure 14. Crack growth as a function of number of cycles curves [28]

Using the fracture mechanics approach an estimation of the probability of failure (or reliability) of the weld can be estimated as a function of time. Failure is considered to occur when the crack equals a critical value, a_c , usually the wall thickness of the structural component. The equation to determine failure is:

$$\psi(a_N) = \int_{a_0}^{a_N} \frac{da}{Y^m(\sqrt{\pi a})^m} = C \sum_{i=1}^{N(t)} (\Delta S_i)^m \quad (8)$$

where $\psi(a_N)$ is an indicator of the accumulated damage associated to crack growth from the initial crack size (a_0), to a crack size (a_N) produced by the number of cycles expected in a time period $N(t)$.

The initial cracks size is closely related to the quality of the weld.

Uncertainties in fatigue analysis

Kirkemo (1988) [28] provides a comprehensive review of uncertainties in fatigue analysis. For simplicity reasons some of the random variables are commonly considered as deterministic values. Among the uncertainties are the following: sea waves, hydrodynamic loads, structural response, hot spot location, stress concentration factors, number of stress cycles, stress ranges, stress intensity factor, geometry of the connection, surface quality of the weld, material parameters, S-N design curves.

IN SERVICE INSPECTION

During the operation staged, underwater inspections are commonly carried out to verify the condition of the structure. Just after the structure installation a general visual examination of the structural components is performed by experienced divers or with remotely operated vehicles to identified possible damages occurred in the transportation and installation stages. Periodic underwater inspections are planned during the service life of the structure to detect and size damages caused by daily operation activities and environmental loads. Among the damages associated with environmental load is fatigue of welded connections. Depending on the type and extension of the damages, structural assessments may be necessary to determine the current condition of the structure and if required repairs and strengthening recommendations may result.

Non-destructive techniques such as magnetic particles (MPI) and electromagnetic are required to detect fatigue cracks. Detailed visual inspection only detects through thickness cracks that present secondary cracks out of the weld toe, when the crack opening makes cracks visible to the neck eye. For the application of MPI and detailed visual inspections the area to be inspected needs to be cleaned to bright metal. Other non destructive techniques do not require high level cleaning for detection and sizing fatigue cracks.

Considering that the number of submerged welded connections in offshore structures can vary from approximately one hundred joints for a shallow water three-pile structure to a few hundred for an eight-pile jacket, it would be very expensive to periodically inspect all welded joints with non-destructive techniques. Instead, operators using their experience and fatigue analyses can determine joints susceptible to fatigue damage, which are included in the periodic non-destructive inspection plan. Risk based inspection methods are also used to determine not only the joints that need to be inspected, but also the inspection frequency to maintain an acceptable reliability level.

The inspection results also have uncertainties, because there is a probability of detection (POD) of cracks associated with the inspection method used. Short and shallow cracks may be missed while large and deep cracks may be readily detected. Some of the factors that affect crack detection are cleaning of

the metal surface, underwater visibility, location and size of the crack. There are several equations for the probability of detecting a crack a_D , the exponential function commonly used is given by equation 8.

$$P(a_D) = 1 - \exp(-a_D/\lambda), \quad a_D > 0 \quad (9)$$

where λ is a detectable crack size.

Figure 15 illustrates probability of detection curves obtained with Equation 8 for two detectable crack sizes ($\lambda=1$ and 2 mm). As above mentioned, for a given detectable crack size the probability of detection increases as the size of the crack increases.

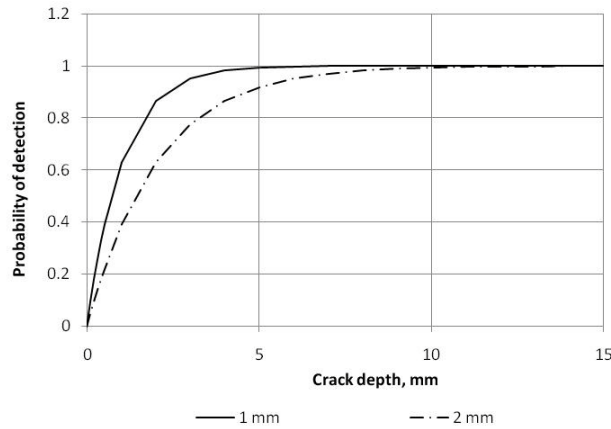


Figure 15. Illustration of probability of detection curves for two detectable crack sizes ($\lambda=1$ and 2 mm)

The degree of reliability of a welded connection is given by a reliability index (β), which is a function of fatigue damage which in turn is a function of time. Thereafter, as the number of cyclic loading increases the fatigue damage increases and the reliability index decreases. After certain period of time the expected fatigue damage is represented by a crack size. An underwater inspection is then required to confirm the expected crack size.

Figure 16 shows an example of reliability index variation as a function of time or number of stress cycles and the updated reliability index after MPI with no crack detected. In this example, the minimum reliability index level is $\beta_{min} = 3.72$ with and associated probability of failure $P_f=10^{-4}$, therefore, the first inspection is scheduled for the fourth year after installation. Since no crack was detected in the first inspection the reliability index is updated ($\beta = 8$) and the next inspection is schedule for the tenth year after installation. No crack was detected in the second inspection, then the reliability index recovers is previous value ($\beta = 8$). The minimum reliability value is reached after the intended service life (i.e. 20 years) of the structure; consequently no further inspections are scheduled, unless the service life is extended the following inspection would be at year 21st.

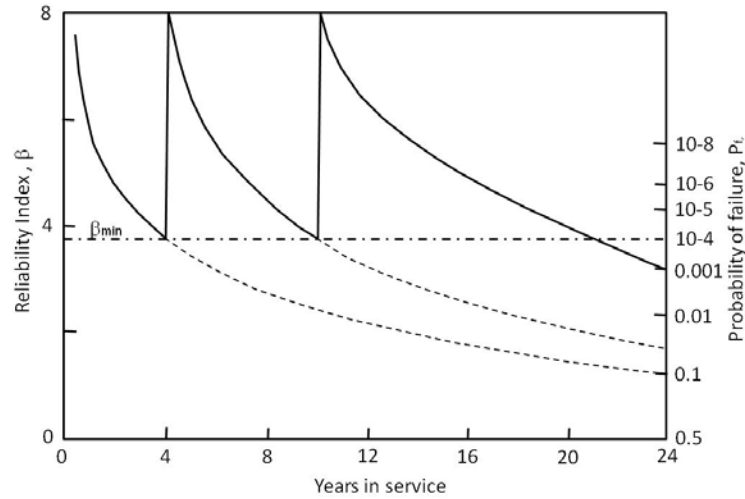


Figure 16. Inspection scheduling and variation of the reliability index with time [28]

Figure 17 shows the variation of the reliability index as a function of time or number of stress cycles and the updated reliability index after MPI with crack detected. The inspection carried out at the fourth year after installation reported a crack. After the crack detection two options were considered: a) the crack is not repaired and b) the crack is repaired. In the first case the reliability index is updated (increasing from 3.72 to 6), it decreases with time at a faster rate than the design reliability index, requiring a second inspection 1.5 years after the first inspection. On the second case, if repair action is taken immediately after crack detection, the updated reliability index recovers its initial value (i.e. 8), which also decreases with time at a faster rate than the design curve requiring a second inspection 2.5 years after repair.

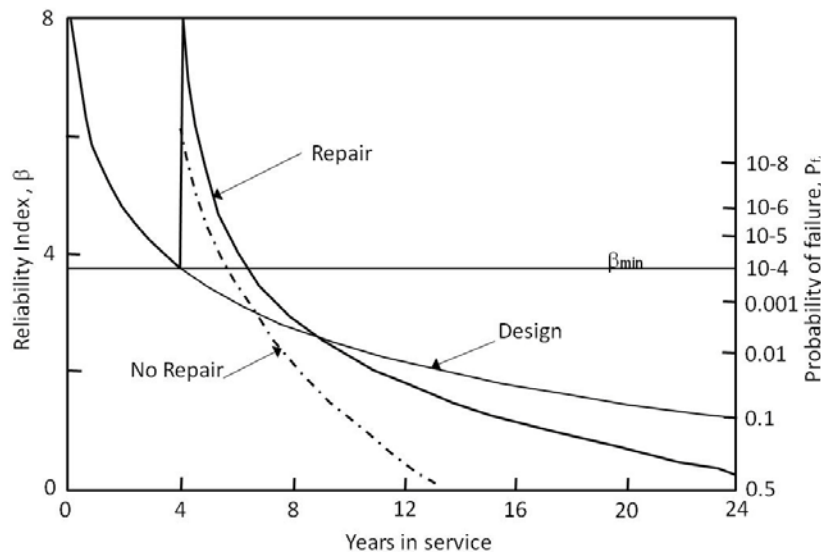


Figure17. Inspection scheduling, repair, and variation of the reliability index with time [28Error!
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A faster decreasing rate of the reliability index for a given underwater weld repair could be associated to the increasing number and size of defects in underwater welds. For this type of analysis S-N design curves for underwater repair welds are required.

Based on structural analyses a single crack in a welded connection of an offshore structure may be unimportant to global strength of the structure. Therefore, in these cases the repair of fatigue cracked joint may not be considered. In some cases the structural member with through thickness cracks in the welded connections has been removed from the structure instead of repairing the damage. This practice is not recommended because the operator may consider adding more equipment or loads or extending the service life of the structure requiring the original or more structural capacity.

CONCLUSIONS AND RECOMMENDATIONS

Based on the information above presented the following conclusions and recommendations are given:

- Hurricanes and storms are stronger than ever before increasing the probability of failure of offshore structures.
- Aging structures have damages or strength demands that may need repair or reinforcement to comply with current codes or to extend their service life.
- Reliable underwater welds need to be design to comply with the strength and fatigue demands.
- During the past years several improvements on wet welding have been achieved, which alone or combined increase the reliability of wet welds.
- Based on structural assessments and appropriate designs reliable underwater welding can be used to repair or reinforce offshore structures
- For reliability analyses inspection of welds becomes necessary to update the reliability indexes.

The new developments in the area of fitness for service assessment procedures discussed above can have significant impact on underwater repair for offshore structures, including:

- Providing theoretical basis for developing fitness for purposed based acceptance criteria for performing underwater wet repair welds by recognizing that some forms of discontinuities in terms of both sizes and distributions are not harmful for intended services
- Eliminating excessive conservatisms in residual stress treatment in deriving fracture driving solutions, e.g., K
- The traction based stress calculation method not only provides a consistent and accurate stress concentration characterization for complex joint types, but also offers a rapid and accurate K solution method for performing fracture mechanics based fatigue and fracture calculations

In order to achieve reliable repairs or reinforcements with wet welding in fatigue sensitive areas, the following recommendations can be applied:

- Geometry improvement methods such as burr grinding, disc grinding should be considered to improve the fatigue performance of the underwater weld.
- Residual stress methods such as hammer or shot peening should be considered to induce compressive stresses at the hot spots.

- Development of consumable electrodes for wet welding typical steels incorporating the finding up to date achieved.
- S-N curves for the developed electrodes are needed to assess the fatigue performance of wet welds.

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Opportunities for Improving Underwater Inspection, Repair and Reliability Analysis

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Underwater inspection, repair, and reliability analysis can draw on recent advances in technology and the use of applied science to make significant improvements in assessing structural integrity as well as inspection and repair economics. To take advantage of these advancements requires cooperation among the functional individuals that make up the team to achieve inspection, analysis, weld repair and make a prediction of remaining service life. The following goals are identified as opportunities for advancement that can improve quantitative and accurate measurements, assessment of structural integrity, rapid assessment, data acquisition, data storage and retrieval, indication location information, weld repair and design, and inspection efficiency.

1. More quantitative nondestructive inspection and evaluation

To make more accurate remaining service life predictions it is necessary to use increasingly quantitative inspection and evaluation techniques to accurately assess the nature and size of indications. Assessing large structures will also require indications to be rapidly and nondestructively located and measured, including a second independent measurement for verification. When the inspector makes the measurement the exact position on the structure is determined with a local positioning system and this position information is transmitted with the inspection data to the center.

2. More information from nondestructive wave analysis

Nondestructive elastic and electromagnetic wave inspection and analyses techniques to achieve multiple independent measurements and correlation to materials microstructure and aging phenomena and precracking evidence, such as residual and local strain intensity and distribution. Both elastic and inductive (electronic) waves have different phenomena but similar mathematical expressions for their impedances. Additionally, both types of waves can lead to resonance behavior in the material at some frequencies, these resonance frequencies can couple with lattice details, such as strain, inclusions, interstitial solutes, corrosion products, coating degradation, etc. The intensity of these resonant signals can be measured, correlated, and used to characterize structural indications. For example, the proper heat treatment for T91 boiler tube steel has recently been assessed by correlating acceptable microstructure and properties with electrical impedance and hysteresis measurements.

A wave signal has both time and frequency as independent variables, i.e., $\sin(\text{frequency} \times \text{time})$. Traditional techniques and practices have primarily used time based information. These techniques have only used some of the information content of the wave based signal and by also using frequency analysis methods more information about the material is potentially available. The frequency content of a wave can be changed to generate a wave with a wavelength that is dimensionally similar to a specific indication size, allowing wave techniques to be tuned to specific types of indications relevant to structural management. There are various frequency analyses techniques such as Fourier analysis, wavelet analysis, harmonic signals, nonlinear techniques and analysis (such as Lamb waves), wave attenuation and velocity information, which can offer significant information as to materials state awareness. Significant advancements have been made in nondestructive instrumentation, rapid data acquisition hardware and mathematical tools for both time and frequency based wave analyses methods.

3. More advancements in nondestructive testing equipment allowing multiple mode readings and signal analysis for verification and improved reliability assessment

The last decade has seen many advancements and significant improvements in nondestructive testing tools. Full frequency scanning NDE technologies allow for the rapid application of various wave measurement techniques and mathematical wave analysis methods. Pulsed laser techniques have been developed for generating and measuring elastic waves within a material. These pulsed laser systems can be applied from a remote distance of up to tens of meters.

The inspector needs to make at least two independent measurements using different inspection practices to verify the indication. There are nondestructive tools that have more than one sensor type e.g. elastic or electronic impedance associated with a single control module. These tools simplify the process of collecting additional independent measurements for indication verification. The manufacturers of nondestructive testing instrumentation are very capable of further producing the next generation of tools and accessories, especially with evidence that the marine inspection community is willing to be trained, can define its informational needs and is willing to make the investments required.

4. More advanced data transfer and storage for rapid analyses and later retrieval

Efficient methods for data transmission and storage are needed to take advantage of the new abilities and opportunities that advanced instrumentation and assessment techniques can now offer. This rapid assessment and signal transmission must include the position of each measured signal obtained by the use of accurate positioning equipment and procedures.

5. More real time rapid coordination of the inspection, quantitative assessment and weld repair portions of the combined inspection-repair task

Increased coordination between the different processes and systems can lead to significant cost savings. For example, the inspector locates and measures an indication and sends the indication signal to nondestructive, structural and fracture engineers for defect and damage assessment, then based on the results of that assessment structural design and weld repair engineers would develop a repair design and procedure which would finally be sent to the site maintenance engineer. If this process can be completed in a time frame consistent with the time spent by the original inspector's at the site, significant savings can be achieved in both cost and time for everyone involved by allowing each individual to focus on their portion of the overall inspection-repair task. The reduction of the time between indication and weld repair is a significant economic factor for large structure NDE assessment.

6. Faster inspection-repair scenarios to achieve economic improvements

After assessing the interactions between the different groups involved in an inspection-repair scenario, an improved system can be developed that defines or redefines the roles of the groups involved. For example, the new role of the inspection team at the site could involve rapid data collection, including the location of the indication and transmission of that data to an assessment center (Underwater Reliability and Repair Center).

7. More advanced and flexible underwater inspection and repair systems to rapidly address issues in increasingly hostile environments

Advancements in this area need continued development.

8. Advance the needed continual education and interdisciplinary training across the underwater engineering systems.

Education on the specific details of practice and the system aspects involved in underwater and marine inspection and in repair procedures of value across disciplines and for the future of several industries.

9. Promote and create standards and codes to achieve the most effective coordination of talents with a system approach.

Standards and codes can encourage the industry to move towards meeting the goal of increased structural reliability and cost effectiveness.

STRAWMAN SYSTEM PROPOSAL

A proposed advanced marine inspection and repair system is introduced here to promote discussion and creativity by the management, engineering, and regulation communities involved. The proposed plan divides the operation into two locations: the inspection site and an advanced reliability assessment and repair design center. Figure 1 shows this two location arrangement. In today's information age there is no reason for the assessment of indications to be performed at the site of inspection. The assessment of indications can effectively be performed anywhere. Multiple sites could serve this role, but any assessment center must manage and store the indication data for fast retrieval for use during the next inspection period of each given structure. The center should have a full complement of analytical capabilities from signal analysis, fracture analysis, structural assessment, data transmission and storage, weld repair design, code compliance, and prediction of remaining service life.

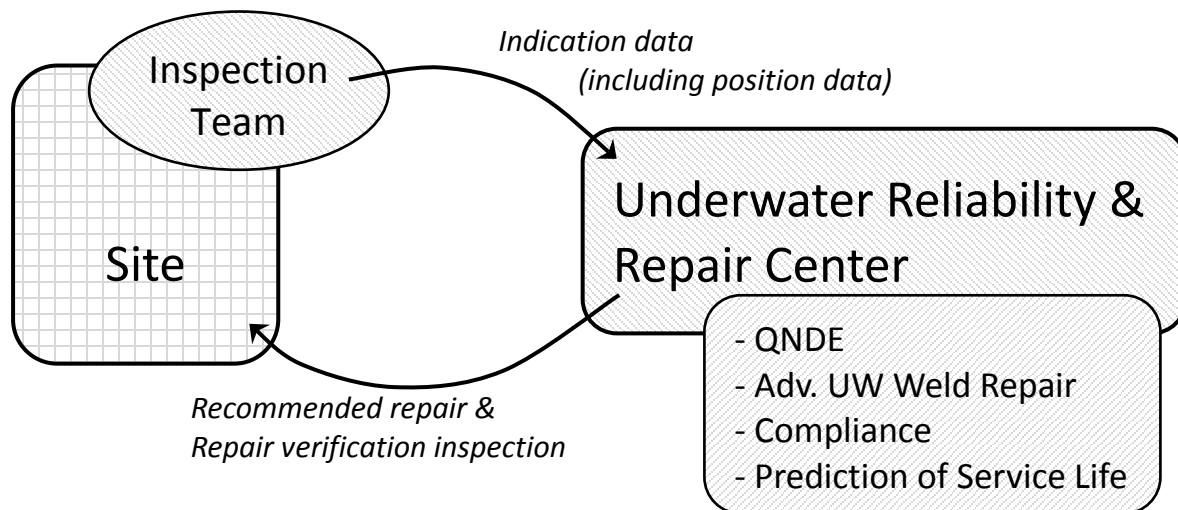


Figure 1: Strawman System Proposal

The proposed system assumes that advanced inspection tools on site are being used to collect both time and frequency based data, and that the indication signal will be transmitted with its position data to the center. In addition to analyzing the indication signals the proposed reliability and repair center has the capability to locate the positions of the indications relative to their drawings of the structure in order to assess the loads and their expected structural responses. Available software and structural loading data can provide data essential to interpretation of the overall health of the part. Fracture analyses and statistical analyses of the signal data can be performed, if necessary, to acquire a quantitative statement

about the materials integrity and expected remaining service life. The indication data can be stored for future inspection of the same structural component. A weld repair procedure can be recommended to the maintenance engineer at the site, the structure's owner and, if needed, the regulatory agencies. The time for full cycle of these NDE events should be achieved within the schedule of the surveying operation.

An overview of the coordination plan between the inspection site and the reliability assessment and repair center with their specific teams of experts is shown in Figure 2. Each of the individuals involved at these two locations have defined responsibilities, which are outlined in Tables 1 and 2 for the site of inspection and the reliability assessment center. For example, the site inspector is responsible for the decision as to whether an indication signal with position data is to be sent to the center.

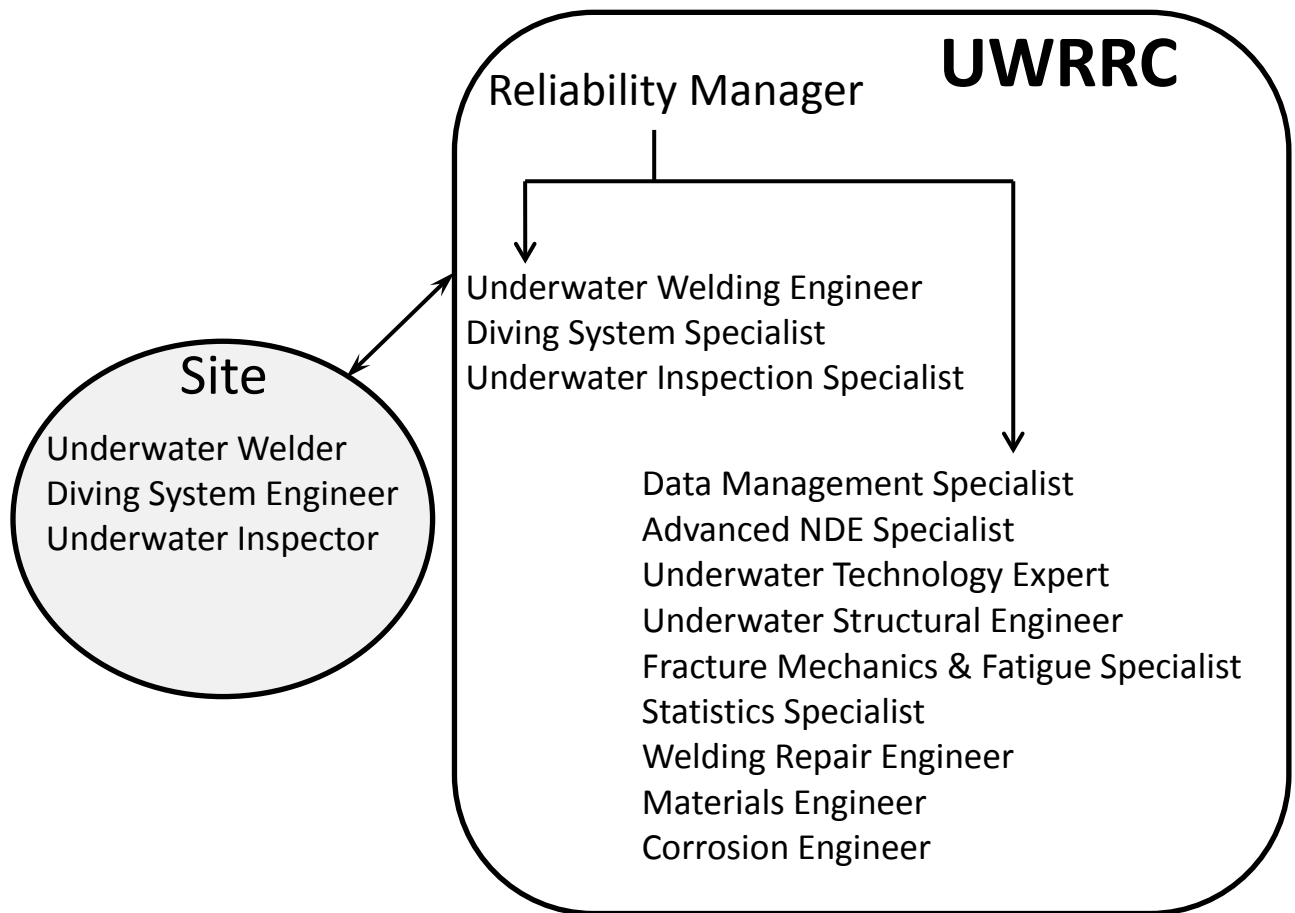


Figure 2: Coordination Plan

Table 1: Advanced Underwater NDE Testing (on site)

Personnel	Function	Outcome
Underwater Maintenance System Engineer	Selection of advanced QNDE technologies (at least two for verification and improved reliability analysis)	Acquire recommended weld repair and make decision
Underwater Inspector	Advanced underwater QNDE technology utilization Sensing and Position Qualitative analysis work with close teamwork with diving system engineer	Report indications and positions
Diving System Engineer	Underwater equipment selection and utilization logistics	Support for underwater inspection and welding operations
Data Management Engineer	Data acquisition, transport, and storage	Send indication and position data for analysis and recommendation to underwater QNDE analytical center

Table 2: Underwater Q-NDE Centers – (UWRRC)

Team/Personnel (UQNDEC)	Function	Outcome
Reliability Manager (Head)	Comprehensive quantitative assessment	Submit repair recommendation for proposed weld repair practice and verification inspection to the underwater maintenance system engineer on site
Underwater Welding Engineer	Welding in underwater condition to achieve acceptable quality	To recommend welding practice
Diving System Engineer	To coordinate recommended activities with welding engineer	To recommend supporting welding practices
Underwater Inspection Specialist	Sensing weld repair Verification of quality of weld repair	To coordinate recommended practices with (site inspector)
Data Management Engineer	Work with site data manager	To receive data at UQNDEC site for proper assessment and storage

The responsibilities of the reliability assessment and repair center are given below:

- To make marine structure and underwater nondestructive evaluation more quantitative allowing for more comprehensive reliability analysis and remaining life prediction.
- To advance NDE technology and practices with elastic, electromagnetic and Barkhausen wave analyses using both time and frequency analytical techniques to correlate and measure material defects and establish a materials state awareness.
- To perform signal analysis including Fourier analysis, higher harmonic analysis, microstructural scaling etc.
- To achieve comprehensive assessment of reliability and prediction of remaining life with integrated multidisciplinary expertise.
- To achieve more rapid inspection and repair in near real time.
- To achieve an inspection and repair system by establishing the most effective and efficient work description for all of the individuals involved.
- To develop the necessary equipment for rapid quantitative inspection of marine structures, data management, analysis and repair practice recommendation.
 - Tools with multiple NDE techniques on a single instrument.
 - Tools for improved efficiency in data transfer and storage.
- To clearly identify the education necessary to achieve wave analysis of NDE applications.
 - Make available approaches to transition the traditional underwater and marine structure inspectors towards these new practices.
 - Educating the supporting engineering staff to assist in developing a level of greater understanding of the staff's needs and roles as a part of the center as a whole.
- To establish the necessary standardization, codes and certification to properly utilize these new technologies, analytical methods, and inspection practices.

CONCLUSION

With the advent of a new level of advanced analytical tools and practices, as well as a sound understanding of the solid state mechanics of structural materials, there are many opportunities for a new integrated quantitative nondestructive evaluation practice. This integrated system can start with the nondestructive inspection of the structure. The collected data will include the position of the indication at the inspection site. The data can be transmitted to an analysis center where the data receives statistical and fracture mechanical assessment and is stored for future inspections. The proposed center also results in a better use of talent with the inspector focusing on the specific location and application of the measurement tools and quantitative NDE personal and a structural analyst handling the interpretation at an analysis center which could be located anywhere in the world. This use of advanced technology will achieve significant cost savings, more thorough inspections, and improve service life predictions, including accurate tracking of indications for any given structural component.

The Role of Performance Demonstration Initiatives to Qualify NDT Methodologies and Inspectors for In-Service Inspections Using Risk Based Inspections Structural Integrity Management

Lawrence Goldberg, Sea Test Services

Peter W. Marshall, Moonshine Hill Proprietary

Sea Test Services (STS) and Moonshine Hill Proprietary (MHP) have recently completed major studies on risk based inspections for fixed platforms and MODUs (jack-ups and semi- submersibles). This was reported in “RBI for Fixed Platforms, MODUs, and Floating Structures” at MTS-IEEE Oceans ’09 in Biloxi. The National University of Singapore is continuing research in this area, and STS is putting together a workshop that would take a significantly difference approach:

Normally, damage statistics have first priority in risk based inspections. However, without understanding the reliability of the NDT methods used to gather the data for further reduction, and the competency of the Inspector personnel involved, it is difficult to assess either the probability of detection (POD) or confidence level to quantify the purity of data found. Sea Test Services finds these as the first two steps when both building risk based inspections and structural integrity management programs.

Additionally, Sea Test Services has provided a JIP in Underwater Weld Inspection Philosophy that delineates the type of fatigue damage found in fixed platforms compared to MODUs.

Performance Demonstration Initiatives (PDIs) for NDT Methods

Sea Test Services has performed over 400 Performance Demonstration Initiatives (PDIs) in the following methodologies:

- a) VT (General and Close Visual Inspection often referred to as GVI and CVI)
- b) MT (Magnetic Particle Testing)
- c) ET (Eddy Current Testing)
- d) FMD (Flooded Member Detection)
- e) Methods for Improving Weld Fatigue Lives (Weld Toe Grinding and Hammer Peening)
- f) ACFM (Alternating Current Frequency Measurement)

While the STS Performance Demonstration Initiative program is somewhat unique, Sea Test Services has used the following standards as reference documents that fit both GOM and other worldwide NDT marketplaces. These PDIs have been a part of ABS’s Certificate of Conformance program from 1981 to 2005. (ABS’s program has since been dismantled, and was not widespread). While the PDIs typically have been offshore oil and gas company based, their importance pertains to drilling contractors and Regulatory Class Societies (RCS). The following are references used by Sea Test Services’ to develop its Performance Demonstration Initiatives program:

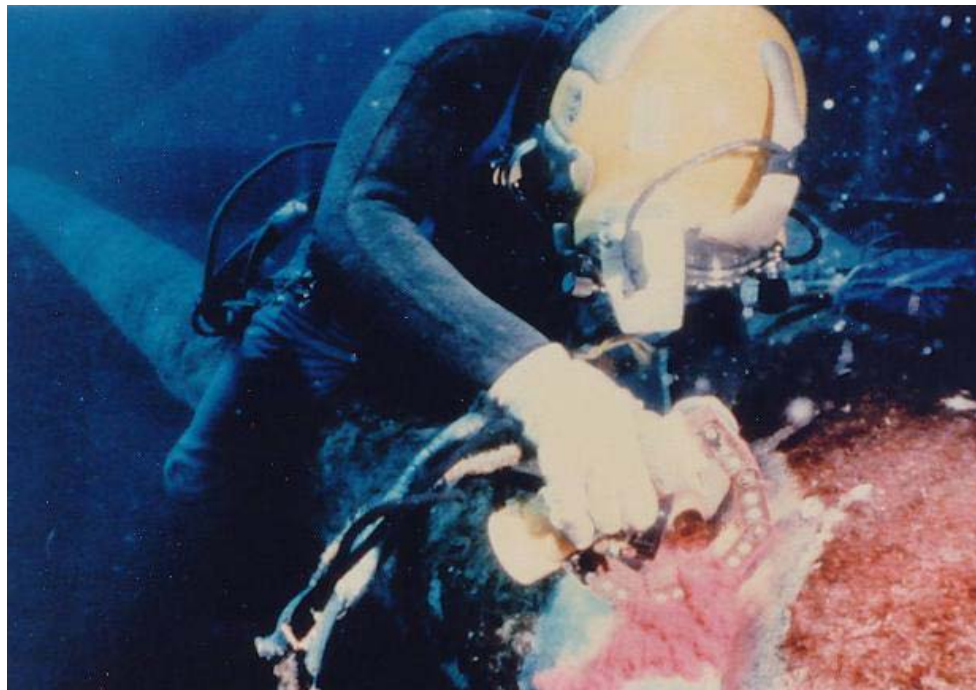
- a) Electric Power Research Institute’s program for validating NDT
- b) ASME Sec XI App XIII, Qualification of UT Systems
- c) ASME SEC XI Article14, Examination of System Qualification

- d) ENIQ document EUR 17299 that provides guidance for setting up performance demonstration initiative programs
- e) ABS NDT Hull Rules
- f) DNV Recommended Practices G103 Non Intrusive Inspection

The core concept of the STS PDI is that a NDT method should be evaluated for its usage. The method itself should be qualified, and the personnel using it should be qualified to the method. In this case, the qualification should be specific to fixed platforms and MODU inspections.

The STS specimen test bed consists of 10-12 specimens having 20-25 indications. The large number of indications includes minimum size indications, typically 1/4 inch L X 1/16 inch D X non visual, as well as variable sized, random indications. It also accounts for tubular T-Y-K joints, butt welds, rat hole, and gusset weld geometries; indications that are in the base metal, HAZ, weld toe, and weld face; and indications in both longitudinal and transverse orientations. The majority of the indications are in the toe of the weld and non visual, as this best replicates offshore indications due to fabrication cracks, in-service cracks and delayed hydrogen cracking. However, other indications do occur and are accounted for in the test bed, as well as a small percent of visual indications. Approximately one half of STS' indication population is from cut-outs of cracks found offshore and inserted into test specimens. Sea Test Services does not use EDM notches because of the poor width to depth ratio, and because they do not simulate crack morphology.

The results from the PDIs determine the “best practice” to be used, whether it is API, BSI, CSA, et cetera. The practice is also designed to have a companion industry standard which is “best case” based on safety, quality, efficiency and cost.



Underwater Magnetic Particle Inspection

- For MT, API RP 2X is used. The core magnetization method used is an ac articulating electromagnet. Using this specification with qualified Inspector Divers, and cleaning to black oxide or bare metal, a POD $\geq 95\%$ is achieved, along with a low false alarm rate.
- For ET, BSI 1711 Inspection of Ferritic Welds is used. The key elements of eddy current inspection are proper training and the correct probe. Its primary use is topside on offshore structures where the coating is too thick for MT (0.008 inch). Using this specification with qualified Inspectors, a POD $\geq 95\%$ is achieved for indications in the toe of the weld and when using correct scanning methods. As well, this method has a low false alarm rate.
- For UT (ultrasonic) and RT (radiometric) FMD, there is not a recognized recommended practice although STS has its own in-house procedures that have been widely distributed to oil and gas companies and diving contractors. It should be noted that API RP 2A has provision for using FMD in lieu of close visual inspection. The key element for FMD is to find members that are flooded, to find the cause of the flooding, and to provide data to the owner so that it can be analyzed in terms of structural significance. FMD will only detect through-wall dimensions such as cracks or pits, and will not detect cracks in the toe of the weld on the leg side.
- For Alternating Current Frequency Measurement (ACFM), typically the user provides their own procedures, although there are ASTM and ABS procedures. In STS' Performance Demonstration Initiatives, the highest POD for ACFM has not exceeded 73% with a false alarm rate that diminishes the confidence level of the results. In comparison to MT and ET, ACFM's PDI performance should exclude its usage.
- For Weld Toe Grinding and Weld Toe Hammer Peening there are industry guidelines, but no specific industry standard. These methods can be taught, as weld toe grinding can increase fatigue life by two hundred percent and weld toe peening by five hundred percent as well as reset the fatigue clock. Weld toe grinding, typically to a depth of 0.080 inch, may be considered a repair if by grinding the indication is completely removed.

Qualification of NDT Personnel

Once best practice NDT methods have been vetted, there are numerous schemes for the qualification of NDT personnel. Some of these schemes besides Sea Test Services' PDIs are:

- a) ASNT-SNT TC-1A Qualification of NDT personnel
- b) BSI Personnel Certification in NDT (PCN)
- c) TWI CSWIP Certification Scheme of Welding Inspection Personnel
- d) CGSB Canadian General Standards Board Certification and Qualification Programs
- e) ISO 9712 Qualification NDT Personnel

While the topic of qualification would seem to have some unity, in general, there is not. ASNT is primarily an in-house company based certification. The BSI PCN program is external. The CSWIP qualification is through TWI, and the CGSB is a government based system. All but CSWIP have a Level I, Level II, and Level III program. CSWIP only has a Level I program (for MT).

ASNT does have an industry sector program but it is based on only using two specimens for its practical test (but there is no program for Inspector-Divers). BSI and PCN usually have 3 specimens: a T, gusset and cruciform, but with only three indications and the minimum size being 1/2 inch long. PCN allows upwards of 3-4 hours for the examination to find 2-3 indications. STS' practical test requires the inspector candidate find at least 20 random indications in 1-2 hours. A Level II can only miss two indications and have one false alarm.

Sea Test Services has been providing NDT Performance Demonstration Initiatives since 1985. STS provides this service to topside inspectors, inspector divers, one atmospheric diving suits (ADS), and ROVs. As a guideline, without any refresher training, the personnel pass rate is as follows:

- 25% Level II
- 50% Level I
- 25% Fail

In 2005, STS addressed the fail rate by providing a one day refresher course prior to implementing the PDI practical testing. As a guideline, with a one day refresher course, the following pass rate applies:

- 70% Level II
- 20% Level I
- 10% Fail

The major difference between the Level I and Level II qualification is not only PDI results, but also as important is actual field experience with the NDT method. While a Level I Inspector Diver may interpret indications, a Level II Inspector Diver is required to provide the final evaluation and documentation.

Another significant difference in present industry based practices of using data recorders is that Sea Test Services' philosophy is to replace the data recorder with an "Inspection Controller." This is achieved in STS' PDI program by including the Inspection Controller in the NDT refresher course and requiring the Inspection Controller to take the written test and to fill out the proper NDT Forms (Technique Sheets, Structural Critical Inspection Point Database Report Sheets and NDT Indication Report Sheets) as information is relayed by the diver inspector during the PDI. This ensures proper communication between the Inspection Controller and the Diver, and correct documentation.

NDT ADS and ROVs

One significant change since the first 1991 MMS underwater workshop is the advancement of one atmospheric diving suits' (ADS) capability. In an industry JIP, an ADS WASP was able to VT, MT, and most importantly, weld toe grind to evaluate shallow MT indications.

Another significant change is an advanced NDT class ROV. This is being developed by a major ROV operator and funded by an offshore oil and gas company for a deep water inspection. The most important capability is having a grinding tool. Such a capability will make the ROV an important asset, for example, by defining an indication in a deep water riser as being relevant versus a false alarm.

Several offshore oil and gas companies have used specialized ROVs to inspect deepwater structures in the Gulf of Mexico and California. These ROVs have advanced cleaning and visual inspection tools, but performing remote visual inspection resulted in a high number of false alarms. An onboard MT tool is being designed and will be able to evaluate visual indications, provide MT on selected structural critical inspection points, and define damage due to installation or dropped objects. High Definition (HD) cameras with zoom now provide clearer views that were not previously available.

Risk Based Inspection and Structural Integrity Management

After qualifying the NDT method, and qualifying the inspectors to that method, an effective inspection plan can be developed based on:

- a) Statistical analysis of known structural critical inspection points having high priority
- b) The capability of having the core inspection plan reduced or expanded based on field results and engineering approval
- c) Flexibility of the NDT survey
- d) Best practice NDT methods
- e) Use of qualified personnel
- f) Best practices based on access
- g) Means to implement repairs, if any

This results in the most cost effective surveys that stay within the risk based inspection and structural integrity management structure.

MODU and Fixed Platform Database Information

Sea Test Services has completed four major studies pertinent to MODUs, and one for fixed platforms. These are:

- a) Aging Jack Ups and Fatigue
- b) Aging Semi Submersibles and Fatigue
- c) Underwater Weld Inspection Philosophy
- d) Repair and Inspection Issues of MODUs and Fixed Platforms

These studies contain databases that have been assembled from records of more than 100 offshore projects involving inspection management for fixed platforms and UWILDs, both underwater and topside. For this reason, these databases have a high confidence level as the data comes from vetted NDT methods and PDI qualified personnel. Lawrence Goldberg, Sea Test Services, was the inspector or inspection manager of all of these inspections.

STS is discussing these studies to provide information for Offshore Oil and Gas Companies, Drilling Contractors, and Diving, ROV, and ADS Contractors to produce optimal results for future inspections.

Fixed Platforms

In two cases, front end planning for structural integrity management were implemented to provide continuous NDT information from fabrication, installation, and periodic inspections until decommissioning. This included:

1. In the Fabrication Yard:
 - Photographic mosaics including a system for marking legs and members
 - Photographs of structural critical inspection points scheduled to be either VT or MT inspected
 - Photographs of anodes including dimensional attributes
 - List of all members that were intentionally flooded
2. First periodic inspection planning including a full set of required recommended practices.
3. Continuing inspections based on past reports.

A JIP, Rationalization and Optimization of Underwater Inspection Planning Consistent with API RP 2A Section 14 used data collected from the CAIRS and STS.

The STS data was collected from 71 fixed platforms, and 1493 structural critical inspection points inspected using both VT and MT (draft API RP 2X) and inspector divers trained to Level I or Level II. There were a total of 52 indications that were evaluated as cracks. It should be noted that 36 indications were found in the conductor bay frames of a Lawrence Allison 8 pile design.

Significant observations interpolated from the inspection data were:

- non visual indications were typically less than 12 inches
- all indications initiated in the toe of the weld
- the deepest elevation that an indication was found was on the second elevation
- MT through black oxide was an acceptable method and reduced cleaning costs

It is noted that though no transverse indications were found within STS's inspections on fixed platforms, they can occur. However they are not common. Excluding the conductor bay, indications often occurred in the toe of the weld on the leg side making FMD ineffective for this condition.

MODU Inspections

Semi-Submersibles

One major study was performed on the Pacesetter class MODU, and the Alaskan Star in particular. Lawrence Goldberg, Sea Test Services, inspected the Alaskan Star ten times over a 20 year period, and thus had good continuity of data. While the structural integrity management process was not recognized at the time, it was used to preplan upcoming inspection opportunities, for example, when the MODU was stacked or undergoing a dry tow.

Twenty five Pacesetters were the primary focus of the study, with an additional ten semi-submersibles, i.e. Super Yatzy, and Ocean Odyssey class.

Primary cleaning was accomplished by HP waterblasting (20 kpsi at 8 gpm) and needle guns. While needle gunning may have been the indication shut in the first to fourth thousandths of an inch, this had little effect on flux leakage field at the indication sight.

One major difference between MODUs and fixed platforms is that nearly one hundred percent of the indications found on MODUs were non visual and occurred in the toe of the weld.

The bulk of the indications found on the Pacesetters was in way of the lower horizontals and tended to reoccur at the same location or nearby. In a sense, they were nuisance indications that were in way of gussets, at gusset intersections, both tips and at joint overlap. In hindsight, hammer peening may have been a means to mitigate the reoccurrence of these indications or to contour grind these welds. Contour grinding on the ODECO Ocean Odyssey class significantly reduced the number of indications found, even at the special surveys.

In the inspection of the Pacesetters, there were four through-wall indications. One was attributed to design and stresses incurred in dry docking (this Pacesetter had an extra column added aft on each pontoon); one was on the vertical diagonal column. The other two were fatigue cracks that grew over a period of 15 years and were situated on fuel tank bulkheads. These were remediated by stiffening internal members. On two Pacesetters, short length indications were occurring on the number 2 column in the face of the weld, indicating that the indications were probably propagating from the root.

Sea Test Services also looked at RCS reports for agreement with predicted data, and in many cases, the reporting of indications in the face of the weld raised “red flags” as to the actual indication being relevant or spurious, (a term used by CSWIP Inspector Divers). Based on STS’ data that shows that >90% of all indications occur in the toe of the weld and that the RCS reports had a ~15% occurring in the face, there was a substantial reduction of the confidence level of the results. Thus these reports were used for information only and to extrapolate cases of “false alarm” rates.

There was another incident where a Lizard Millstrong instrument was used to inspect a DnV rig. During this inspection, there were concurrent MT inspections, and out of the 16 indications found by MT, only one was found by the Lizard inspection. This included indications that were from one to 18 inches long.

Jack-Up Design

The STS’ MODU reports for SEDUs focused on Marathon LeTourneau designs, 82SDC and 116C class, and Bethlehem mat supported rigs. These designs were studied as Lawrence Goldberg, Sea Test Services, had >25 inspections on each class studied.

STS has also assessed inspection reports for agreement of typical damage for these classes. When such reports do not agree with expected types of damage found, the lessee might require further inspection beyond those of the owner and RCS.

Marathon LeTourneau (MLT) Class Rigs

The MLT Class Rig has redundant details and is a robust design. In planning inspections for this design, a database is used to keep track of the required critical inspection points and the NDT methods used. Typical items include:

1. Jackhouse structure
2. Frame assemblies for upper guide and lower guide
3. Jacking system including elevating pinions (visual)
4. Crane pedestals
5. Helideck (visual, sampling)
6. Cantilever holdowns and beams
7. Visual inspection of tanks with UT thickness for wastage or other NDT as required for other types of damage (i.e. dents or cracks)



MLT 82 SDC Truss Type Spudcan



MLT 116-C Truss Type Spudcan

By knowing historical damage, the inspections are carried out, and normally a small sampling of inspection points will be taken in areas where no damage has historically been reported.

The majority of damage on these rigs is typically found at spud can details such as

- the web frame (shear plate) to spud can
- the shear plate to spud can deck
- the shear plate to I beam
- the I beam and gussets to the back plate
- the filler plate which joins the spud can to the back plate

In areas of damage, vigilance remains, as well as implementing designs to reduce stress raisers, or to use weld improvement methods such as hammer peening. In the repair process, certain steels require a 24 or 72 hour wait period (ABS rules) to account for hydrogen underbead cracking. To expedite the need for further repairs, it is important to check the weld repair at frequent intervals (8 hour).

In the 25 inspections that Sea Test Services has managed, the most severe indication was one that ran across the filler plate and continued 18 inches into the spud can with a through-wall dimension.

Bethlehem Mat Supported Rigs

Sea Test Services has performed approximately 23 Bethlehem mat supported rig inspections. The primary areas of inspection and damage are the mat to wrapper, wrapper to column, column to column stub, and pin holes. Of these surveys, based on damage found, there have been 5 dry dockings required by ABS for three different owners. The most severe indications of these rigs were through-wall and had lengths greater than 6 feet in way of the column to mat connections.

Historical knowledge shows one case, the Ranger 1 (1970's), toppled 6 days after an ABS visual survey. It was determined by metallurgical analysis that the crack was preexisting for approximately 1 year.

In another case, a pinhole fracture of the leg resulted in a through-wall crack that was 50% of the leg circumference.

Due to the damage history of the Bethlehem design, it is imperative to have the proper NDT procedures and qualified inspection personnel.



Bethlehem Mat Supported Rig

RECOMMENDATIONS

1. To improve the confidence level of the inspections, industry should standardize “best practice” inspection methodologies and implement means to verify the competency of inspection personnel. Proper NDT methods performed by competent inspectors should be used for inspections.
2. NDT methods and equipment used within the methods should be proven to be reliable by means of a performance demonstration. If the equipment cannot find indications on test specimens with a high degree of reliability and a low false alarm rate (assuming a qualified inspector is performing the inspection), the NDT method and/or equipment within the method should not be used in industry. It is difficult to have confidence in the inspection results when best practices and best methods are not used.
3. “Competent” inspectors should prove their competency in each NDT method by means of a practical test with test specimens that are equivalent to the type of geometries and welds that will be inspected in-situ.
4. The type of inspection method previously used should be a consideration when reviewing prior inspection records to determine if additional inspections are warranted. The NDT method should use recognized standards and not depart from these practices.
5. The results of inspections, especially on MODUs, in which visual testing alone is used will be unreliable because historically, the majority of indications are non visual. Thus, the confidence level will be recognized as low.
6. Flooded Member Detection (FMD), which is an acceptable method in API RP 2A in lieu of close visual inspection, should have an industry recognized recommended practice.
7. ADSs and ROVs that have NDT capabilities should be tested similarly to diver inspectors by means of a practical performance demonstration to prove competency and reliability in the NDT method.
8. In most cases, following these practices will result in detecting damage in its incipient state before it becomes an expensive repair.
9. One of the primary items left out of this white paper is a discussion on corrosion. Corrosion is difficult to reproduce its topography and wall thicknesses. Tools such as UT scanning thickness meters, pit gages, accurate drawings (especially if there is an area of perforation), and stereophotogrammetric cameras will improve understanding the corrosion loss values and if the member’s strength is compromised. It is possible to make a corrosion assessment based on reviewing previous inspection reports (with photos), and structural photos that show weld profiles and tightly adhering black oxide.

RBI for Fatigue Life Extension OF Fixed Platforms

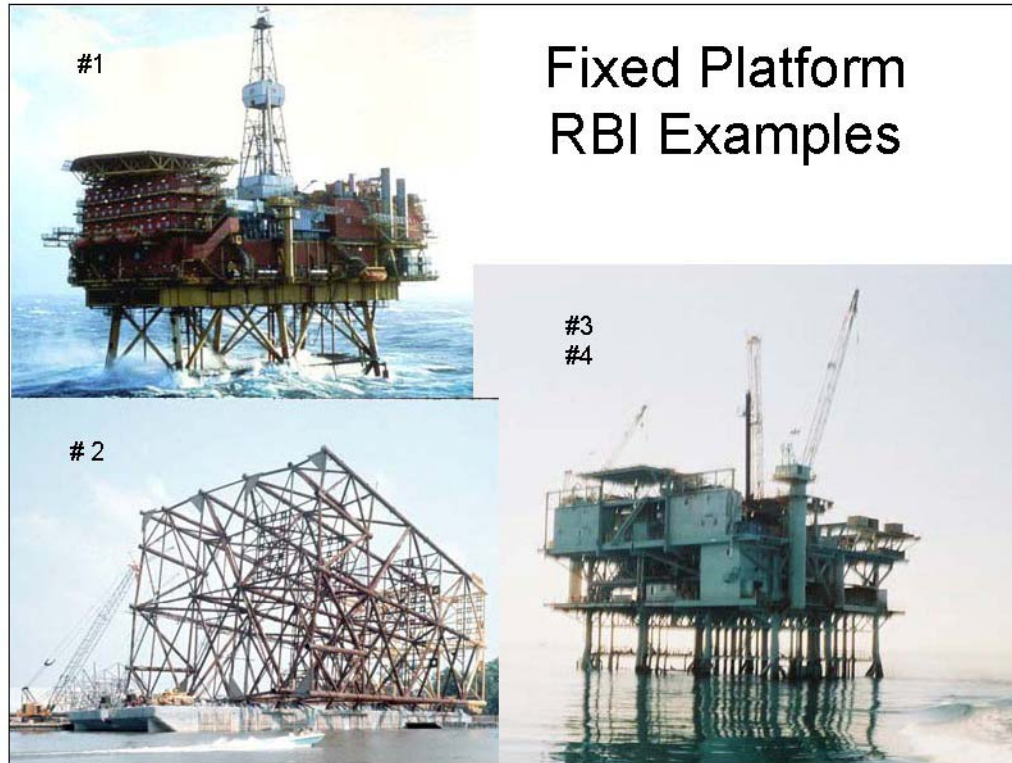
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11 Nov 2010

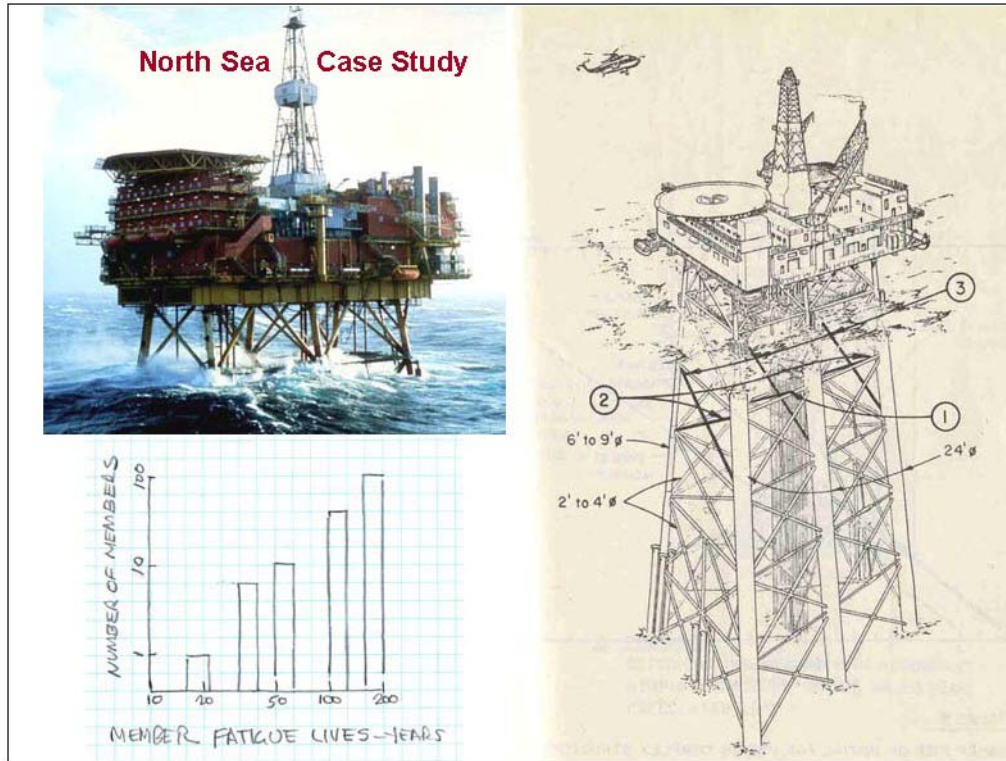


Fatigue test data are used to quantify the bias and uncertainty in total fatigue life and the interval between detectable crack initiation and member failure. Sources of additional “hidden” bias in fatigue life calculation are also considered: e.g. characteristic wave steepness, hydrodynamic coefficients, stress concentration factors, joint flexibility, S-N curves, and the interval between first member failure and structural collapse. Using case studies of two 40-year-old platforms with a calculated life less than five years, various levels of inspection are examined for their relative credibility *vis-a-vis* the calculation. Targeted MPI of a limited number of joints, selected using the fatigue analysis, is examined for its ability to provide fatigue life extension of up to 20 years, with periodic inspection at shorter intervals providing the same level of safety as a new design at a damage ratio $D=0.5$ and no inspections beyond Level II fly-by.



Two Pacific OCS platforms in Federal waters (right) are 40 years old, and one has already suffered fatigue damage to some of its conductor guides, due to excessive marine growth and unanticipated vertical wave forces. Earthquake considerations required a very robust design, including heavy-wall joint cans, and fatigue due to wave action was not considered. Even with marine growth removal, however, after-the-fact fatigue calculations indicate several members in the primary load-resisting structure whose allowable fatigue life is theoretically already exhausted. Worldwide, there are many other platforms in this predicament, leading to risk-based inspection becoming a growth industry.

Two earlier examples will be reviewed first.



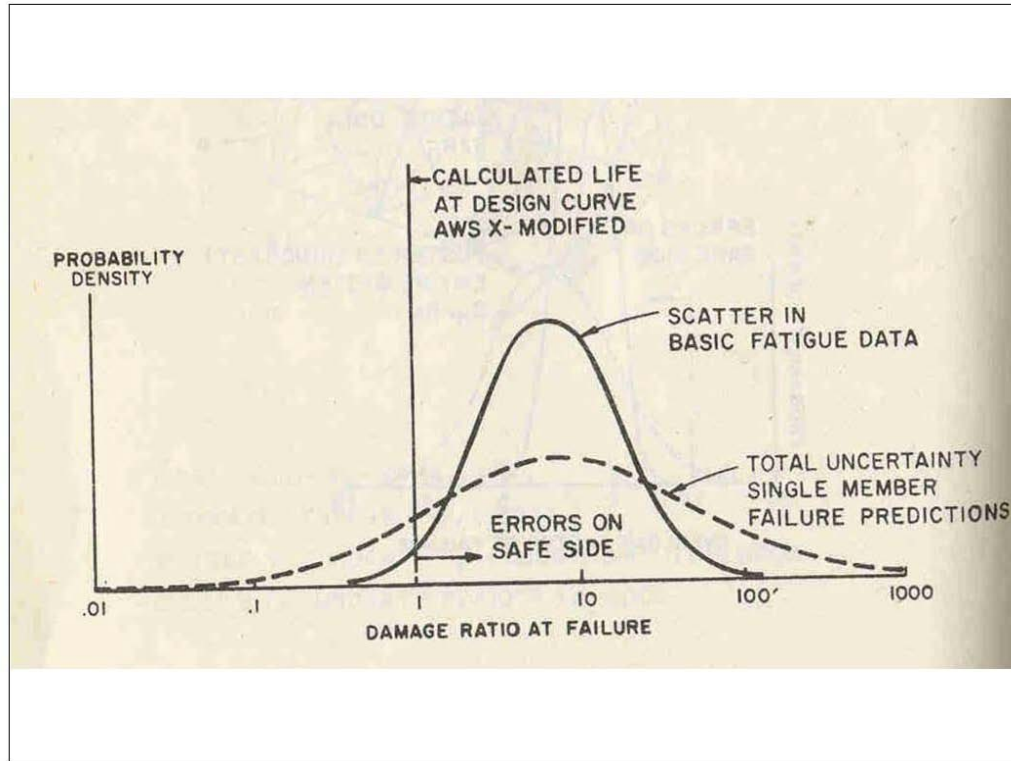
Calibration of the safety factor to be applied in fatigue design may be considered in reference to examples like this 1976 North Sea structure. It is still in service today, despite having a calculated fatigue life of only 20 years at $D=1.0$, using the upper SN curve "X" and the optimistic Alpha Kellogg stress concentration factors (Marshall & Luyties, 1982). The detailed fatigue analysis indicated the distribution of member lives shown in the histogram.

In the example structure, the elevation with the lowest fatigue life has 6 parallel members with the following calculated fatigue lives: one @ 20 yr, two @ 60 yr, and three over 200 yr.

It can be shown that that in the initial condition, the median collapse load for this type of structure is on the order of twice the design load. Variation in the annual extreme load is also indicated, reflecting upside variation in annual extreme waves, conversion from wave height to dynamic base shear, and uncertainty in that conversion, as used in Gulf of Mexico criteria development. There is some overlap between the distributions of resistance R and load (or stress) S . The average annual risk rate or probability of failure P_f is given by

$$P_f = \text{prob} \{R/S < 1\}$$

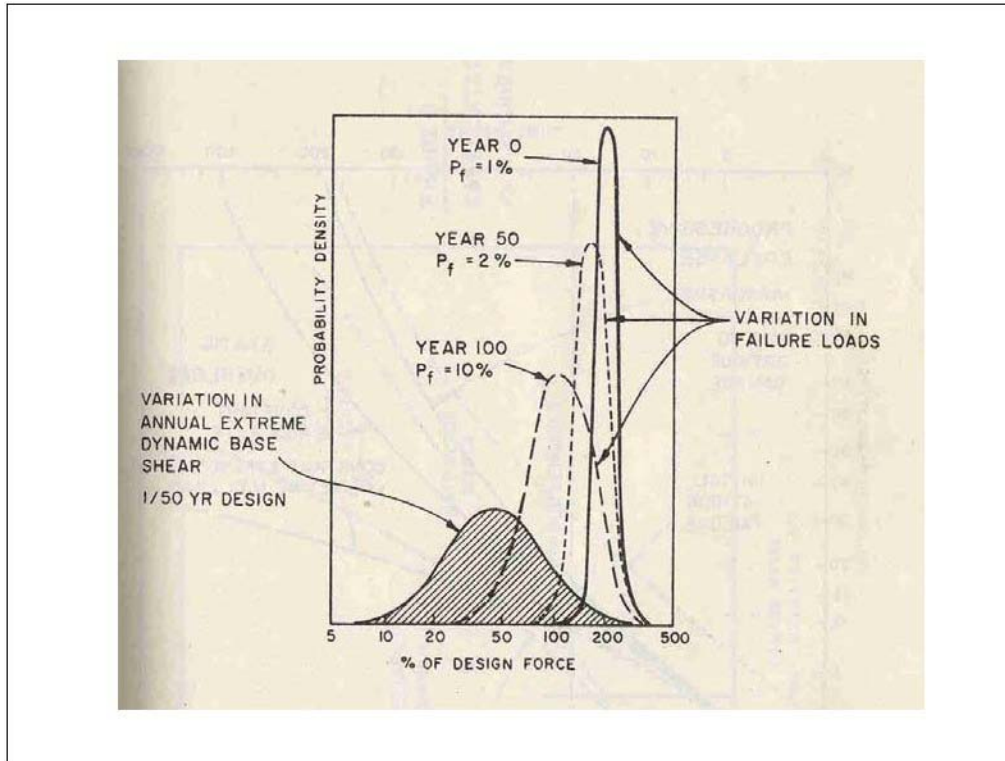
or about 1% annually, for a Gulf of Mexico structure having an A-2 Economic rating of 100% [Marshall, 2008]. Overload risks for the actual North Sea structure would be much lower due to additional safety factors and a flatter upside risk curve.



Statistical analysis allows us to deal rationally with the scatter and uncertainty inherent in the fatigue problem. Scatter in the basic fatigue S-N data is approximately log normal, with the AWS-X modified design curve corresponding to 97% survival. The median fatigue life is 5 to 8 times that given by the curve, and the 2-sigma scatter band ranges from computed damage ratios of 1 to 50 (Marshall 1976).

Applied loads and stresses also have a large measure of uncertainty. Consideration of known scatter in oceanographic forecasts and wave force measurements, along with uncertainty in global and local stress analysis, indicates the 2-sigma band on hot spot stress ranges from 0.56 to 1.8 times the computed value. Other elements of major uncertainty in the fatigue analysis are the effects of size and environment, and errors introduced by the use of Miner's rule. It will be assumed that present criteria accounting for these effects introduce no bias (mean error) but that the 95% confidence band includes a spread in fatigue life ranging from 1/8 to 8 times the calculated value (Marshall, 1976).

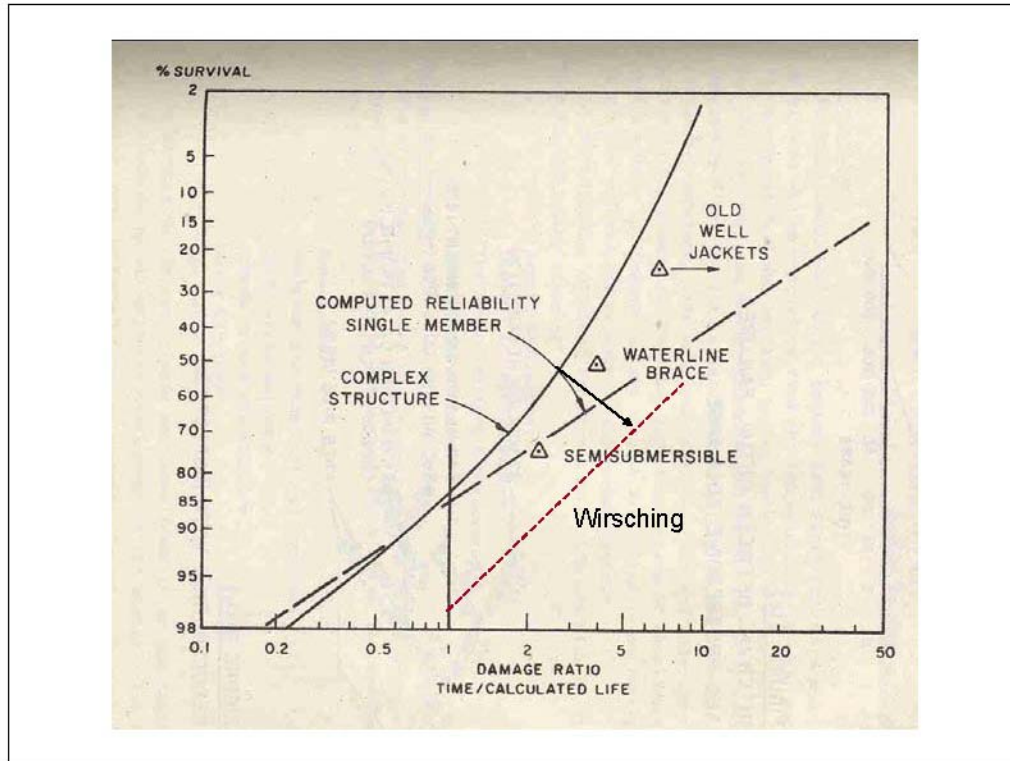
When all these additional sources of uncertainty are considered, as shown here, results indicate that the predicted fatigue life can be in error (at the one standard deviation level) by a factor of 6. Thus, relatively little confidence can be attached to computed fatigue lives. In the high cycle region, where the fatigue curves are flatter, the potential for error is even worse.



We now consider what happens after the initial fatigue failure.

Restricting our attention to braces in the critical bay with short calculated life, the median time for the first failure is 50 years. At this point in time, such failure is not certain; there could be no failures or more than one failure. However, in the expected case, we have one failure, which because of multiple parallel load paths still leaves the structure with 80% of its original resistance to lateral loads. With the decreased mean resistance and increased strength uncertainty, the risk rate has now increased to about twice its original value, or 2%.

The initial failure also increases the cyclic stress level -in the next two members, accelerating their rates of fatigue damage. Thus, their expected time of failure is pushed up to year 100, as opposed to their 300 year median life in the original structure. With expected failure of half the members in the given bay of the structure, the overlap between loads and resistance is so great that the structure is ripe for failure (annual $P_f = 10\%$), and nearing the upper limit of probable lifetimes.

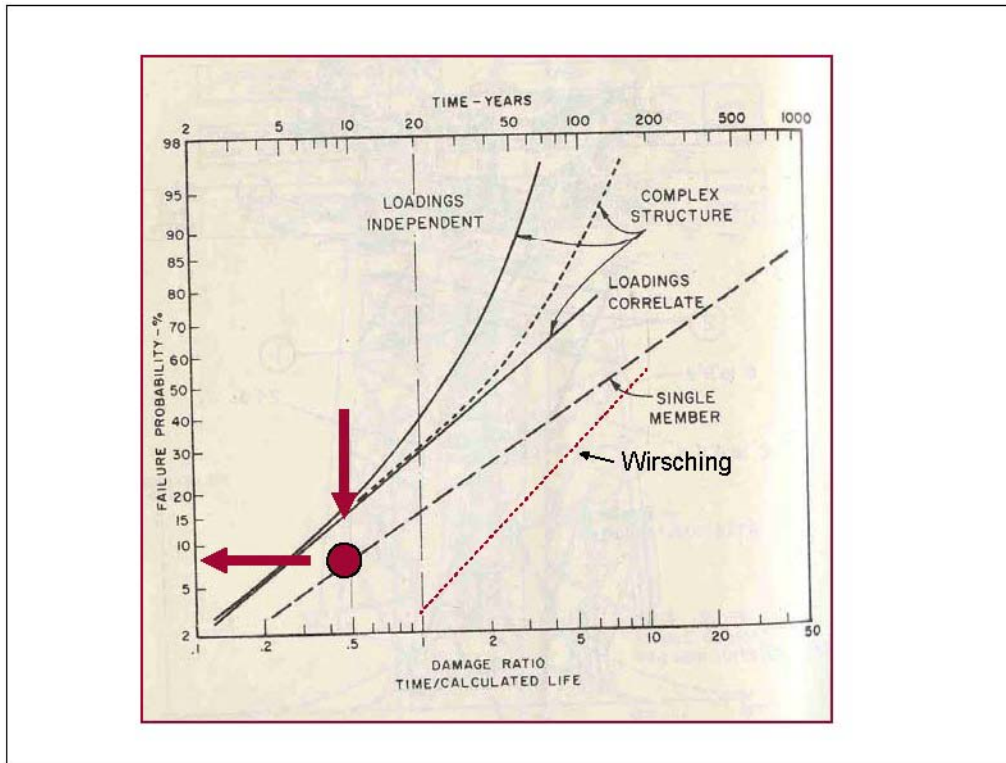


The cumulative probability of failure, with an increasing hazard function or risk rate, $pf(t)$ is given by

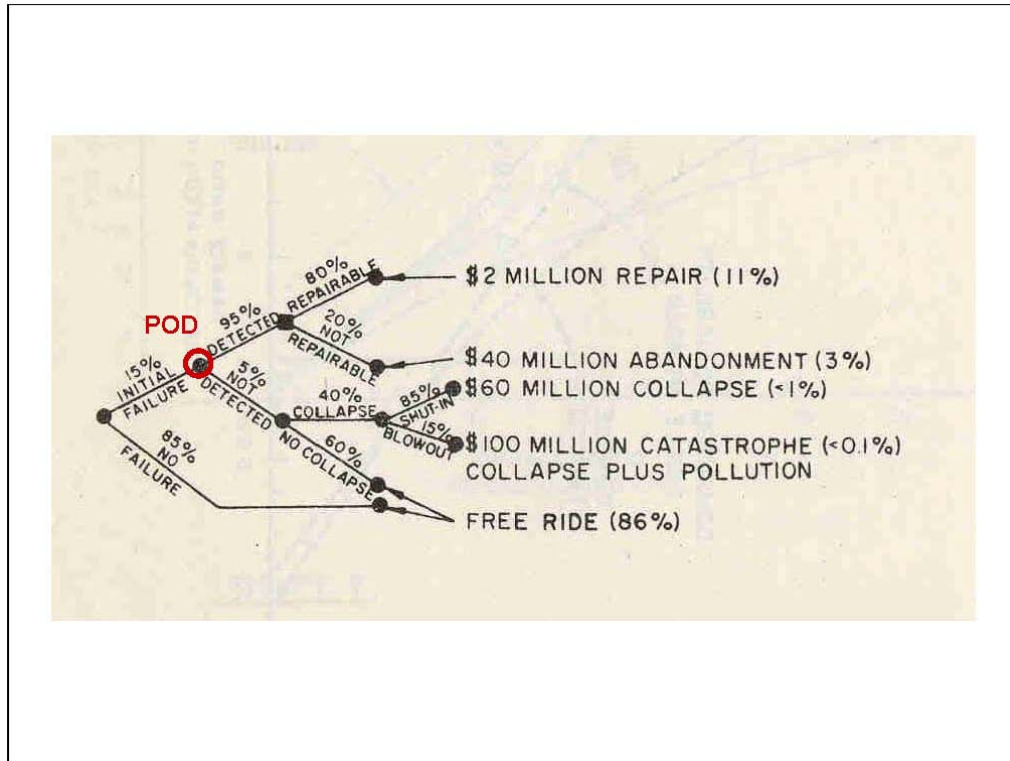
$$\text{cum Pf} = 1 - \exp [-\sum pf(t) Dt]$$

The resulting cumulative probability of failure due to progressive collapse is plotted here (Marshall, 1976) along with the single member risk curve. Structural redundancy is seen to mitigate the multiple member risk.

The red line is a less pessimistic evaluation of the single member risk, developed in a subsequent joint industry-API-ASCE study by Wirsching.



In this Figure, the vertical red arrow indicates the reduction in risk that results when a safety factor of 2.0 on fatigue life is introduced, i.e. limiting the Miners damage ratio D to 0.5. The horizontal arrow suggests that the corresponding target single member risk would be 8%, considering all uncertainties and the effect of structural redundancy.



The risk estimates made so far all assume no inspection; that is, any failures would be allowed to progress to ultimate collapse without any kind of intervention. In practice this is not necessarily what should happen. If one uses a half-normal probability spread for the time interval between initial failure and subsequent failures of a nominally identical member in progressive collapse, as was developed during the example structure study. For calculated (85% survival) fatigue life of 20 years, the expected interval between first total brace failure and subsequent failure of a nominally identical 20-year brace is 11 years, with 95% probability that the interval will be at least one year--that is long enough to permit the damage (complete loss of one brace) to be found in an annual inspection and repaired. The inspection interval would be extended where the second-to-fail brace has a longer calculated life, or where Level III inspection is performed to detect incipient fatigue cracks and reap the benefits of a substantial fatigue propagation period.

Within the 20-year example platform life, the added risk of collapse due to fatigue (beyond the overload risk of 18% without fatigue) is on the order of 4%. Given inspection opportunity, the lifetime risk of catastrophic total collapse due to fatigue is reduced to less than 0.1%. In most cases of initial failure, detection would permit the structure to be either repaired or abandoned in an orderly fashion. These outcomes for the example structure are shown in the event tree shown here.

A large part of this risk reduction is achieved through secondary safety measures such as (1) subsurface safety valves for well control, (2) hurricane shut-in and evacuation procedures, and (3) down-rating platforms with known deficiencies. Much of the risk which remains is an economic one on the part of the platform owner, rather than a hazard to human life or the public interest. The strategy of inspection and secondary safety measures deserves consideration, rather than simply specifying large safety factors or requiring early abandonment.

Probability of Detection (POD) is a key issue here, and is discussed in the next slide. 95% opportunity and 95% detection reliability would translate to 90% POD, doubling the indicated risk of catastrophe.

	CVI Limited Cleaning (Black Oxide)	CVI Complete Cleaning (Bare Metal)	MPI Limited Cleaning (Black Oxide)	MPI Complete Cleaning (Bare Metal)
Detectable Crack Length	12" and greater	12" and greater	1" and greater	1" and greater
Detectable Crack Width	0.006" and greater	0.002" and greater	0.001" and greater	0.001" and greater
Detectable Crack Depth	0.03" and greater	0.03" and greater	0.03" and greater	0.03" and greater
Cleaning Time	3-5 min/ft ²	10-30 min/ft ²	3-5 min/ft ²	10-30 min/ft ²
Estimated Relative Cost per Foot	1.0	1.8	1.2	1.9
Reliability of Detecting Crack 4" L x 0.001" W x 0.03" D	5%	20%	80%	90%
Reliability of Detecting Crack 12" L x 0.01" W x 0.03" D	75%	80%	90%	90%
Reliability of Detecting Crack 24" L x 1" W x 3/8" D	90%	90%	90%	90%

Source: SeaTest Services

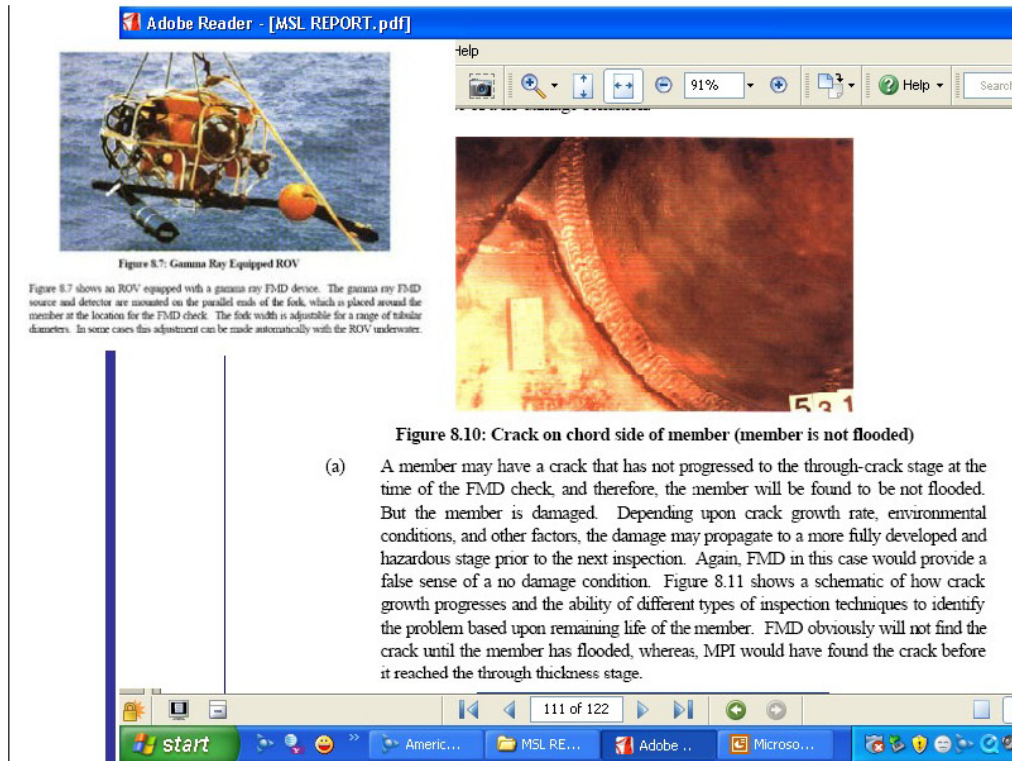
POD Reliability and Cost Estimate for CVI and MPI

PROBABILITY OF DETECTION THRESHOLDS

Fly-by general visual inspections and flooded member detection only detect underwater fatigue cracks at an advanced stage, either through-wall or severed member. The crack propagation period has already been spent, and only alternative load paths (structural redundancy) are preventing accelerated terminal stage crack growth and collapse. When such defects are found, immediate action is required (which may simply be consideration of the structure with the missing member). Closer inspection is required to claim the extended propagation period which results from "no find" of N2.

Cleaning to bare metal, followed by close Visual Inspection (CVI) and Magnetic Particle Inspection (MPI) are considered appropriate for level III and level IV inspections, respectively. Less thorough cleaning, removal of heavy marine growth but not tightly adhering scale, yields reduced sensitivity. However, MPI through black oxide scale is less expensive and more definitive than CVI on bare metal. Either may be considered the equivalent of laboratory visual crack initiation, N2 (30 % of life remaining); CVI with black oxide (1 mm crack opening) is not. Laboratory fatigue cracks can be observed under load. In-service fatigue cracks may become non-visual under zero load or compression, unless the crack tip has been plastically deformed up to the 0.01" CTOD targeted by API RP 2Z.

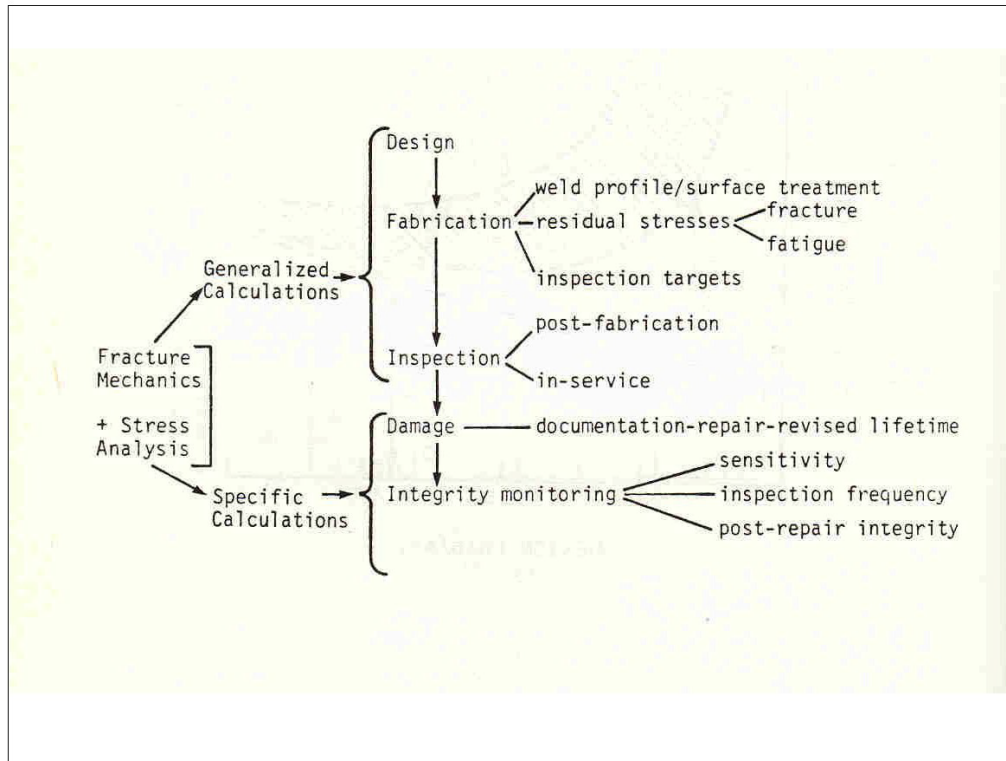
The table above was taken from the MMS-sponsored inspection JIP conducted by MSL Engineering in 2000, using data provided by Sea Test Services [9]. STS uses 95% POD as the top number. The PODs are for cracks which exceed all three dimensions given. Note: the last row should read 0.1" W.



Flooded member detection (FMD) by gamma ray with an ROV has the advantage of no cleaning and the ability to be used below diver depth. However, at best, it indicates whether or not the thru-crack fatigue propagation life N3 has expired. Where the fatigue crack occurs in the jacket leg or joint can, FMD is useless. Its popularity in the North Sea may be traced to pervasive fatigue problems in the single-sided closure butt welds used with node pre-fabrication.

For the California structure with both thick joint cans and grouted piles, fatigue failure on the brace side of the tubular joint intersection weld is more likely, so FMD may be applicable. Also, for overlap mid-frame K-braces, at least one of the members would be flooded by a thru-crack.

These last slides were taken from the inspection JIP conducted by MSL in 2000, based in part on data provided by SeaTest. This work, and the subsequent draft API RP 2SIM, attempts to bring post-Cullen UK safety standards into the United States' OCS.

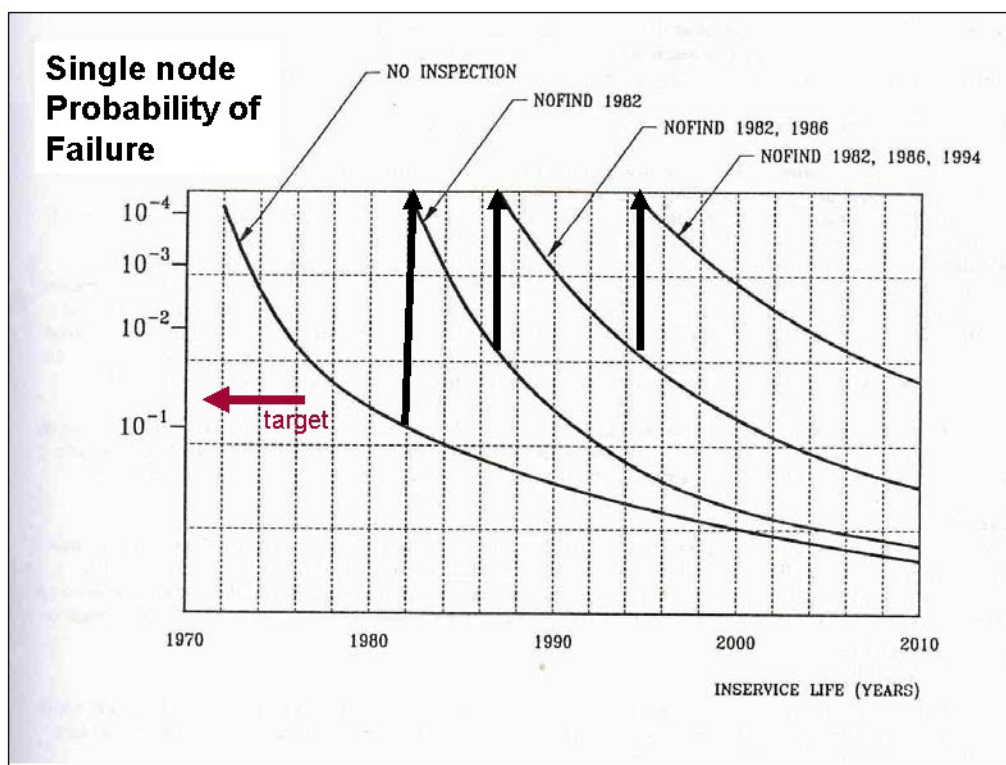


Once the basic requirement of static strength has been met in an offshore tubular structure, fracture mechanics may be applied to evaluate the other modes of failure, as indicated in this Figure (Bristoll, 1978). Since the applicability of linear plane strain fracture mechanics usually means that one is in trouble already, empirical design procedures based on Charpy correlations, the Fracture Analysis Diagram, or Crack Opening Displacement tests are used. Fracture mechanics is also used to evaluate the fatigue growth of cracks from small and harmless up to terminal size.

Case Study #2



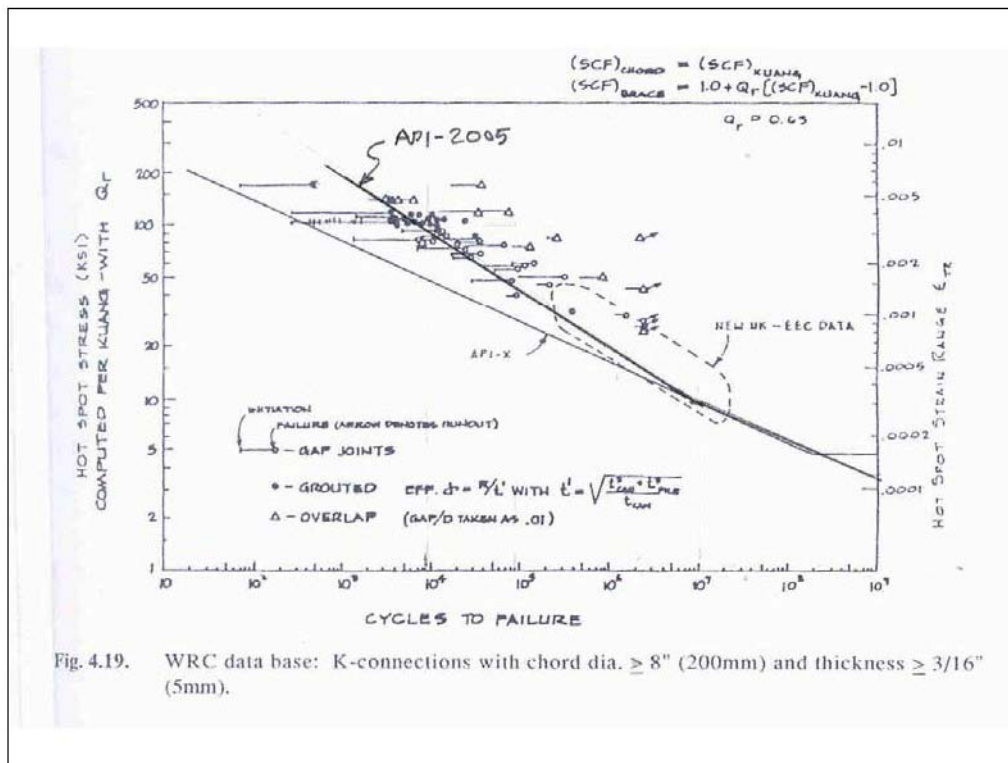
The example here is for a node having a calculated fatigue life of ten years, representing the 1972 McDermott 12-pile platform for the Ekofisk field offshore Norway [Lotsberg 1993].



Probabilistic fracture mechanics can be used to link in-service inspection to the probability of fatigue failure. The process is similar to that described earlier, except that crack size replaces SCF and Paris' law replaces the S-N parameters, along with their bias and uncertainty.

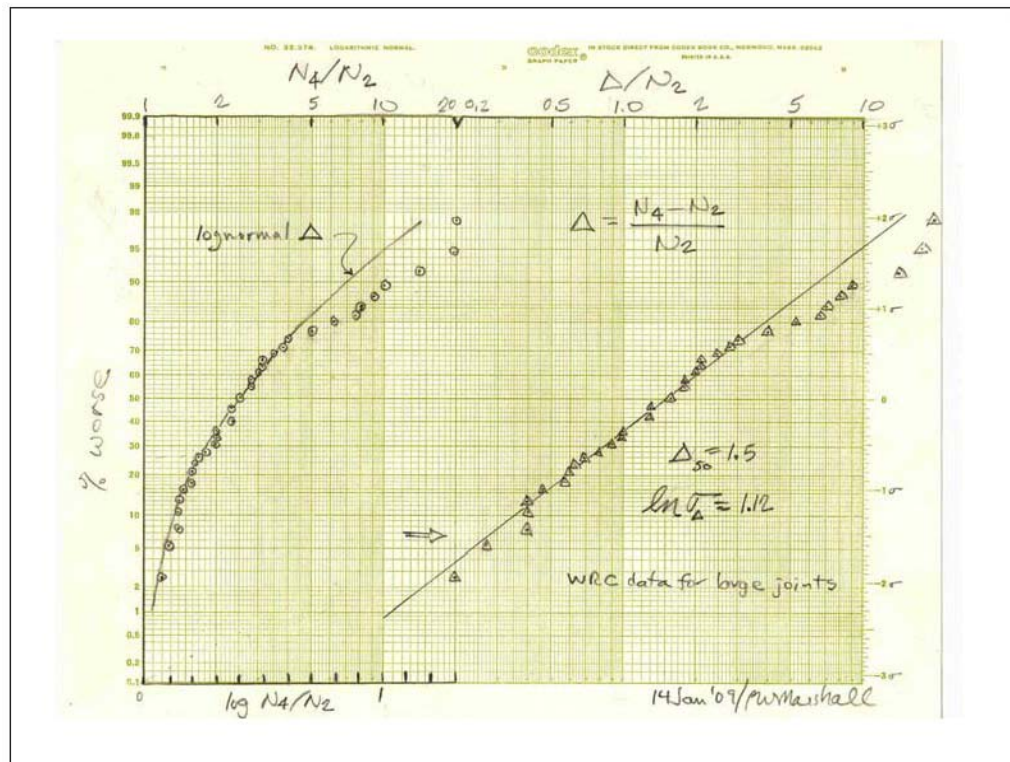
“No find” results from Level III inspection of the critical node using magnetic particle inspection (MPI) are used to update the crack size, i.e. to the probability of detection (POD) threshold of say 1mm deep x 1.5 mm long. The risk of failure degrades towards the limiting target as the fatigue crack grows over time, but is reset with each successful inspection (or repair). Re-inspections are at intervals of 0.4 to 0.5 times the “no find” crack-free life each time, out to the current platform age of 37 years. Structural system effects are also considered to further mitigate the risk, as described elsewhere in this paper.

This strategy is termed Risk Based Inspection (RBI). Baseline inspection during fabrication, and Performance Demonstration Initiatives (PDIs) to qualify the nondestructive testing procedures and personnel are essential, if this exercise is to be credible [Abadie, Goldberg, et al, 1993; Goldberg, 2009]. Repeated findings of unexpectedly long crack-free service might further be used with Bayes' theorem to update bias factors for other parameters of the fatigue analysis, e.g. hydrodynamic coefficients or environmental fatigue acceleration factors.

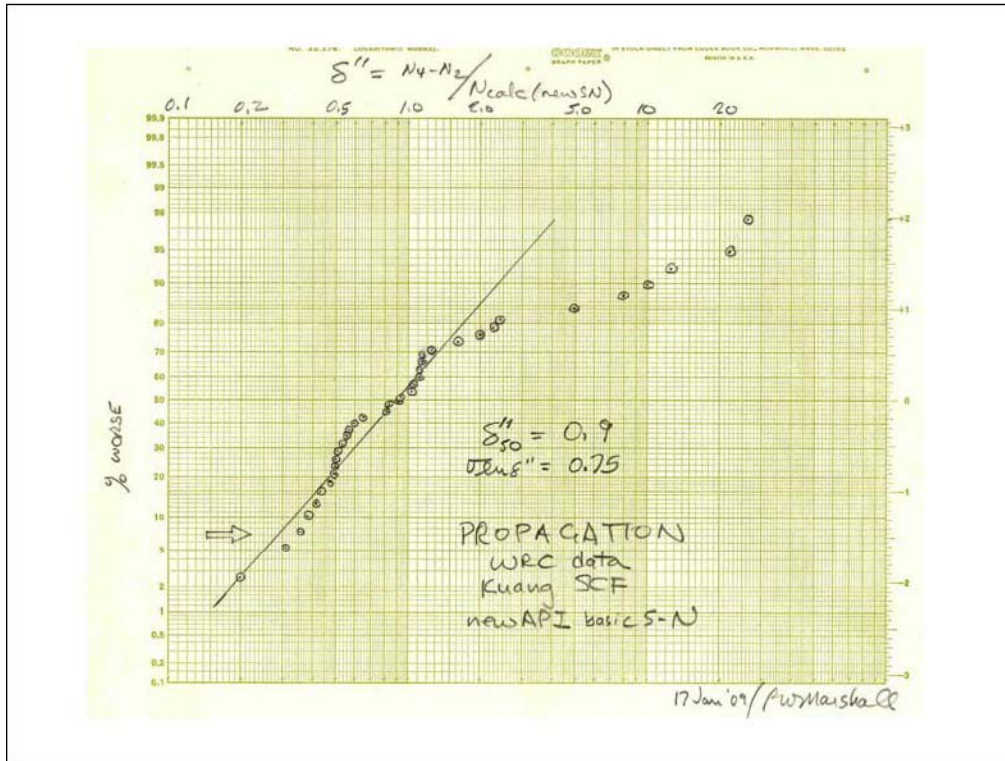


K-joint data set from WRC Bulletin 256 [Rodabaugh, 1980] can be used to get a more empirical handle on the fatigue crack propagation period. Newer data from the European research falls mostly within the dashed area. The horizontal lines representing propagation start at an initial crack size, based on visual detection rather than MPI or ACDP. Hot spot stress is based on the use of SCF from Kuang, as has been done in a re-assessment, rather than measured with strain gages as in a laboratory. Both the original API

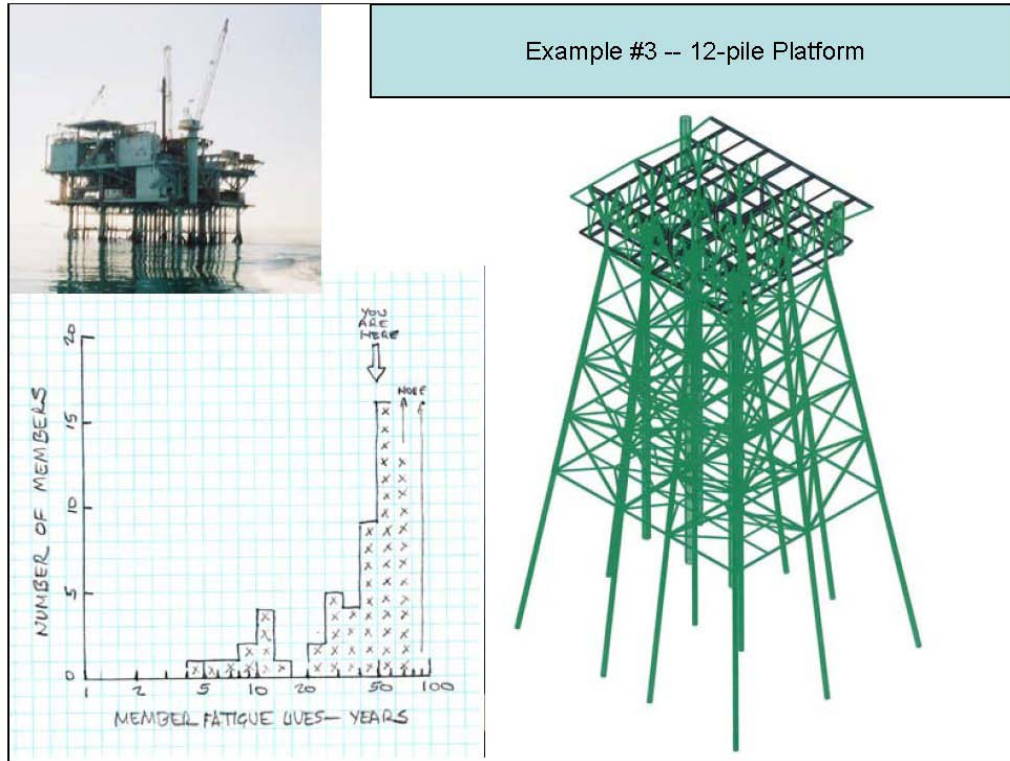
curve X and the 2005 revision are shown. In the low-cycle region, this interpretation shows an apparent safe side bias factor of four on life, relative to the original data interpretation based on measured uni-axial hot spot strain.



The relation between visual initiation N_2 and terminal failure N_4 is interpreted here, without regard to S-N curve or how the hot spot stress is determined. The interval (Δ) between initiation and failure has a median value of 1.5 times the initiation life, with a lognormal COV of 116%. The horizontal arrow indicates that the target single member reliability would be met by taking a characteristic value of 0.3 times N_2 for this interval.



Here, the crack propagation interval is related to the calculated fatigue life, rather than the observed initiation. The new S-N curve (API, 2005) has a slope consistent with fracture mechanics crack growth. When used with the Kuang SCF, it gives a reasonably good correlation, with the propagation interval having a median value of 0.9, a lognormal COV of 75% on the side that counts, and a characteristic value of 0.3 times the calculated life. Using the old S-N curve “X” did not give a useable correlation, because its slope exponent does not match the Paris Law.



Practical application of RBI using member propagation lives and structural redundancy will be illustrated using an example 12-leg platform in 40-50m water depth, similar to Ekofisk and the ones shown in Figure 13. Here, the dominant overload risk is seismic, but the long term wave load distribution has a Weibull shape factor of 1.0, like the North Sea (Marshall, 1982).

The platform is now 40 years old. Despite generally mild met-ocean conditions, the first underwater conductor panel suffered early fatigue failure, was found to be redundant, and retired from service. Heavy marine growth and underestimation of vertical wave forces due to “bulb effect” blockage on the conductor panel contributed to the problem. The design procedure was corrected, and marine growth is now routinely removed.

Calculated fatigue lives for the members remaining in service are shown in the histogram. Today’s plans for enhanced oil recovery would require extending the platform life by another 20 years (total of 60) with safety equivalent to a factor of two on future life being required by reassessment rules. Level II visual underwater inspection indicates that all these members remain intact, but we appear to be getting into the “tall weeds” of lots of members with expired calculated life. The engineer’s dilemma: What to do?

The calculated fatigue life N_f is just an estimate, and should be considered with appropriate skepticism. The sources of uncertainty in fatigue life are many and considered to be random variables. Thus, for new designs, it is desirable that the calculated fatigue life should be a multiple of the intended service life.

12-pile platform

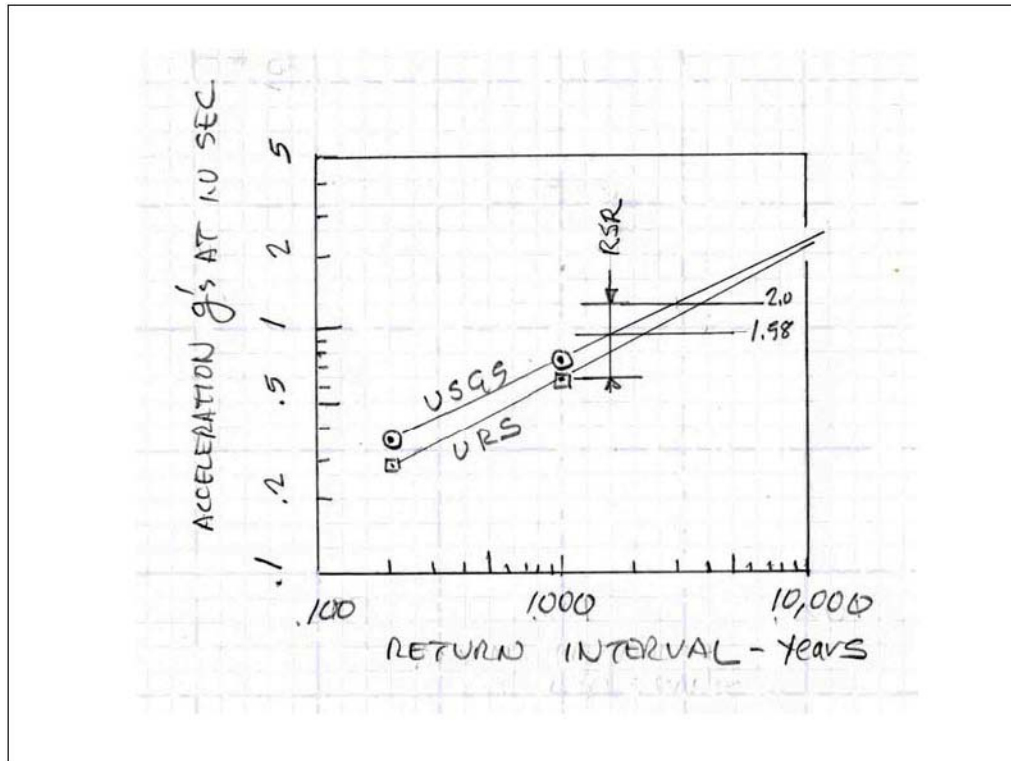
- Redundancy
 - 8x broadside, 9x end-on
 - 238 bracing members, 153 in critical load path
- Group A lives – inspect all 10
 - 1 @ 4 yr
 - 1 @ 6 yr
 - 3 @ 8 yr – 1 critical
 - 5 @ 10 yr – 2 critical
- Group B lives – inspect 6 critical
 - 4 @ 20-30 yr – 2 critical
 - 8 @ 30-40 yr – 4 critical

Fatigue calculations can still provide guidance for future inspection strategies. Here we make use of the empirical propagation life Delta. Level I is topside and CP monitoring. Level II adds an underwater fly-by. Level III includes underwater inspection of selected nodes, with MPI through tight oxide scale or high-definition video after cleaning to bright metal, which can be used to re-set the fatigue lives to a value consistent with the target for single member reliability by calculation. Level III crack detection inspections are repeated whenever the safe propagation life is expired, with Levels I and II inspections being conducted more frequently. The following inspection intervals are proposed:

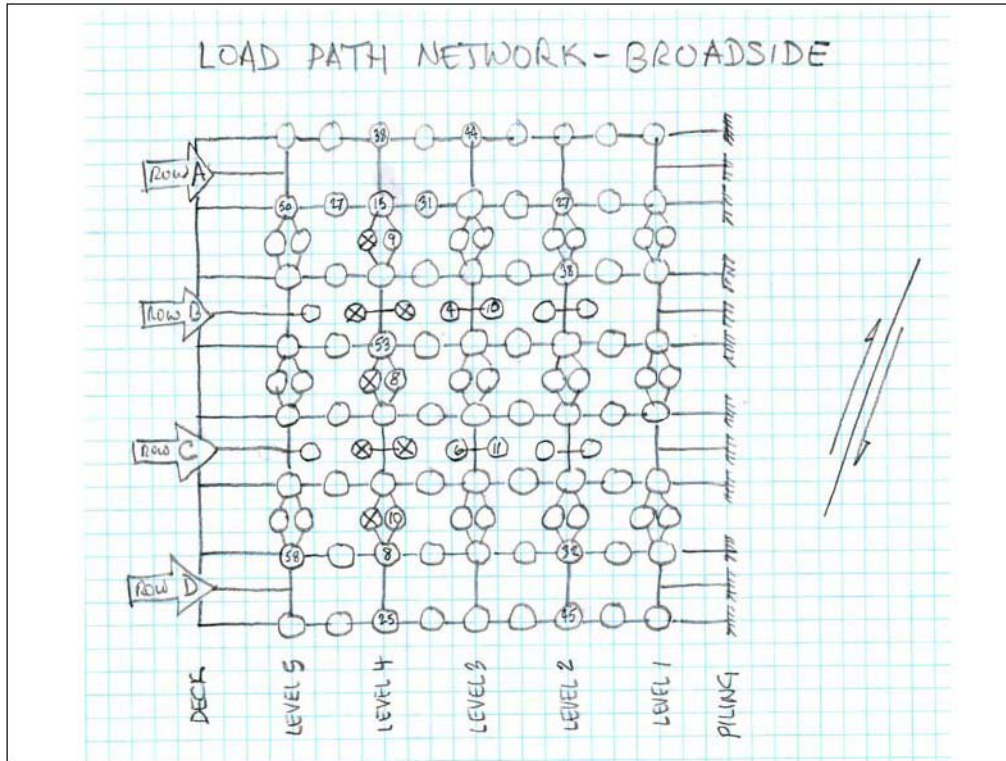
Level I – annual topside and CP;

Level II – $N_f / 8$ or $\Delta / 4$, and after major events;

Level III – $N_f / 2$ or Δ , whichever is greater.

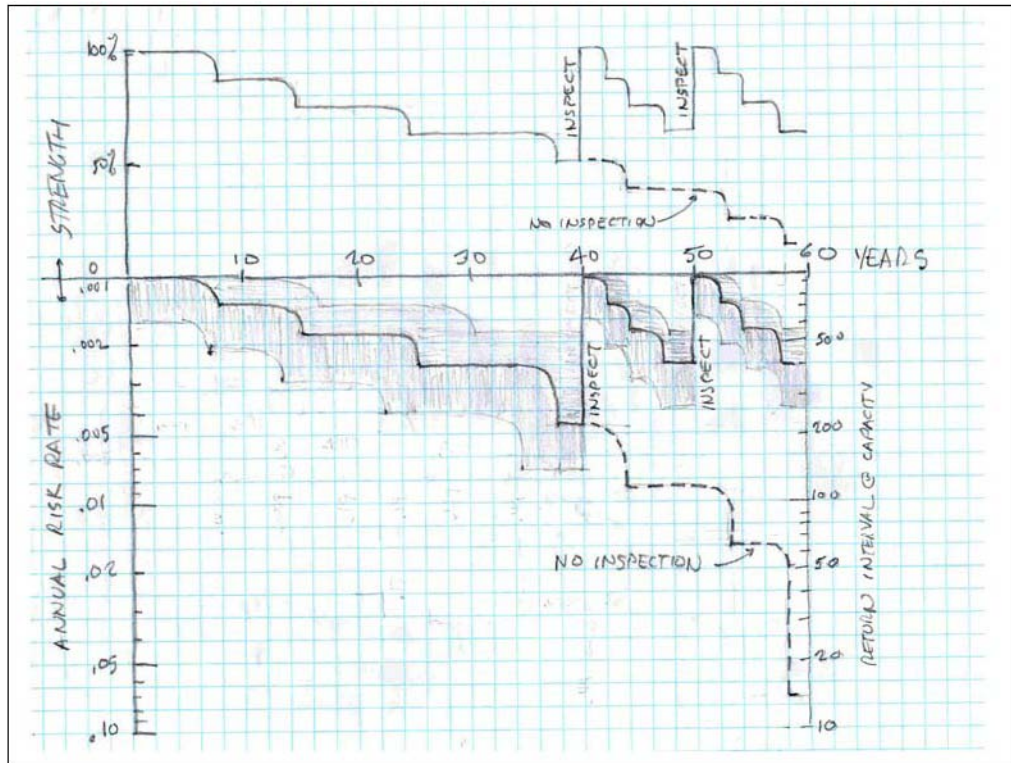


Progressive fatigue degradation of the platform strength is evaluated against the seismic hazard shown here. The intact platform is presumed to withstand the URS site-specific 1000-year event. Pushover analysis has indicated that its sister platform would do so with the reserve strength ratios shown, corresponding to return intervals for the collapse event of 1500 to 4000 years.



This figure shows a load path network representation of the example 12-pile platform jacket for broadside loads. There eight parallel load paths – two each in rows A, B, C, and D – with a diagonal and horizontal being in series at each level of “N” bracing. There are load redistribution opportunities at levels 1, 2, 3, 4 and 5, with the six horizontal diagonals occurring in parallel pairs. The dead-end load paths represent conductor guides, not part of the main load path from seafloor piling to deck level.

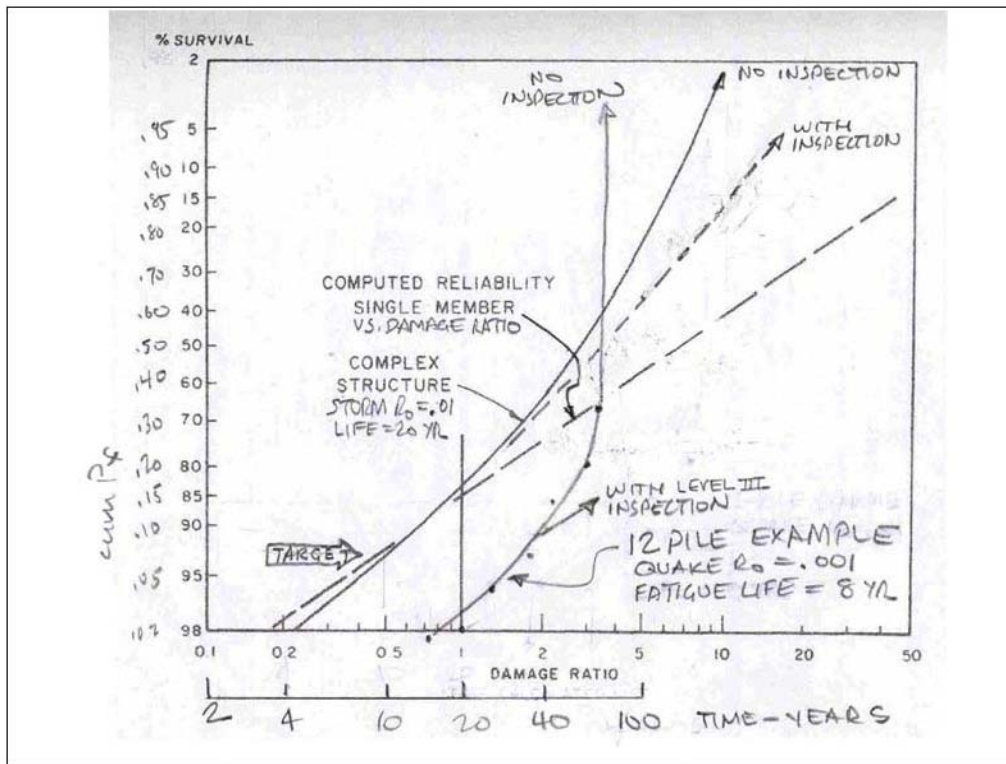
Numbers in the circles represent calculated fatigue life in years. The “X” members are in the retired conductor guide area. Examination of the diagram indicates that many of the early-failing members are not in the primary load paths. The critical failures causing loss of a load path are calculated to occur in years 8, 15, 25, 38, 44, 53 and 58.



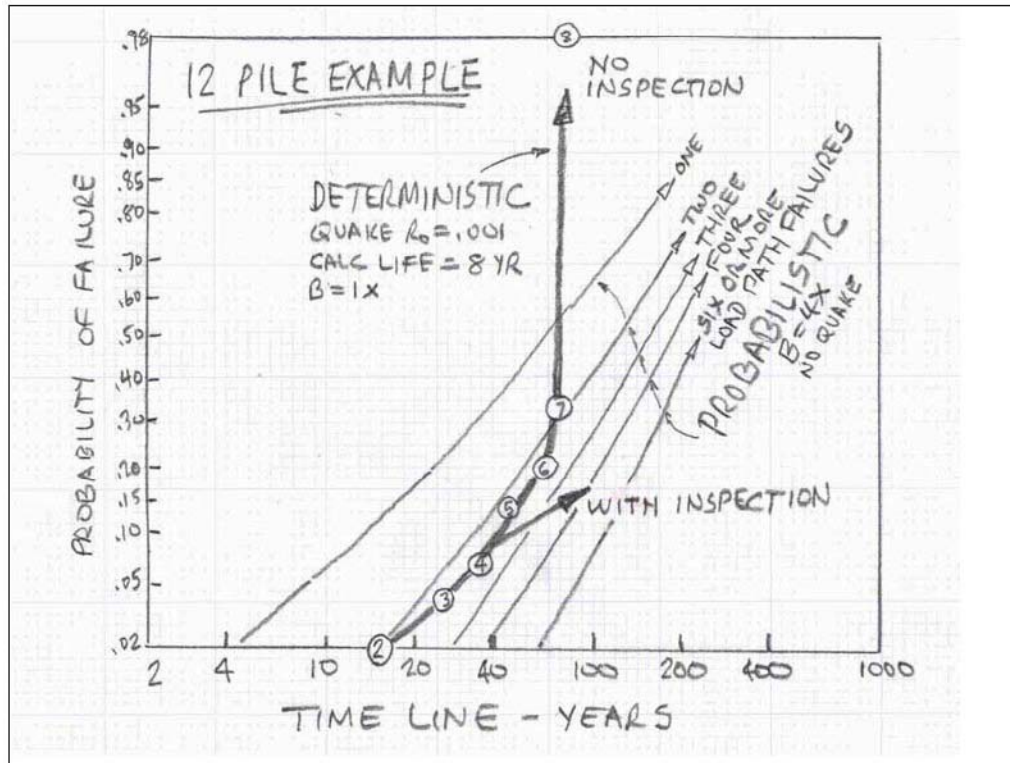
The top plot here is a deterministic (and pessimistic) scenario of load paths failing exactly on their calculated fatigue life schedule. With ductile materials, weakening of a member does not occur until close to the end of the fatigue life, as large cracks reduce the available net section.

Corresponding to the loss of a load path, there is a reduction in platform strength and return interval for the collapse event, with an increase in the annual risk rate as shown in the lower figure. These risk rates are shown with a fuzzy band to indicate the possibility of a more severe hazard (e.g. USGS) or safe side bias and uncertainty in the fatigue analysis. A fatigue bandwidth of only two is shown, as showing more realistic values (e.g. 4 to 8) would make the figure difficult to read.

Each Level III inspection (either “no find” or repairs) resets the propagation clock to zero. Re-inspection at ten year intervals keeps the risk under control, favorably comparable to that of a manned A-2 Gulf of Mexico platform subject to sudden hurricanes. However, with no inspection, load paths continue to be lost, the strength approaches zero, and the risk rates descend into hell, increasing to unacceptable levels.

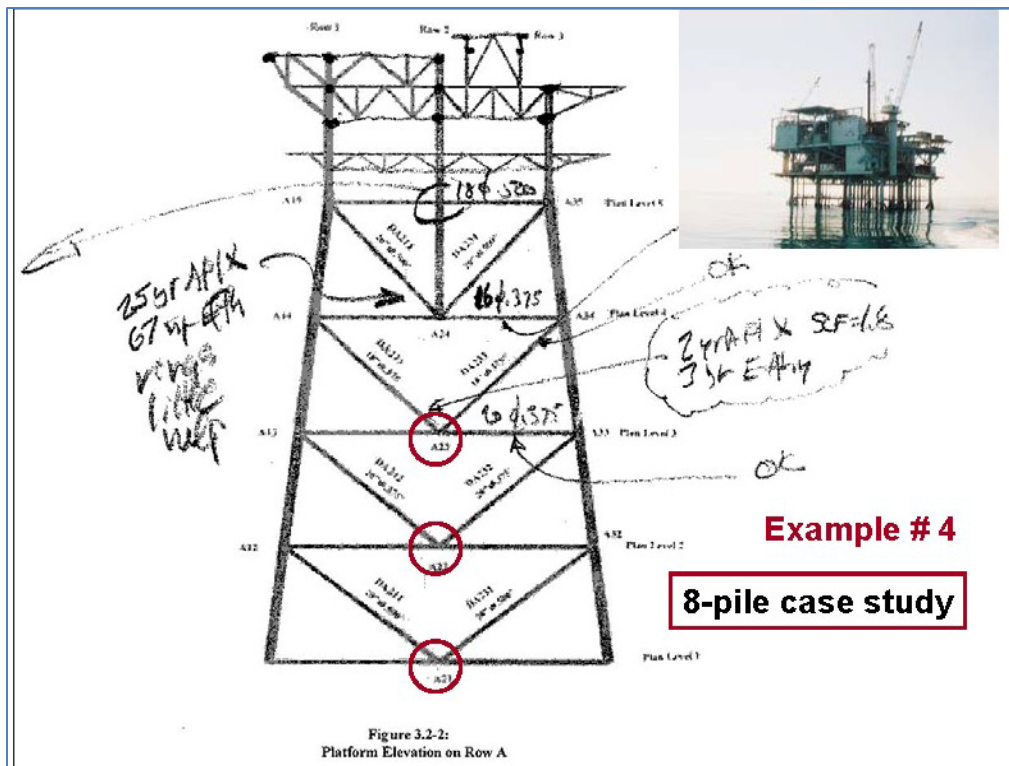


Cumulative risk is the risk rate integrated over time, from day one. This figure compares risk for the deterministic 12-pile scenario to that of the North Sea type structure – although there are substantially different calculated fatigue lives and overload hazards. Going forward with no inspection appears to be clearly unacceptable, whereas Level III inspections keep the risk low. From today forward (not from day one) the risk remains below the target set by a new-design structure at a fatigue damage ratio D of 0.5.



The deterministic “no inspection” doomsday after year 60 is by no means a certainty. This figure attempts to give the 12-pile example a more probabilistic interpretation. Starting with single member failure risks for successive load path failures, the cumulative hazard is the sum of these, which eventually exceeds unity. This is reduced to P_f for the first load path failure using the Poisson expression. A bias factor of 4, as evidenced by the WRC 256 plot, is introduced. Having more than one load path failure is treated as a compound event. The resulting failure probabilities are for wave-induced fatigue only, with no big earthquake and no fatigue acceleration due to increasing stress levels.

Nevertheless, we see that the deterministic “on schedule” scenario corresponds to the probabilistic 2% risk, and remains a conservative and useful representation of progressive structural failure under fatigue loading.



While the 12-leg deck here is similar to sister platform #3, the jacket has been optimized to the point where it has shorter calculated fatigue lives and less structural redundancy – making it a more challenging case study.

Rows 1 and 3 have grouted joints, and are loaded primarily by the milder cross channel wave environment, so they do not present a fatigue problem. The jacket has six degrees of redundancy level for loads in this direction.

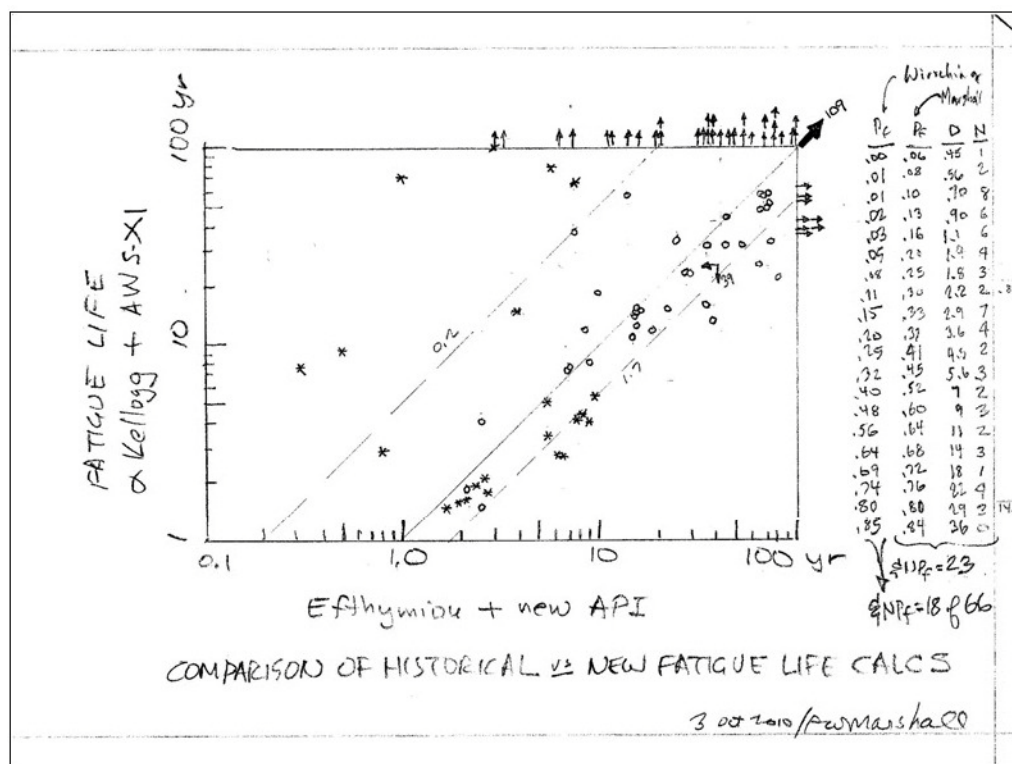
Row 2 does not have grouted joints, and diagonals crossing the waterline are calculated to have significant fatigue damage from out-of-plane bending when Efthymiou SCF are used with the rigid joint assumption. OTC 7155 describes how the traditional method implicitly takes credit for joint flexibility to give better calculated fatigue lives. These diagonals are not part of the primary load path resisting seismic loads, but provide additional redundancy to the support of vertical loads from Row 2 deck legs.

Findings for Row A are given in the above scan and in the text below. Rows B, C and D are similar. Horizontals are considered here as part of the primary load path. Low calculated fatigue lives at plan levels 4 and 5 do not consider that there are diaphragms inside the Row 2 legs. When the diaphragms are taken into account, these members are no longer a problem, even when the ultra-conservative API-X' and Kuang base cases are used. Furthermore, they cannot be considered as bellwethers for members elsewhere in the structure.

The mid-frame K-joints at plan levels 1, 2 and 3 are the most critical joints in the structure. There is overlap but no joint cans in these joints, giving very low calculated fatigue lives. Failure of either of the diagonals renders the entire K next to useless. Rows B, C and D are similar to Row A, so the jacket only

has the redundancy of four independent parallel load paths for broadside loads at these levels. A full 12-pile structure would have at least 8 independent parallel load paths.

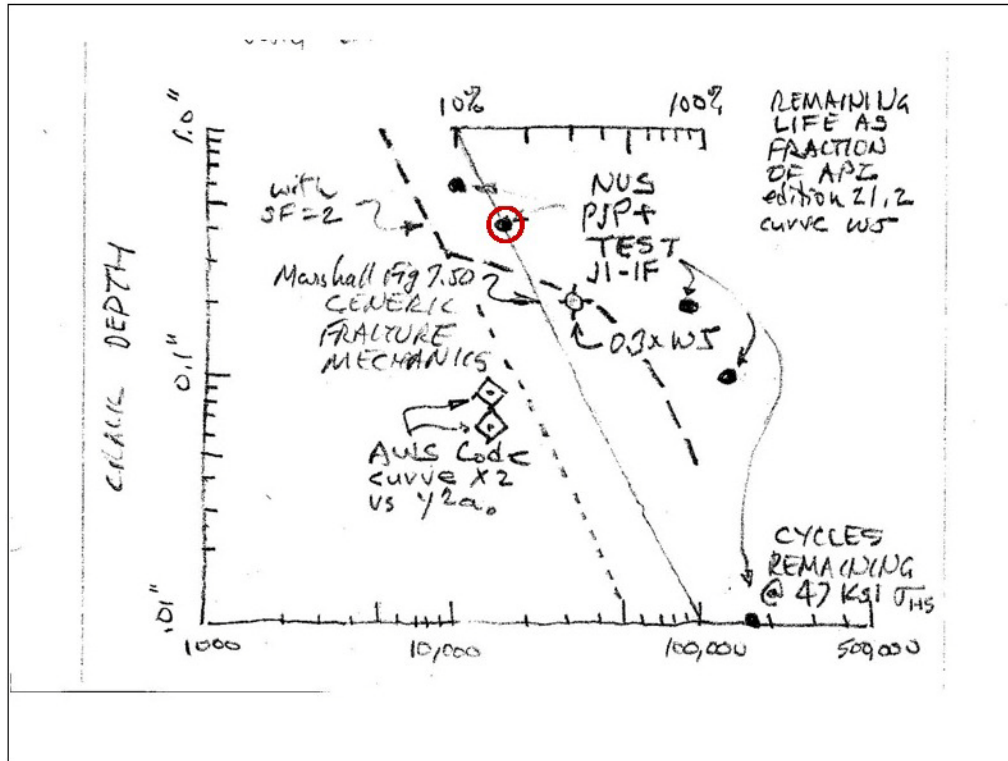
To complicate matters even further, the lowest Level 1 is buried under a debris pile, and inaccessible for inspection. Even if we assume that the debris pile immobilizes the horizontals at low load levels, avoiding their accumulation of fatigue damage, the K-brace diagonals remain fully loaded, fully susceptible to fatigue damage, and critical to survival of an extreme seismic or storm wave-in-deck event.



Design of the Cognac and Bullwinkle deepwater platforms used Alpha Kellogg stress concentration factors (SCF) together with the old AWS/API S-N curve X. This is the methodology on which fatigue reliability was originally calibrated in the 1970s. Subsequent research centered around the North Sea refined the methodology with Efthymiou SCF and a new ISO/API S-N curve WJ.

Some 98 main member ends have calculated fatigue lives less than 100 years by at least one of these two methods. Of these, the 39 primary joints with calculated fatigue lives less than 40 years by the latest ISO/API methods and less than 25 years by traditional AWS/API methods contribute 92% of the fatigue risk, as indicated by Wirsching's calibration. Underwater inspections to date have found no members severed by fatigue, but were not detailed enough to find incipient fatigue cracks.

The old and new methodologies do not give identical results, but are split 50-50 on which one is more conservative. The new 15-85 percentile fatigue lives are 0.2 to 1.7 times the old, as shown in the plot above.



There are a number of possible strategies for dealing with this dilemma. One would be to perform detailed inspection – e.g. underwater MPI – on all the mid-depth mid-frame K-joints, to serve as bellwethers for the deeper and inaccessible K-joints. A second would be to perform frequent close visual inspections of all the accessible K-joints, and flooded member detection (FMD) for the diagonals leading to the inaccessible buried K-joints. Severance of one diagonal at the K-joint would flood the other one, due to the overlap, even if failure occurs in the punching shear mode with the pull-out plug intact. More strategies may evolve from ongoing work for this platform and the upcoming inspections of nearby platforms by a major operator.

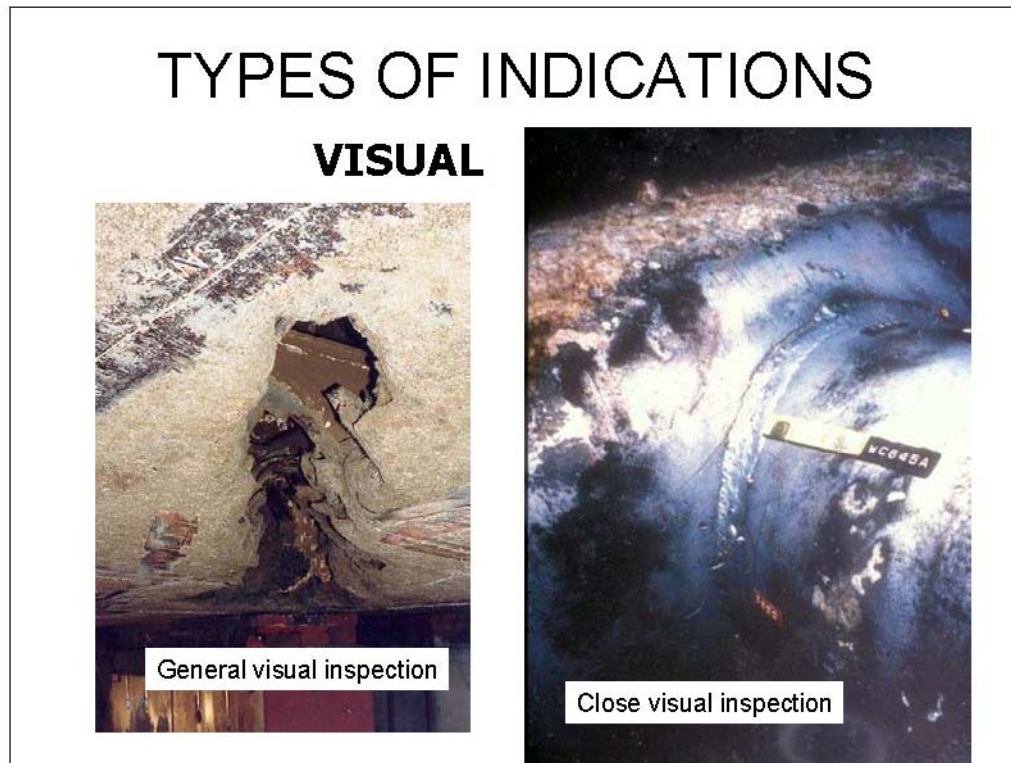
The foregoing figure is taken from a proposal for the inclusion of underwater magnetic particle inspection (MPI) in API RP 2X, and is based upon ongoing research at NUS. To make a particular member safe from fatigue failure within an inspection interval of 1/10 the life-to-date, it would be necessary to ascertain that there are no cracks deeper than 0.4-inch, or 2 to 4 inches length with an aspect ratio of 5 or 10 to 1, as indicated by the red circle.

Targeting a remaining life of 0.3 times the curve WJ calculation would require finding smaller cracks, say 1-inch long. Tight fatigue cracks this small are not reliably detectable by visual inspection, unless one is observing a whitewashed specimen under load in laboratory conditions.

This fitness-for-purpose approach may be contrasted with the more stringent workmanship-based inspection standards in the AWS Code.

Summary of Alternative Strategies

1. To make every particular member absolutely safe from fatigue failure within the next inspection interval, it would be necessary to ascertain that there are no cracks deeper than 0.2-inch, or 1-inch length with a conservative aspect ratio of 5:1. Tight fatigue cracks this small are not reliably detectable by visual inspection, and would require underwater NDI, with the attendant prospect of false alarms.
2. The alternative strategy of only looking for severely cracked or flooded members does not reserve significant remaining fatigue life for the particular member. Rather, the first member is assumed to fail during the next inspection interval, and one depends on structural redundancy to maintain residual strength in parallel load paths. This fail-safe-while-manned fracture control strategy was presented by Marshall at the 1979 ISSC plenary session on safety, and subsequently published by Bureau Veritas.



Close visual inspection after cleaning to bare metal can find mid-life fatigue cracking in members not preloaded in compression. However, it is expensive, and usually applied to pre-identified areas of concern. General visual inspection (fly-bys) find major damage, provided the ROV operator does not blink or yawn at the wrong time.

THE INSPECTION PART OF R.B.I.

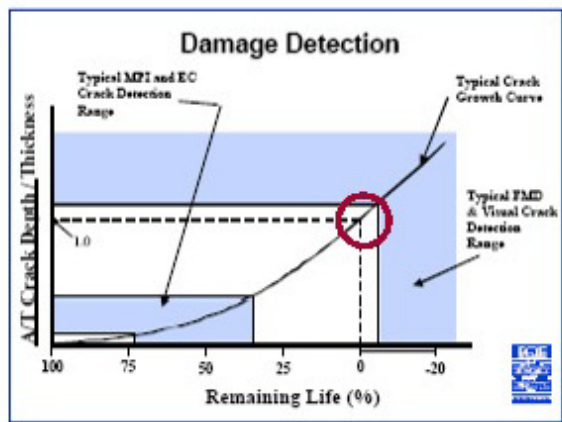
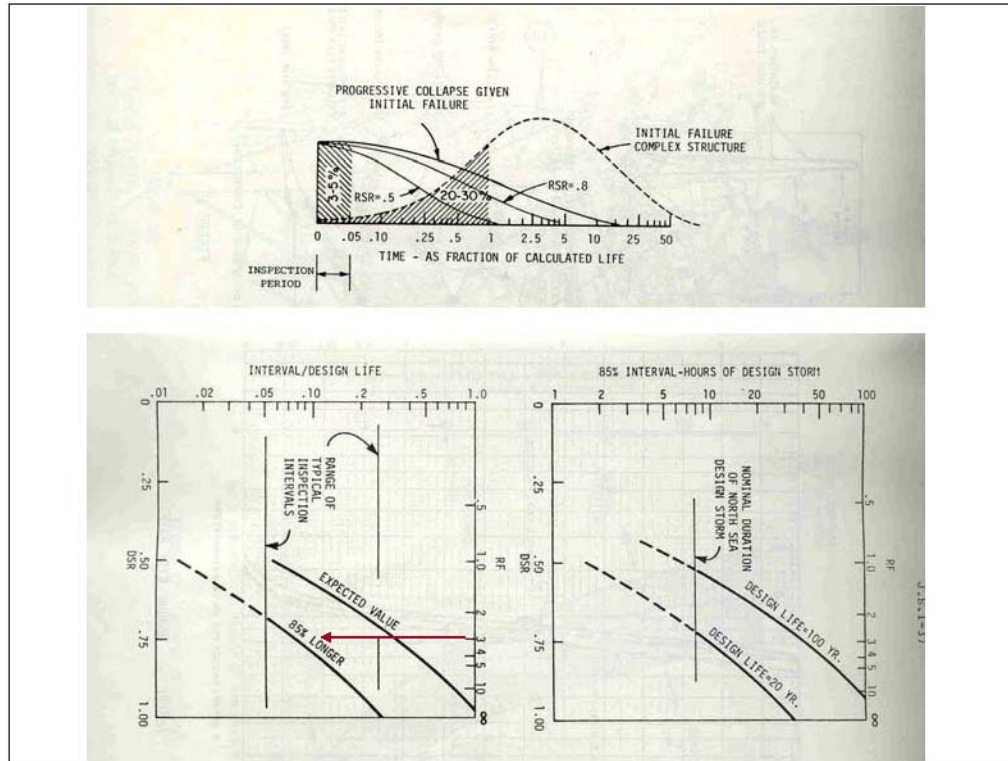


Figure 8.11: Ability to detect a crack in member for different NDE techniques

Fly-by general visual inspections and flooded member detection only detect fatigue cracks at an advanced state, either through-wall or severed member. The crack propagation period has already been spent, and only alternative load paths (structural redundancy) are preventing collapse. When such defects are found, immediate action is required (which may simply be consideration of the structure with the missing member).



The alternative strategy of only looking for severely cracked or flooded members does not reserve significant remaining fatigue life for the particular member. Rather, the first member is assumed to fail during the next inspection interval, and one depends on structural redundancy to maintain residual strength in parallel load paths. This fail-safe-while-manned fracture control strategy was presented by Marshall at the 1979 ISSC plenary session on safety, and subsequently published by Bureau Veritas. For a structure with four similar parallel load paths there would be 85% reliability that the interval between the initial failure and subsequent failures would be more than 10% of the design life. For Houchin, read 1/10 of life-to-date.

By the same token, 85% reliability is similar to that of a new structure that is operating within its calculated fatigue life (safety factor of 1.0), without scheduled underwater inspection. If this does not meet the BOEMRE safety targets, annual structural dynamic monitoring can be used in lieu of more frequent underwater inspections. Changes in natural frequencies and mode shapes are used to detect gross structural damage, e.g. the loss of more than one load path at a given level. It would be necessary to perform a benchmark reading concurrent with the underwater inspection, and to keep track of major changes in deck mass, e.g. casing strings onboard, emptying of mud tanks, and relocation of the drilling rig. This methodology was pioneered by Aerospace Corp in El Segundo in the late 1970s, and is now offered on a call-out basis by Fugro in Houston.

Inspection Challenges for Offshore Facilities

Faisal Al-Abbas, Inspection Department, Saudi Aramco, Dhahran, Saudi Arabia

Introduction

The oil and gas offshore producing facilities are essential part of the production and transportation systems. These facilities encompass platforms, process equipment and undersea pipelines. During operation, some structures are exposed to damages that might jeopardize the safety of these installations or might lead to high cost impact due to process interruptions. Proactive inspection, online monitoring and risk managing programs are needed to ensure the integrity of offshore gas producing facilities.

Background

To ensure the integrity of offshore installations it requires a holistic integrity program. Establishing such a holistic integrity program involves four main steps: confirmation, mitigation, control, and feedback. The confirmation is to detect causative factors of damages. The design, operating and physical conditions should be factored in to gauge the system vulnerability to different damage mechanisms. During this stage, different detection strategies including Non-destructive Testing (NDT) methodologies and prediction models are used as proactive measures to prevent system failures and process interruptions. The mitigation strategies are important to eliminate and control the reported damages (i.e., mechanical and corrosion flaws). Examples of mitigation measures include chemical methods, working conditions control, design modifications and material selections. In the control stage, once the damage is treated in the system by utilizing the correct treatment and mitigation programs, it is good practice to measure and track the effectiveness of these methodologies and whether they meet their objectives or not. It is useful to maintain and enhance that level of protection by having feedback loop by means of documenting history and other details of confirmation, mitigation and control programs.

Oil and gas industries utilize available Non-destructive technologies (both advanced and conventional) to monitor the offshore facilities integrity. These non-destructive methods are crucial part of the offshore facilities integrity programs because they could provide online quantitative or/and qualitative measurements without the need of process interpretation. Selected examples of the advanced NDT technologies utilized by oil and gas operations are presented in the following:

- Guide wave Ultrasonic Technology Strip used for corrosion Monitoring.
- Magnetostrictive Sensor System used for structural monitoring.
- Guided wave Ultrasonic Technology used for structural monitoring.
- Acoustic Emission Dolphin used for Offshore Platform Piles Crack monitoring.
- Time of Flight Diffraction (TOFD) used for Hydrogen Induced Cracking (HIC) detection and sizing.
- Phased Array Ultrasonic Technology used for HIC detection and sizing.
- 360 Pocket Ultra sound (UT) used for OSI (On Stream Inspection).
- HPCM used for OSI sensors.
- Off shore P-Scan System used for sub-sea pipeline corrosion mapping.
- Remotely Operated Vehicle (ROV) used to inspect the subsea structures.

Despite the number of available inspection technologies, still there are challenges and gaps that will require further innovative or further research developments. This report communicates the offshore inspection challenges and needs.

Inspection Challenges

Inspection teams routinely review the inspection programs and highlights in the areas of inspection improvements for the day-to-day inspection activities. This is an important step in the Asset Integrity Program to ensure the readiness and effectiveness of the deployed detection methods and their capabilities to monitor the condition of the offshore facilities. The following highlights the areas of improvement that Saudi Aramco is seeking to resolve. It is believed that in order to overcome these challenges, the deployed inspection technologies might require further advancement or development of new innovative technologies.

1. Inspection for the external and internal corrosion of elevated piping networks on offshore and onshore facilities

The elevated piping systems at both offshore and onshore facilities are subjected to external and internal corrosion damages. There is a wide variety of sizes ranging from 2 to 60 inches. Current inspection techniques include on stream UT inspection (OSI) and scanning methods such as Phased array and TOFD. However, these techniques require scaffolding erection which is costly and time consume. Therefore, an inspection method that has the capability to check the integrity of these pipelines without the need of scaffolding installations will be needed.

2. Inspection method for non-scrappable pipelines and risers on offshore and onshore facilities

There is several non-scrappable piping at different sizes that range from size 6 to 16 inches. It is difficult to check their internal conditions as the In Line Inspection (ILI) via pigs cannot be performed due to their size limitations. Moreover, these systems are not equipped with launching and receiving facilities that are required for running pigging instruments. Inspection technology is required to check the integrity of these pipelines.

3. Leakage inspection for the subsea when they are in the close position

There are several valves with different sizes range from size 8 to 42 inches and are at a depth of 30 meter. Leakage detection method is required to check for the hydrocarbon leaks while the valve is in close position.

4. Remote inspection method for the structural installations located between the water level and deck platform

The underwater offshore structures are routinely inspected by using a remotely operated vehicle (ROV). However, ROV cannot be used to inspect the part of the structures located in between the water level and under the deck. Instead, this part can only be inspected during the turnaround schedule of the platforms and requires scaffolding installation and grit blasting prior to performing visual and UT inspection. Advancement in inspection technology that provides remote inspection capabilities and

video recording for the aforementioned portion of structure will result in great cost saving and will enhance the effectiveness of the inspection program.

5. Risk-Based Inspection (RBI) for offshore structures

Most of the available Risk-Based Inspection (RBI) programs focus on process equipment and piping systems. To our knowledge, there is no RBI program that is capable to determine the risks qualitatively for the offshore and onshore structures. The RBI program is crucial to define risks and quantify hazard and consequences associated with operation of the offshore structures. Ultimately the RBI outputs will be used to enhance the proactive measures and optimize inspection and maintenance programs. The program should be bundled with computational capabilities that combine statistical analysis with modeling to prioritize and focus the inspection efforts and costs.

6. Enhancement of Remotely Operated Vehicle (ROV) Inspection

Inspection of underwater structure can be performed by remotely operated vehicles (ROV), by trained divers, or by both based on the extent and the level of inspection. As example, level-4 inspection mandates the service of diver inspectors. The implications of using divers lie in the high cost and safety which with time has increased with the stringent regulations. Therefore, further development of ROV technology will be required to perform further detailed inspection and substitute the need of diver inspectors.

7. Finding innovative methods for degradation control of aging facilities and for corrosion under marine fouling, concrete coating and clamps

The inspection of degradation mechanisms under the marine bio-growth is performed by using either visual or NDT via ROV and divers. This requires the cleaning of scale buildup by either blasting or other mechanical tools; however, these procedures yield high cost. On the other hand, there is no inspection method that can be used to inspect the area under the concrete coating that is used to balance the bouyancy load for subsea pipeline. Furthermore, the area beneath the support clamps that are used to fix the riser to the platform structures cannot be inspected by any of the available inspection techniques. Both areas (that is under the concrete, clamps and bio-growth) are subjected to corrosion and innovative NDT methods will be needed to ensure their integrity.

8. Finding proactive and remote on-line monitors for Cathodic Protection

Periodic surveys are conducted to ensure the functionality of the Cathodic Protection (CP) systems in the offshore installations. These surveys are scheduled in defined intervals. Over protection or under protection could impact the integrity of these installations. It is believed that periodic survey is not totally effective in the offshore installations as the CP systems might malfunction at any time. Therefore, it is recommended to develop and adopt innovative systems that will provide remote on-line monitoring of cathodic protection and alerting system for CP of subsea structures and submarine pipelines to ensure continuous protection.

Working Group Reports

Working Group 1

Impact of Material Quality Control on Underwater Welding, Inspection and Reliability

Tom Myers and Marcus Cridland, ABS; Tony Rallis, PHMSA; Kirk Brownlee, Stress Engineering Services; Donald Drake, ExxonMobil Pipeline

Working Group 2

Standards and Certification for Underwater Welding and Inspection

Roger Holdsworth, Chevron; Chris Jones, Diamond Offshore; Mike Wheatcroft, ABS; Lance Shupe, OxyLance; Greg Cain, Brian Warzecha, Paul Sturgill and Tom Reynolds, Global Divers & Contractors

Working Group 3

Underwater Wet Welding Consumables Development

Valter Rocha dos Santos and Mauricio de Jesus Monteiro, PUC-Rio; Alexandre Queiroz Bracarense, UFMG; Ezequiel Caires Pereira Pessoa, IFMG; Uwe Aschemeier, Terracon; Len Andersen, Wet Welding; Dave Gibson, Proserv Offshore; James Merritt, DOT/PHMSA; Clint Levine, Phoenix; Keith Moline and Grant Folkmann, Devasco; Intl., Rodger Spriggs, Ranking/Broco; Stephen Liu, Colorado School of Mines

Working Group 4

Training and Certification of Personnel

Jack Couch, Ocean Engineering; Mik Else, BOEMRE; James Merritt, DOT/PHMSA

Working Group 5

Reliability of Underwater Wet Welding for Offshore Structures

Faustino Perez, IMP; Pingsha Dong, UNO; Juan Carlos Madeni, CSM; Daniel Roldstad, Jacob Fichter and Chris Williams, Global Industries; Christopher Jones, Diamond Offshore Drilling Inc.; Jason Tillman and Christopher Brehaut, Foster Wheeler-Atlas Upstream; Zachary Clement and Timothy Steffek, BOEMRE; Angelique Lasseigne, Gen 2 Materials Technology; Shai Meir, Ben-Gurion University of the Negev; Joe Cray, Iowa State University

Working Group 6

Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures

Peter Marshall, Moonshine Hill Proprietary; Lawrence Goldberg, Sea Tests Services

Working Group 1: Impact of Material Quality Control on Underwater Welding, Inspection and Reliability

Tom Myers and Marcus Cridland, ABS; Tony Rallis, PHMSA; Kirk Brownlee, Stress Engineering Services; Donald Drake, ExxonMobil Pipeline

- I. Introduction
- II. Underwater Inspection
- III. Underwater Welding
 - A. Dry Environment Welding (One Atmospheric- Cofferdam)
 - B. Dry Environment Welding (Hyperbaric)
 - C. Wet Welding
 - D. Welding Problems
 - Hydrogen Cracking
 - Excessive Porosity
 - Arc Physics
- IV. Specific Environments / Structures
 - A. Offshore Platforms
 - B. Marine Vessels / Ships
 - C. Pipelines
 - D. Docks and Terminals
 - E. Bridges
 - F. Dams
 - G. Nuclear Power Plants
 - H. Miscellaneous
- V. Conclusions

Recommendations

- Stress industry awareness/emphasis on material test report traceability with respect to specific locations in an underwater structure or system.
- Develop a gathering venue on underwater welding applications/ successes (CSM, AWS, OTC, API, etc.)
- Develop industry recommended practice for material sampling to properly determine chemical composition/heat treatment (delivery) condition.
- For insitu chemical composition testing, there is a need for an acceptable positive material identification (PMI) technique at depths.
- Investigate whether acceptable butt welds can be made underwater using wet welding.
- Investigate the influence of carbon and carbon equivalence on the cracking susceptibility of underwater wet welds (e.g. Graville diagram.)

Obstacles

- Identification of material to be repaired which becomes more difficult with depth. If you do not know the chemistry, then you cannot properly design the WPS.
- Material in welding qualification may not represent the chemical composition, delivery condition, or mechanical properties for production. For example, the material grade used in welding qualification could be the same grade to be welded, but permissible fluctuations in chemical limits within the specification range can mean that the CE of the grade to be welded might be higher than the CE of the grade used for welding qualification.
- Satisfactory WPS in qualification can crack in production if CE and/or C is higher.
- Steel production techniques have advanced. Steels of today achieve mechanical properties by thermal mechanical processes and have lean chemistry and max CE limits.
- Older grades normally have C and CE higher than modern steels. Older grades may have no CE limits specified.
- For older steels, it may be difficult to obtain the proper steel for welding qualification in order to replicate the steel to be welded.
- Cleanliness of steel to be welded might be a weldability issue. This might be an area for further study.
- Logistics, technology costs, and the limited technology development will hinder deepwater hyperbaric welding.
- Good quality underwater wet butt welds are currently unachievable.
- It is not possible to anticipate where underwater repairs will be needed. These repairs are not planned events. Therefore it is difficult to be prepared.
- Underwater welding procedure qualifications are costly.

Means to address obstacles

- Stress industry awareness/emphasis on material test report traceability with respect to specific location in an underwater structure or system.
- Develop a gathering venue on underwater welding applications/ successes (CSM, AWS, OTC, API, etc.)
- Develop industry recommended practice for material sampling to properly determine chemical composition/heat treatment (delivery) condition.
- Investigate the influence of the interaction of carbon and carbon equivalence on the cracking susceptibility of underwater wet welds (e.g. Graville diagram.)

Working Group 2:

Review of Standards and Certification for Underwater Welding and Inspection

Roger Holdsworth, Chevron; Chris Jones, Diamond Offshore; Mike Wheatcroft, ABS; Lance Shupe, OxyLance; Greg Cain, Brian Warzecha, Paul Sturgill and Tom Reynolds, Global Divers & Contractors



Review of Standards and Certification for Underwater Welding and Inspection

Working Group II - Closing Remarks

Standards and Certification

By: Rodger Holdsworth & Tom Reynolds



Working Group II Standards and Certification

- List participants of Working Group II - Thank Participants
 - Roger Holdsworth
 - Chris Jones, Diamond Offshore
 - Mike Wheatcroft
 - Lance Shupe
 - Greg Cain
 - Brian Warzecha
 - Paul Sturgill
 - Tom Reynolds



Working Group II Standards and Certification

1st Objective

- Understand the current status of U/W

Welding Standards

- Group was able to capture the status of various U/W Welding, Inspection and related standards

The 2010 Edition of the AWS D3.6 U/W Welding Code is scheduled to be available mid December 2010



Working Group II Standards and Certification

- The first U/W Wet Welding Electrode Classification Specification A5.35 is finishing the balloting process and should be available the 1st quarter of 2011.
- Group discussed the importance of other standards and Regulatory Requirements related to Inspection and Training such as:
 - API RP 2D WSD and 2X
 - US Army Corp of Engineers
 - CSWIP, ASNT, ISO, EN, ABS, DNV, ASME, BOEMRE, etc.



Working Group II Standards and Certification

– Marine Industry U/W Welding and Inspection Needs

- Expand guidelines / commentary on design for U/W repairs and techniques used
- Develop a Marine CWI Guideline to improve the quality of CWI performance on U/W Welding and Inspection Projects.
- Need to further develop testing criteria and requirements for Marine CWI's
- Need to develop criteria for training programs
- Need to develop Training / Qualification requirements for U/W welders, inspectors and UWCWI and typical Industry performance expectations.



Working Group II Standards and Certification

– Marine Industry U/W Welding and Inspection Needs Cont.'

- Expand provisions unique to Ship Husbandry, Ports, Bridges, Locks and Dams
- Expand Inspection requirements to include provision for emerging technology such as Alternating Current Field Measurement (ACFM), Phased Array UT
- Expand provisions to include new applications such as Friction Stud Welding
- Address new training / qualification requirements implemented by US DOT.



Working Group II Standards and Certification

– 2010 International U/W Welding Workshop vs 1994

- 1994 emphasis was on improving requirements for design, workmanship, technique, qualification, inspection, testing and quality assurance
- Developing aids to help end users such as Procedure and Welder Qualification Forms, Commentary providing useful guidelines and better understanding, etc.
- Developing a Specification for classification of wet electrodes
- Aligning with other International U/W Welding Standards.



Working Group II Standards and Certification

– 2010 International U/W Welding Workshop vs 1994 Cont'

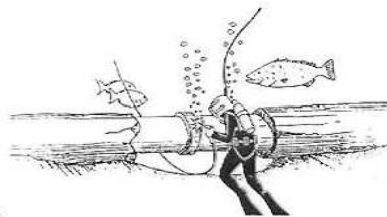
- 2010 emphasis is on updating and expanding existing sections of the standard such as Inspection, testing, weld processes, etc.
- Increased emphasis on improving Marine CWI qualifications
- Increased emphasis on diver welder and inspector training criteria
- Expanding provisions to include other Marine Industries
- Continuing to work with other Standards Organizations to collaborate and maintain Alignment

Working Group 3: Underwater (Wet) Welding Consumables Development

Valter Rocha dos Santos and Mauricio de Jesus Monteiro, PUC-Rio; Alexandre Queiroz Bracarense, UFMG; Ezequiel Caires Pereira Pessoa, IFMG; Uwe Aschemeier, Terracon; Len Andersen, Wet Welding; Dave Gibson, Proserv Offshore; James Merritt, DOT/PHMSA; Clint Levine, Phoenix; Keith Moline and Grant Folkmann, Devasco, Intl.; Rodger Spriggs, Ranking/Broco; Stephen Liu, CSM

Underwater (Wet) Welding Consumables Development Working Group 3

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Clint Levine – Phoenix - USA
Keith Moline – Devasco - USA
Grant Folkmann – Devasco - USA
Rodger Spriggs – Ranking/Broco – USA
Stephen Liu – CSM - USA



White paper

1. Introduction
2. Review from sixties to the 1st Workshop on Underwater Welding – 1994
3. Summary of Working Group Discussion (1994)
4. Developments from 1994 till now
5. Qualification
6. Conclusions
7. Research Needs and Future developments

Research Needs on wet welding consumables development

Priority 1: *Reach class A and improve class B weld properties while maintaining electrode operability (actual data developed for 33 ft water depth)*

Priority 2: *Development or improvements of welding processes and techniques*

Recommendations

Priority 1: *Reach class A and improve class B weld properties....*

- a) Consistent Class A welds for base metal steels with 0.2% C_{max} and 0.4% C.E._{max}.
- b) Development should target shallow waters (≤ 33 ft) prioritizing SMAW process.
- c) Electrode operability properties to be considered are: Slag detachability, arc start and restarts, coating stability, arc stability, waterproof coatings, and electrode tip conditions for initial arc start.
- d) Ease of use as well as weld bead appearance are important factors for consideration.

Priority 1: Reach class A and improve class B weld properties....

e) New consumables should be developed based on **oxidizing** or **rutile** type electrodes. If the development is based on oxidizing type, titanium oxides and/or other compounds and alloying elements should be added to improve operational features and mechanical strength. On the other hand, if the development is based on rutile type, iron oxides and/or other compounds should be added to reduce diffusible hydrogen.

e.1) The following critical criteria for development based on **oxidizing** electrodes are suggested:

- enhanced operability
- diffusible hydrogen content lower than 20 ml/100g
- porosity content less than 0.5%
- minimum 18% elongation in the all weld metal tensile test
- reduced susceptibility of weld metal root cracks

Priority 1: Reach class A and improve class B weld properties....

e.2) The following critical criteria for development based on **rutile** electrodes are suggested:

- enhanced operability
- diffusible hydrogen content lower than 50ml/100g
- porosity content less than 1%
- minimum 18% elongation in the all weld metal tensile test
- reduced susceptibility of weld metal and HAZ hydrogen cracking

f) Continue development of electrodes for depths to 100 ft to achieve consistent performance, in particular impact toughness and bend test results, towards Class A weld qualification

Priority 2: *Development or improvements of welding ...*

- a) development of welding systems that utilize self shielded tubular wires, optimize power sources and wire feed systems, develop new wire formulations.
- b) development of innovative SMAW electrodes without the requirement of waterproofing layer
- c) development of applications of friction “stitch” welding for crack repairs
- d) development of mechanical devices or automated systems to improve welding performance
- e) development of thermite consumables to reduce HAZ hardness

Recommendations

- a) Basic fundamental research should focus to better understand the physical and chemical phenomena in metal transfer and metal-slag interaction underwater
- b) Development of electrodes for higher C_{max}: 0.2% and C.E._{max}: 0.4% are desirable.
- c) Review the application and techniques of single or multiple temper beads
- d) Development of innovative localized post weld treatments and techniques for reduction of HAZ hardness
- e) Continue to explore the concept of using specific consumables for different depths and/or different parts of the same weld joint (such as: root pass, filling and finishing)

Recommendations

- f) Establishment of a database listing historical data (mechanical – yield, tensile, elongation, Charpy, bend, etc.) of wet welding electrodes
- g) Establishment of a database of commercially available consumables, manufacturers and trade names. Standardize marking system similar to that used for topside electrodes, e.g. printing classification onto coating, color coding, etc.
- h) Validation of published results related to the reduction of carbon content of core rod with the reduction of porosity in the weld metal of rutile base electrodes.

THANK YOU!!!!

**Working Group 4:
Training and Certification of Personnel**

Jack Couch, Ocean Engineering; Mik Else, BOEMRE; James Merritt, DOT/PHMSA

**2010 Underwater Welding
Inspection and Reliability Marine
Structures and Pipelines**

**GROUP 4
SUMMARY PRESENTATION**

**TRAINING AND
CERTIFICATION OF
PERSONNEL**

Current Practices:

New Hires (Entry Level) from the Commercial Dive Schools

Employer trains by OJT Apprenticeship and in-house training

Data management to track diver qualifications and create teams

Personnel demand, One year horizon for work?



Current Practices (cont):

Training material, dive tanks, facilities, qualified instructor, equipment

Somewhat of a disconnect between the schools and the industry.

Qualification to codes or specifications, with destructive testing, and yearly requalification.

Training to include, testing, recertification, class room testing, online instruction and testing.

Proactive approach to ensure best available practice and personnel training. To avoid the use of sub-par personnel.



Obstacles and Limitations

Wet welding school training

Better Communication with On-shore industry

Technical advisory board to review and advise commercial schools

Training facilities not very receptive to advice on their curriculum

Dive school welding instructors lacking offshore experience

Advance curriculum for students to be better suited for industry

Long range forecast of diver/welder demand needed

Cost of training (School cost are high, students enter work force with debt burden)

Unrealistic Expectations, Hard Hot work, I want it now! (Start at the top)

Time and distance away from home and family!



Obstacles and Limitations (Cont)

Lack of Public Awareness About the Industry to Educators and Individuals

AWS, Create Public Source of Information on the Welding Industry

Cost of training, get loans, hope to get a job to pay for the training. After hour part time jobs for students for on the job training and to help defray the cost of training.

Personnel demand, One year horizon for work?



Direction and Recommendations

Increase awareness of the students to the existing codes and standards and essential variables of these and where to get them.

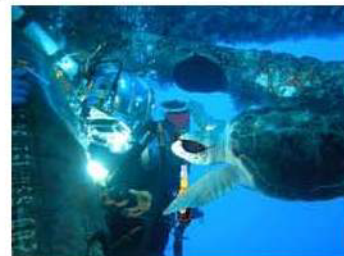
Inspection of structures should have uniform standards, how you find and report damage. Increase the probability of detection.

Quantitative indications in the underwater environment. MT has no ability to determine depth of indication.

Better capture and use of data from documented near miss or failure, or proven reliability.

The numbers of personnel were talking about are very small.

Assemble Best practices.



Working Group 5: Reliability of Underwater Wet Welding for Offshore Structures

Faustino Perez, IMP; Pingsha Dong, UNO; Juan Carlos Madeni, CSM; Daniel Roldstad, Jacob Fichter and Chris Williams, Global Industries; Christopher Jones, Diamond Offshore Drilling Inc.; Jason Tillman and Christopher Brehaut, Foster Wheeler-Atlas Upstream; Zachary Clement and Timothy Steffek, BOEMRE; Angelique Lasseigne, Gen 2 Materials Technology; Shai Meir, Ben-Gurion University of the Negev; Joe Cray, Iowa State University

Abstract

A review of the reliability of underwater welds made to AWS D3.6 welding specification was carried out in Working Group 5, the results achieved are presented in this paper. Several topics are closely related to the reliability of underwater welds (UW), such as:

- a) There is a need of an underwater option for the repair and reinforcement of offshore structures, which is an opportunity for underwater welding
- b) AWS D3.6 requirements
- c) Fitness for service
- d) Reliability assessment of underwater weldments using the fatigue approach
- e) In-service inspection to retrofit the reliability index updates and fatigue performance.

From the discussion held in the working group on the previous areas, barriers and obstacles for an extensive use of UW were identified. Also, improvements have been suggested in order to produce reliable UW not only to increase the reliability of the UW, but also, to increase the reliability of the whole structure.

Introduction

Hurricanes and storms are stronger and more frequent than ever before, increasing the demands for the repair of existing damages, reinforcement of structural members and joints or both. UW is a viable repairing or reinforcing option to increase the reliability of existing structures that do not comply with current codes.

However, underwater wet welding (UWW) is still not considered a primary repair alternative. Even when reliable UWW can be produced at water depths down to 330 ft (100 m) using commercial electrodes, Class-B wet welds along with proper designs of the UWW connection (scallop sliding sleeves, doubler plate, K or T type reinforcement repairs, etc.) can overcome the strength reduction due to internal weld defects. In order to verify and update reliability indexes of such underwater welds in-service inspections are required.

Barriers and Obstacles for the Use of Underwater Welding

Based on interactions and deliberations between participants a consensus was accomplished on the identification of barriers and obstacles for an extensive use of UW.

- Lack of technology transfer from research institutions to industry

- Important developments should be transferred to the industry for field application Not enough support from involved bodies for research activities and in situ testing of potential improvements (i.e. companies willing to test new electrodes)
- Proprietary information on consumables and welding procedure specifications (WPS)
- Lack of definition of the fitness for service concept that considers the effect of defect size, defect location and distribution within the weld metal on the stress concentration factor
- Information is not shared between UW users of successful and unsuccessful applications
- Lack availability of historical information on wet welding applications and its performance over the years
- Obtaining historic data on performance of specific structures, particularly with regards to underwater welding repairs

Suggested Improvements Towards Reliable Underwater Welding

In order to produce reliable UWW improvements were suggested in the areas of applications, codes, availability of information, reliability assessments, and inspection techniques.

- Collaborative efforts between companies, operators, and regulatory agencies to fund field test applications of UWW (in actual conditions with sea currents, low visibility, etc.)
- AWS D3.6 needs to be updated with new information and quantitative approaches related to effects due to defect types, size, location and distributions within the weldment
- Development of a database on wet welding application projects and lessons learned.
- Availability of an updated directory of companies and people involved in UWW to set up an industry network
- Training not only in using the tools and methodologies for reliability analysis but also training on the input information (metocean, material, uncertainties, etc.) required by these tools
- Development of specific reliability procedures for UW, reviewed and updated continuously
- Including more cost effective inspection techniques (ACFM, UT, Phase array UT, FMD) for underwater applications
- Development and improvement of inspection procedures and data interpretation
- Relying more on RBI as part of the system integrity management
- Development of regulations and procedures for qualification of inspectors and supervisors
- Research projects need to continue towards the incorporation of the current state of the art of technology into consumable electrodes made available to the industry
- Standardize procedure on RBI (system integrity management)
- Making UWW a primary repair or reinforcement option
- State of the art document on underwater welding, processes, qualification and application to existing structures including case studies
- UWW recommended practice document with case studies
- Association of UWW making people aware of the reliability of UWW for repair and reinforcement
- Definition of the role and responsibilities of regulatory bodies, industry bodies, classification societies, API, to integrate the recommendations

Working Group 6:

API RP 2SIM – Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures

Peter Marshall, Moonshine Hill Proprietary, Lawrence Goldberg, Sea Tests Services

API RP 2SIM (draft on hold)

Recommended Practice for the Structural Integrity Management of Fixed Offshore Structures



- The SIM process has been developed around internationally recognized industry standards including API RP2A [1] and ISO 19902 [2] and is based on global industry best-practices.
- This recommended practice details engineering practices for the evaluation, assessment and **inspection** of fixed offshore structures to demonstrate their fitness-for-purpose.

Underwater Inspection Priority List

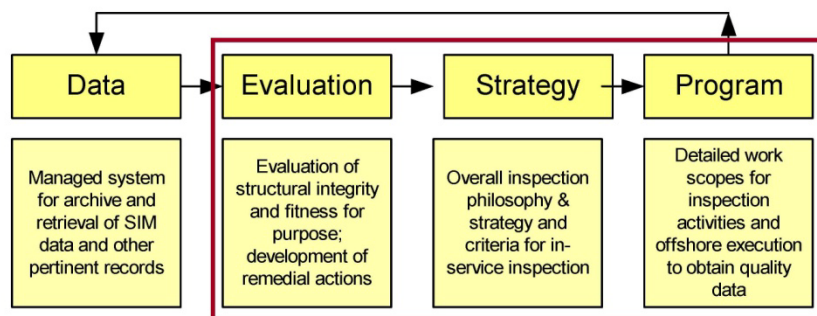
(HHHH)

- API RP 2SIM needs to be completed and published.
 - (New Imperative) Life extension of structures: Protocol, New Tech, Change of emphasis.
 - (Perpetual) Management of Change: Policy, Life cycle deterioration, modifications
 - (Perpetual) More quantification and less Bullshit!

Risk Categorization Matrix

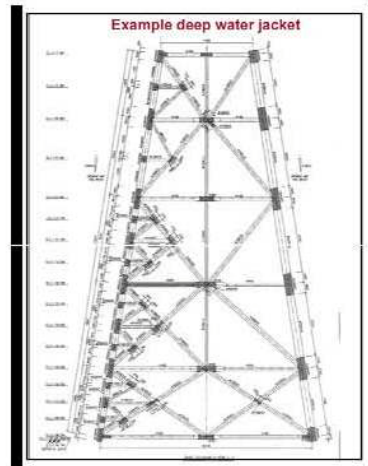
Consequence of Failure	High	Risk Level 2	Risk Level 1	Risk Level 1
	Medium	Risk Level 3	Risk Level 2	Risk Level 1
	Low	Risk Level 3	Risk Level 3	Risk Level 2
		Low	Medium	High
		Likelihood of Failure		

Figure 1.1-1: SIM Process



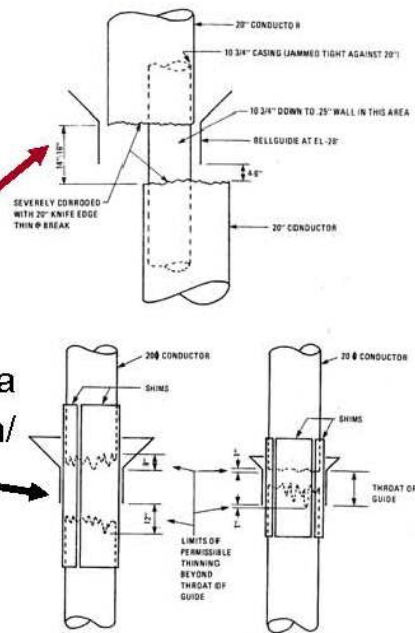
Characteristic Data

- baseline data that defines the structure at installation:
 - General platform data
 - Design data
 - Fabrication data
 - Installation data



Condition Data

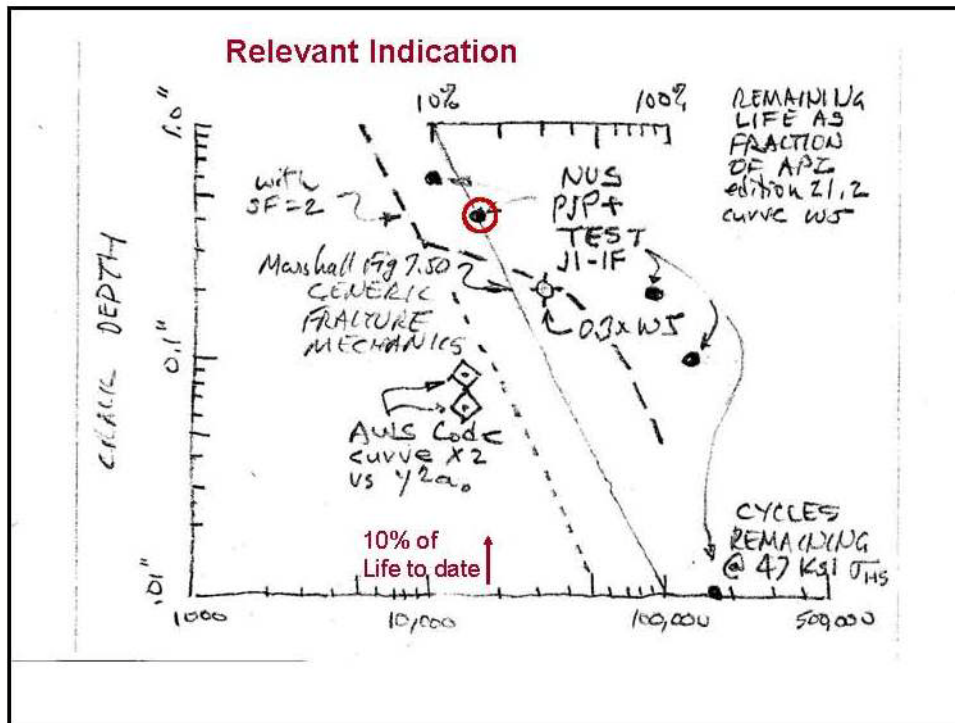
- Platform modifications
- **In-service inspection data**
- Damage evaluation data
- Corrosion protection data
- Structural assessment data
- Strengthening/Modification/Repair (SMR) data
- Condition monitoring data
- Operational incident data



Underwater Inspection Priority List

- (HH) Definition of relevant/ non relevant indication.
- (HH) Strategy of risk based inspection of the structure as a system.
 - What to inspect, Reliability of results, Probability of detection.
 - Qualifying Inspector Diver or Inspector ROV pilot.





Summary of Alternative Strategies

- 1. Level IV inspection with ROV
 - **no cracks deeper than 0.2-inch, or 4-inch length** with the STS typical aspect ratio of 20:1.
 - Tight fatigue cracks this small are not reliably detectable by visual inspection
 - prospect of false alarms.
- 2. Level II plus monitoring
 - looking for severely cracked or flooded members
 - **depends on structural redundancy** to maintain residual strength in parallel load paths.
 - fail-safe-while-manned fracture control strategy presented by Marshall at the 1979 ISSC and subsequently published by Bureau Veritas.

Probability of Detection

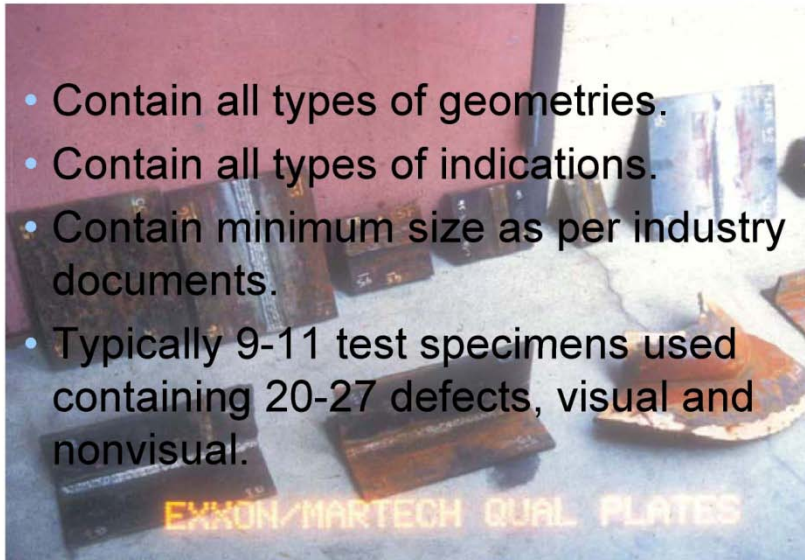
- The following are POD's for NDT methods based on Sea Test Services' and JIP's Performance Demonstration Initiatives, with test specimens validated by subject matter experts:

(Minimum size indication: ¼ inch L X 1/32 inch D by nonvisual)

- MT = POD $\geq$ 95% API RP 2X
- ET = POD $\geq$ 95% BSI 1711
- ACFM = POD $\leq$ 73%



TEST SPECIMENS



- Contain all types of geometries.
- Contain all types of indications.
- Contain minimum size as per industry documents.
- Typically 9-11 test specimens used containing 20-27 defects, visual and nonvisual.

Underwater Inspection Priority List

- (H) Fast path assessment. (Olson cycle)
 - A system in place to inspect and react (repairs) on site.
Integrated capability for monitoring, underwater, assessment.
- (H) Determine needed competency for task completion. Quality based competency map.

Assessment & Evaluation

requires consideration of numerous factors

- Platform age, condition, original design criteria;
- Analysis results and assumptions for original design or subsequent assessment;
- Platform reserve strength and degree of structural redundancy;
- Degree of conservatism or uncertainty in metocean criteria;
- Fabrication quality and occurrence of any rework or re-welding;
- Occurrence of any damage during transportation or installation;
- Extent of inspection during fabrication, transportation, and installation;
- Previous inspection findings
- Learning from structural performance of other similar platforms;
- Platform modifications, additions, and repairs/strengthening;
- Accidental (fire, blast, vessel impact, dropped object, etc.) overload
- Metocean or other extreme event overload;
- Fatigue sensitivity;
- Past performance of corrosion protection system;
- Criticality of platform to other operations (i.e. as a hub);
- Platform location (frontier area, water depth);
- Platform monitoring data if available;
- Field exit planning (e.g. decommissioning, divestiture, etc.).

Underwater Inspection Priority List

- (H) Level 4 inspection by a Remotely Operated Vehicle.
- H) Quantitative risk analysis or processes plus structures. Optimal risks are not necessarily the same in every region.

2009 **risk evaluation** task group

Objective

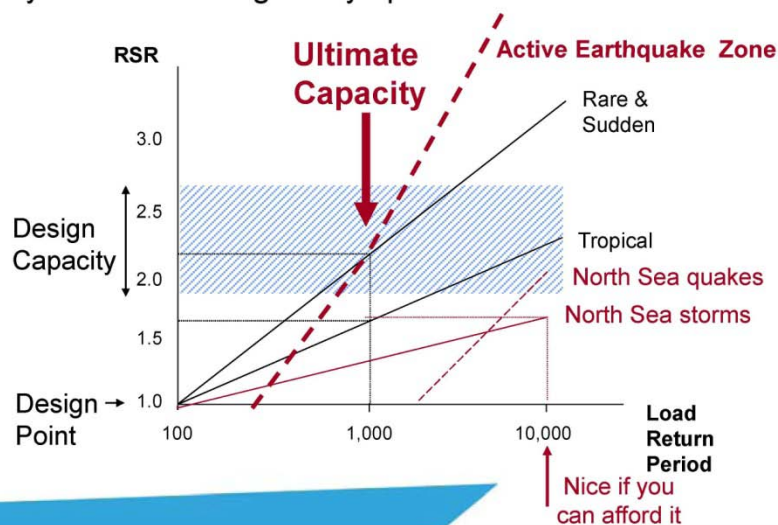
To provide acceptance criteria that delivers a consistent minimum reliability (against environmental overload) for offshore platforms around the world.

Consistent approach, not identical risk

New build not same as rehab in place

The Need

Why do we need regionally specific risk criteria?



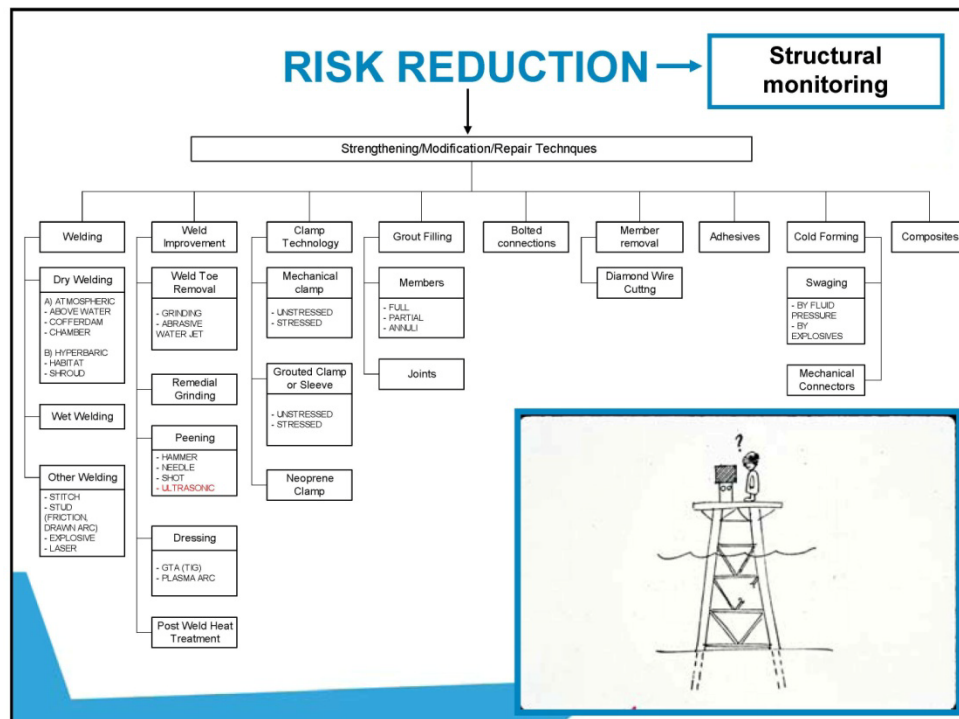
Tricky Question

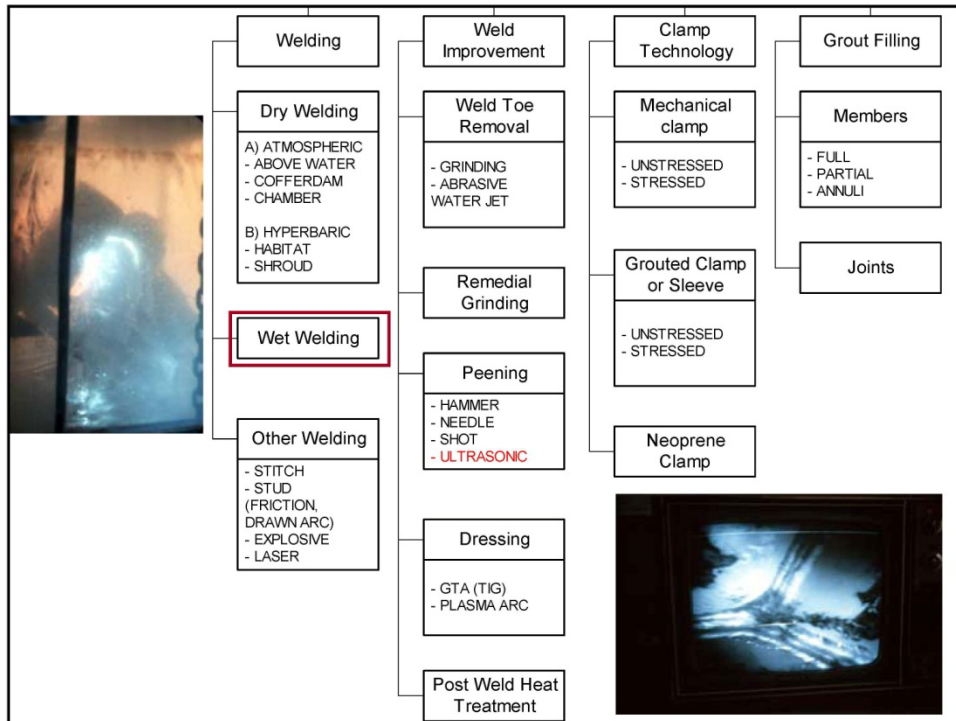
What level of **minimum** reliability do we want?

Available Sources of Reference:

1995 E&P Forum

- ISO 19902: Fixed steel offshore structures
- ISO 19901-2: Seismic design procedures and criteria
- **API RP 2A and Bull 2INT**
- **NAE Marine Board & MMS regulations**





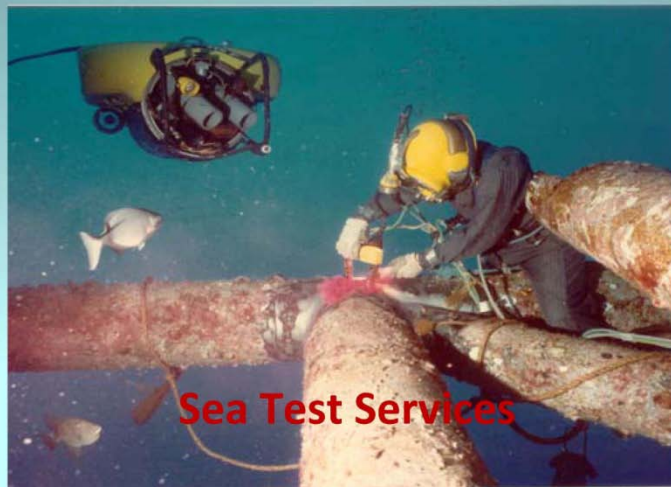
Underwater Welding in RP 2SIM

- Welding is often regarded as the best strengthening or repair technique and no doubt would be used even more often if it were not for certain operational difficulties in its execution. There are several underwater welding techniques that can be considered:
 - Dry welding at or below sea surface at one atmosphere using a cofferdam or pressure-resisting chamber;**
 - Hyperbaric welding using habitats;**
 - Underwater wet welding.**
- Repairs by both cofferdam and hyperbaric habitat welding techniques have proven track records and can produce high quality welded connections. The disadvantages to both are the high cost and extended schedules associated with cofferdam or habitat design, fabrication and deployment and the associated hazardous diving operations.
- Wet welding is underwater welding, when the arc is operated in direct contact with the water. The principal advantage over conventional welding is the ability to weld below the water surface without the need for a welding habitat or chamber. Provided the weld is suitable designed for low stress, good fit-up can be assured, and the parent material is tested to ensure compatibility, wet welding can be a viable solution.

Underwater Inspection Priority List

- (M) Public discussion and consensus on fragility curve.
- (P) Ethics and cultures of risk analysis.
 - Collaborative effort in the industry vs region by region.
 - “ALARP” does not mean “As Little As Regulations Permit”.
- (?) Inline inspection of non-pig gable pipes and risers

The Role of Performance Demonstration Initiatives in Structural Integrity Management and Risk Based Inspections



Group Photograph of Workshop Participants



Group Photograph

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