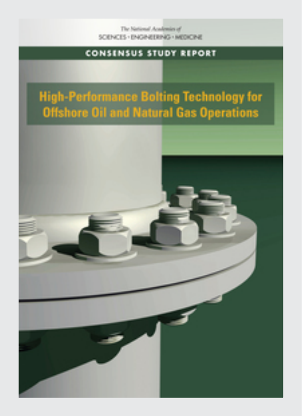

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High-Performance Bolting Technology for Offshore Oil and Natural Gas Operations

Committee on Connector Reliability for Offshore Oil and Natural Gas Operations

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

National Academy of Engineering

A Consensus Study Report of

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Cover: The cover plainly depicts a bolted pipe flange in full clarity as an analogy of the state reached by the committee since the start of the study and the initial workshop. This should be compared to the artistic expression on the cover of the workshop proceedings where the nature of the same bolted pipe flange is obscured by shadows, moving light and flickering, also as an analogy. Graphic artist: Erik Svedberg.

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NOTE: See Appendix M, Disclosure of Conflict of Interest.

[1] Member, National Academy of Engineering.

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Acknowledgments

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report:

Dianne Chong, NAE,[1] Boeing Research and Technology (retired),
Millard S. Firebaugh, NAE, U.S. Navy (retired) and University of Maryland, College Park,
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Alan Turnbull, National Physical Laboratory, and
Joseph A. Yura, NAE, University of Texas, Austin.

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[1] Member, National Academy of Engineering.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Aziz I. Asphahani, NAE, QuesTek Innovations, LLC. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

The committee also thanks the guest speakers at its meetings, who added to the members' understanding of bolting technology for offshore oil and natural gas operations and the issues surrounding it:

Bruce Craig, President, Metcorr,
Carl Szczechowski, Technical Lead for Physical Oceanography, Oceanography Department, Naval Oceanographic Office,
Chris Johnson, Director of Engineering, NOV,
Holly Hopkins, Senior Policy Advisor, American Petroleum Institute,
Michael Demkowicz, Associate Professor, Materials Science and Engineering Texas A&M University,
Narasi Sridhar, Program Director, Materials Technology Development Section, DNV GL,
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Roger Boyer, NASA Johnson Space Center,
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Steve Eckman, Drilling Operations Manager, Anadarko Petroleum Corporation,
Terry Lechinger, Stress Engineering Services, and
Vinod Veedu, PhD Director of Strategic Initiatives, Oceanit Laboratories, Inc.

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Partha Sharma, DNV GL,

Pascal Berthaud, Cameron, a Schlumberger company, and
Pat Boster, Stress Engineering Services,
Tim Haeberle, Chief Consulting Engineer, Baker Hughes (formerly GE Oil and Gas),
Tina Panontin, Chief Engineer, NASA Ames Research Center (retired).
Tom Goin, President, U.S. Bolt Manufacturing, and
Trent Fleece, BOP Team Lead, BP.

In addition, the committee thanks the experts who attended the preceding workshop. Their discussions were instrumental in allowing the committee to achie1ve a balanced understanding of the field. The committee also wants to thank the companies that provided valuable information to the committee such as Stress Engineering, BP, NOV, Cameron, and DNV GL. The excellent support of the National Academies staff is especially appreciated. Special thanks go to Erik Svedberg, Neeraj Gorkhaly, Henry Ko, and Joe Palmer, who were indispensable to our accomplishing this study. We also thank NAE's Al Romig and Proctor Reid for their help getting the study launched and for their continued support throughout the study process.

Robert Schafrik, *Chair*, and Robert Pohanka, *Vice Chair*
Committee on Connector Reliability for Offshore Oil
and Natural Gas Operations

Preface

Tremendous oil and gas resources exist in the continental shelf and are becoming accessible with advances in drilling technology. This has sharply increased the number of drilling rigs at work in deep water environments, primarily within the Gulf of Mexico. The large oil spill due to the Deepwater Horizon accident has focused more attention on preventing oil releases into the ocean. In addition to the Deepwater Horizon environmental release, there have been several near misses due to bolt failures over the past 15 years. Even though in-service fastener failures (bolts and connectors) are rare and have not led to a major release of oil, eliminating or further reducing the possibility of a failure has become a priority for both industry and government. A summary of selected subsea bolt failures is compiled in Appendix E. The emphasis is on those fasteners that hold together critical pieces of safety equipment, particularly blow out preventers (BOP), and those that secure the pressure boundary in risers.

This report of the Committee on Connector Reliability for Offshore Oil and Natural Gas Operations is the second of two major deliverables requested by the sponsor, the Department of the Interior's Bureau of Safety and Environment Enforcement (BSEE). The first deliverable was a proceedings of a workshop that was held in Washington, D.C., on April 10-11, 2017.[1] The goal of the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations was to develop an

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[1] National Academies of Sciences, Engineering, and Medicine, *Bolting Reliability for Offshore Oil and Natural Gas Operations: Proceedings of a Workshop*, The National Academy Press, Washington, D.C., 2017.

understanding of the outstanding issues (materials, design loads, coatings, corrosion protection, failure prediction and prevention, and quality management), associated with these previous bolt failures and to discuss possible paths for reducing risks associated with bolts used in subsea oil and gas operations.

This current report comprises the second deliverable. The committee's work built upon and extended the information developed during the workshop. The detailed statement of task for this study is contained in its entirety in Appendix A. There were eight tasks requested of the committee:

- Task 1: Assessment of the critical drill-through equipment fastener systems and the appropriateness of materials and coatings selected for incorporation into fasteners, for optimal performance for subsea environment operating conditions.
- Task 2: Analyze the role that design issues and human-systems interaction play in the entire lifecycle of the bolts.
- Task 3: Suggest options for improving safety of offshore drilling and pipeline operations as related to the use of fasteners for critical drill through equipment components like the lower marine riser package (LMRP) and pipeline fasteners.
- Task 4: Evaluate the performance of fastener systems currently in use, including the process of manufacturing, corrosion protection, installation, maintenance and inspection processes associated with fastener systems.
- Task 5: Assess the subsea environmental effects on the mechanical properties of bolts and corrosion resistance.
- Task 6: Evaluate the impact of cathodic protection systems on fastener performance in a subsea environment.
- Task 7: Identify the similarities and differences in industry standards related to the design, material specification for strength, hardness, coatings, corrosion resistance performance in atmospheric as well as subsea application conditions, cathodic protection, performance and maintenance requirements as related to fastener systems worldwide.
- Task 8: Identify ideas and concepts taken from industries outside of oil and gas which can be integrated into the offshore oil and natural gas community to effect improvements on safety and environmental protection.

The mapping of these tasks to the chapter/section in the report where the task is addressed is presented in Appendix B. All the above tasks were performed, except for Task 7 which requested "Identification of the similarities and differences in industry standards. " Appendix H contains a summary and brief explanation of the most commonly used bolting regulations and standards, including the pertinent federal regulations; industry standards, specifications, and recommended practices from API and ASTM; NACE Materials Requirements; NORSOK materials standard; and API flange bolt design specifications. Analyzing the similarities and differences in these standards was beyond the capability of the committee to perform in the timeframe of the study. BSEE has commissioned Argonne National Laboratory (ANL) to perform this task.[2]

In line with its statement of task, the committee did not make recommendations for actions that BSEE should take, but did provide a number of options that, if taken, would likely improve the reliability of subsea bolting. The committee further provided recommendations to the oil and gas industry that do not require regulatory action that would likely improve the reliability of subsea bolting.

The committee found this study to be quite challenging, not only from a technical perspective that involved many disparate disciplines, but also due to difficulty in obtaining requisite data and information on prior failure investigations and specifications/standards that are deemed "proprietary." The committee needed this information as background material and to more completely assess the reasonableness of the conclusions and recommendations. Because this report is a public document, no proprietary information is included. In a number of cases, the committee was not able to obtain the historical data and information, and thus the conclusions and recommendations in some areas are necessarily generalized. Nonetheless, in areas not deemed proprietary, the committee received extensive cooperation from a number of companies and engineering organizations.

In this report, the terms "fastener," "bolt," and "connector" are used to describe threaded components that are used to facilitate assembly and disassembly of offshore equipment. This report does not deal directly with the design of a connection itself.

The role of hydrogen in embrittling fastener materials is the subject of some discussion and analysis in the report. This phenomenon has multiple terms associated with it. The committee choose to standardize on "hydrogen assisted cracking" (HAC). However, this term is not meant to imply that existing cracking must be present to be enhanced by the uptake of hydrogen. Other terms used by different authors to describe the phenomenon include hydrogen embrittlement (HE), hydrogen environment-assisted cracking (HEAC), hydrogen (enhanced) cracking (HEC), hydrogen induced cracking (HIC), hydrogen-enhanced decohesion (HEDE), and hydrogen-enhanced local plasticity (HELP).

The committee was composed of 16 experts with the following expertise areas: analysis of structural systems, ceramic materials and coatings, corrosion science

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[2] Dr. Candi Hudson, Ph.D., Bureau of Safety and Environmental Enforcement, "BSEE Bolts Technical Evaluation Approach," BSEE-API Meeting, June 22, 2016, https://www.bsee.gov/sites/bsee_prod.opengov.ibmcloud.com/files/tap-technical-assessment-program/api-bsee-june-22-2016-presentation-api-bolting-workgroup.pdf.

and engineering, failure analysis and forensic investigation, human factors, laser processing of materials, marine drilling rig operation, materials for marine environments, metallurgical engineering, nanotechnology, pipeline technology, risk assessment, structural materials, and welding engineering.

The committee met the following six times between February and September 2017:

- The initial meeting was in Washington, D.C., on February 15-16 during which the committee laid out the plan for the study and starting to develop the agenda for the workshop.
- The committee conducted a site visit to Houston, Texas, on March 22-23 to become acquainted with the equipment and fasteners that are the focus of this study. The companies visited are summarized in the Acknowledgements section of the report.
- The workshop was held at the Keck Center of the National Academies of Sciences, Engineering, and Medicine in Washington, D.C., on April 10-11. It was well attended by representatives of the oil and gas industry, as well as BSEE personnel. A proceedings of that workshop was published in 2018. Afterwards, the committee met on April 12 in Washington, D.C., to review the key issues raised during the workshop, develop preliminary conclusions and recommendations, and plan the next meeting.
- The fourth committee meeting occurred June 7-8 in Washington, D.C. The committee reviewed the various chapter drafts that had been prepared and had several invited speakers who provided information of interest to the committee. The speakers are listed in the Acknowledgements section of the report.
- The fifth meeting was held at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, California, on August 28-29. The committee reviewed the draft chapters, broke out into working groups by chapter to add to the material in each chapter, then met together to refine the conclusion and recommendations. Several speakers were invited to inform the committee on key topics of interest. The speakers are listed in the Acknowledgements section of the report.
- The sixth and final meeting occurred at the J. Erik Jonsson Conference Center of the National Academy of Sciences in Woods Hole, Massachusetts, on September 27-28. This meeting was totally dedicated to completing the report and gaining committee concurrence on the conclusions and recommendations.

This report has six chapters plus several appendices. Chapter 1 is an introductory chapter that sets the stage for the remainder of the report. Chapter 2 reviews the critical design factors and requirements for subsea fasteners and summarizes failure modes. Chapter 3 discusses existing fastener standards and specifications and quality assurance options and presents options for improving government oversight of the fastener life cycle. Chapter 4 describes the important role of human factors in preventing fastener failures. Chapter 5 describes research and development opportunities that could advance fastener performance and reliability. Chapter 6 reiterates the key conclusions and recommendations contained in the report; it also contains Summary Recommendations 6.1 and 6.2, which are seen as the options that BSEE and industry can take, respectively, and consists of relevant recommendations from the previous chapters.

Appendices that supplement the material in the main body of the report include the following: Appendix D, a synopsis of the more than 70 years of U.S. subsea oil exploration effort; Appendix E, a synopsis of selected subsea bolt failures; Appendix F, a summary of current activities by the oil and gas industry and BSEE to improve bolting reliability; Appendix G, additional details for the subsea environmental factors discussion of the subsea environmental factors that impact fastener design; Appendix H, a summary of U.S. bolting regulations and standards; Appendix I, details on drilling riser design; Appendix J, a discussion of the different factors that affect bolting preload and safety factor analysis; and Appendix K, a presentation of the different failure modes experienced by threaded fasteners.

Reducing the risks inherent in extracting natural resources from deep-water environments is a challenge equal to exploration in other extreme environments. It requires continuing study, diligence, attention to detail, and incorporation of suitable new technology, the need for which becomes ever greater as industry goes into deeper water environments. As Albert Einstein noted, “we cannot solve our problems with the same level of thinking that created them.”

Contents

APPENDIXES

Summary

Commercially significant amounts of crude oil and natural gas lie under the continental shelf of the United States. Advances in locating deposits, and improvements in drilling and recovery technology, have made it technically and economically feasible to extract these resources under harsh conditions.[1] Offshore drilling in the U.S. Outer Continental Shelf (OCS) has progressed to greater depths of water over the years; currently deep-water wells are located in areas where the water depth is 1,000 ft. (305 m) to 10,000 ft. (3,050 m) and beyond.[2] The preponderance of oil exploration in the OCS occurs in the Gulf of Mexico where significant resources have been identified. These resources are recovered by drilling, producing, and transporting the product to the market using platforms, barges, ships, and pipelines. There remains considerable potential for further exploration and recovery of oil in the OCS; the Gulf of Mexico will continue to be an important location for oil exploration and recovery into the future.

Extracting these offshore petroleum resources involves the possibility, however remote, of oil spills, with resulting damage to the ocean and the coastline ecosystems and risks to life and limb of those performing the extraction. The environmental consequences of an oil spill can be more severe underwater than on land because sea currents can quickly disperse the oil over a large area and, thus,

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[1] American Oil and Gas Historical Society, “Offshore Petroleum History,” http://aoghs.org/offshore-history/offshore-oil-history/, accessed March 13, 2017.

[2] Bureau of Ocean Energy Management, “Assessment of Undiscovered Oil and Gas Resources of the Nation’s Outer Continental Shelf,” 2016, https://www.boem.gov/2016-National-Assessment-Fact-Sheet.

cleanup can be problematic. As the water depth increases, the response time to well control events become more challenging. Due to concern about the possibility of oil spills, state and federal governments have passed numerous laws restricting oil exploration and production and providing for oversight of drilling operations.[3,4]

The U.S. Department of the Interior began regulating the offshore energy and mineral extraction industry in the late 1940s; its jurisdiction was formalized by the Outer Continental Shelf Lands Act (OCSLA) of 1953. After the April 2010 Deepwater Horizon tragedy in the Gulf of Mexico, the regulatory structure was changed. The Bureau of Safety and Environment Enforcement (BSEE) was established to provide emphasis on safety, enforcement, prevention of oil releases into the environment, and rapid response in case an oil release does occur. Other agencies are charged with OCS oil and gas lease sales, marine safety, and revenue generation.[5]

At the request of BSEE, the National Academies of Sciences, Engineering, and Medicine studied subsea threaded fastener failures. The result is this report of the Committee on Connector Reliability for Offshore Oil and Natural Gas Operations, which is based on the somewhat limited data provided to the committee. This report summarizes strategies for improving the reliability of fasteners used in offshore oil and natural gas exploration equipment, as well as best practices from other industrial sectors. Bolted connections are an integral feature of deep-water well operations. In any offshore subsea wellhead and marine riser system, there are numerous large fasteners (primarily bolts), typically between 5 cm (2 in.) and 9 cm (3.5 in.) in diameter, in a wide range of applications. Most fasteners in subsea drilling riser systems hold together and transfer load through components of the systems used daily to drill the well and to transport drilling fluids. A fewer number of fasteners are directly related to holding together critical well control components or maintaining the well pressure boundary mechanical integrity. Therefore, the structural reliability of these bolted connections is directly linked to maintenance or loss of the pressure boundary while the system is in-service.

The overarching objective of this study is to identify actions that can improve the reliability and thus reduce the probability of a fastener failure that could cause an unintended release of oil, natural gas, or drilling fluids into the ocean environment. The focus is on critical bolting—bolts, studs, nuts, and fasteners used on critical connections. A critical connection is defined as one which, if it failed, would result in the release of hydrocarbons and drilling fluids into the sea. An example

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[3] R. Jervis, W.M. Welch, R. Wolf, and USA Today, "Worth the Risk? Debate on Offshore Drilling Heats Up," *ABCNews*, July 14, 2008, http://abcnews.go.com/Business/story?id=5367966.

[4] E. Kuhr, "To Drill Or Not to Drill—Debate Over Offshore Testing and Drilling in the Atlantic," *Time*, January 14, 2014, http://time.com/3249/to-drill-or-not-to-drill-debate-over-offshore-testing-and-drilling-in-the-atlantic/.

[5] Bureau of Safety and Environmental Enforcement (BSEE), "History," https://www.bsee.gov/who-we-are/history, accessed August 2, 2017.

is the bolting that connects the blowout preventer (BOP), an essential piece of safety equipment, to the wellhead on the seafloor and also attaches the shear rams to the BOP.

To date, a few dozen mechanical failures among thousands of bolts in critical pressure boundary applications have been reported in the field, with the overall bolting failure rate estimated to be in the range of 10^{-4} to 10^{-5} based on the total reported failures divided by the number of fasteners employed in-service.[6] However, this small number provides little comfort, or basis for analysis, given the "censored data" problem produced by lack of an industry wide program to inspect for bolts that are progressing to failure, or have failed completely and are merely being held in position by gravity. Sobering accounts, such as the failed studs on the Seadrill's West Capricorn (WC) that were only discovered (and thus reported) because an engineer put his hand on one, illustrated the compelling need for an industry wide continuous connector monitoring problem so that such failures can be discovered in progress, and not by accident.

Managing risk for low-probability, high-impact events is quite challenging. The root cause of these events is usually difficult to precisely determine and thus eliminate because they occur so infrequently, and measuring success requires large data samples over an extended period. The management of the risk requires improvements in standards, procedures, human factors, materials, controls, inspection, improved regulations and maintenance as well as sharing of best practices among/within the oil and gas industry and the government; taken together, these actions can be grouped as continued improvement in the safety culture. These actions require expenditure of time and effort that can be challenging to justify without taking the view that reducing low-probability but high-impact events is cost effective in the long term.

No major oil spills have resulted from a fastener failure. But there have been minor releases and near misses caused by unexpected bolt failures, and to the committee's knowledge, no injuries or fatalities have resulted from the reported fastener failure. The question is this: Is this lack of catastrophic failures due to excellence in engineering and field implementation, or is it due to fortuitous circumstances in which bolts failures were detected early before a major system failure occurred, or is it a combination of both? The answer is still unknown, but the committee found multiple opportunities for improvement in the engineering design, specification, manufacturing, and application of these critical fasteners, and life cycle oversight of the fasteners. The overall proactive strategy discussed in this report is one of risk reduction by prioritized continuous incremental improvement. This strategy

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[6] K. Armagost, Anadarko Petroleum Corp, "Root Cause Failure Analysis In Support of Improved System Reliability," presented at Connector Reliability for Offshore Oil and Natural Gas Operations Workshop, Washington, D.C., April 11, 2017.

is based on accurately accessing equipment field performance before failure and acting on the results, devising roadmaps to conduct and implement research and development in areas that have the potential to improve the reliability of fasteners. Reactive strategy of improved communication of failures and promulgating best practices related to fasteners throughout the entire oil and gas industry, including all the supply chain and equipment operator stakeholders, is also discussed in the report.

The design of a drilling riser system and, its components, is a challenging engineering task requiring numerous technical disciplines at multiple companies. The bolted flange connectors within the drilling riser system are deceptively simple pieces of equipment. But because of the varied and dynamic forces acting on a bolted flange connector in subsea drilling applications, the design of a flange connector is complex. There are uncertainties in the quantitative assumptions commonly made in the design of a riser and its components. Of particular importance are the assumptions related to the operating environment, installation, operation, and maintenance practices that occur in shops and on rigs that affect the loads on the riser/BOP system. The challenge for the design engineer is to integrate the various levels of uncertainty to arrive at the appropriately conservative design for each mechanically-fastened connection, and then for each individual fastener/bolt. Because bolts are subject to multiple time-dependent failure modes in addition to mechanical overloads, all potential failure modes must be identified and the risks must be mitigated during the design process.

Further, there are important environmental factors that directly influence the rate of degradation of fastener materials, such as ocean water salinity and chemistry, the presence of hydrogen from cathodic protection systems or the presence of hydrogen, hydrogen sulfide (H_2S) and carbon dioxide (CO_2) from natural sources. Because drilling rigs and riser systems are designed to move to different ocean drilling locations and be employed by different operators over their lifetime, the design of a riser system must accommodate operating requirements beyond any specific location. Thus, unless the connectors are conservatively designed for every environment, a design analysis and risk assessment should be conducted each time a rig's location is changed.

An integral part of the design process is the identification and review of all applicable, up-to-date specifications and standards that must be followed, as well as incorporation of all recommended best practices. It is important to realize that industry standards typically represent minimum requirements and thus, at the discretion of the design engineer, may be supplemented. Since some rigs are moved internationally, additional country-specific specifications and standards may need to be considered.

Once the loads and environmental factors are established, fastener materials and protective coating systems can be selected to provide the required service life.

Typically, medium carbon, high hardenability alloy steels are used, such as AISI 4130 or higher strength AISI 4340.[7] For applications in which hydrogen sulfide or other corrosive gases are present, a corrosion-resistant alloy is used; the iron-nickel superalloy, Alloy 718, is commonly selected. These alloys can be processed by a variety of methods, and the resultant quality levels depend on the initial chemistry and the processing route. Oftentimes, there is no requirement to track each processing step for a particular fastener. Thus, the pedigree of the material depends on the integrity of the adherence throughout the entire supply chain to qualified manufacturing processes as verified by specified quality assurance methods. Thus, re-creating the exact processing steps for fasteners that fail in the field is challenging because there normally is scant traceability of specific processing steps for a specific fastener.

The critical requirement for pressure boundary fastener installation is to ensure that sufficient tension is accurately created within the bolt (without exceeding design limits) to safely maintain compressive contact between the mating surfaces as specified by the design engineer who can adopt or exceed industry specifications. During service, the fasteners must be preloaded in sufficient tension to sustain the required compressive forces on the flanges during service conditions. These fastener tensile loads applied during installation must be maintained over the lifetime of the connection. Procedures must be put in place to minimize the possibility that the specified applied tensile loads that meet the connector compression requirement are accurate, will not exceed bolt yield strength, and not degraded during service. Damage-induced modifications to fasteners include corrosion, fatigue crack nucleation and growth, and crack nucleation and growth by environmentally assisted cracking mechanisms, including hydrogen embrittlement[8,9] and stress corrosion cracking.[10]

Fastener failures have an service environment, mechanical, human, and material component. The predominant failure mode depends on the application environment and processing history. Detailed analysis of failures can determine the root cause, which is necessary to devise appropriate corrective actions to minimize future failures through improved mechanical design, material selection, or

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[7] B. Lillebø, Det Norske Veritas, Bergen, Norway, "Bolting Materials Subsea," presentation at Materials in Offshore Constructions, Esbjerg, June 2, 2006, http://www.offshorecenter.dk/log/filer/1_7%20DNV.pdf.

[8] D.A. Jones, "Environmentally Induced Cracking," Chapter 8 in *Principles and Prevention of Corrosion*, 2nd ed., Prentice Hall, Upper Saddle River, N.J., 1996.

[9] B. Craig, "Hydrogen Damage," pp. 367-380 in *ASM Handbook Volume 13A: Corrosion: Fundamentals, Testing, and Protection* (S.D. Cramer and B.S. Covino, Jr., eds.), ASM International, Materials Park, Ohio, 2003.

[10] R.W. Hertzberg, R.P. Vinci, and J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, Wiley & Sons, Hoboken, N.J.

manufacturing processing. These failure analyses should determine the root cause of each failure and assess contributing factors such as the system design, actual applied loads, and actual material properties. The failed connectors that have been studied, and where such studies were made available to the Academy committee, have fractured by both ductile and brittle mechanisms.

Brittle fracture can occur at low-stress loading. The general model for this kind of fracture, often referred to as the Griffith model, is that a microcrack is nucleated at a particle or defect and then, once it attains a critical size, it serves to concentrate the stress, and propagates rapidly across the sample in a manner consuming little energy.[11] Many types of environments can cause low-energy fracture in steel, but environmentally assisted cracking is the most common for subsea applications.[12] Essentially all metals used in structural applications are susceptible to hydrogen assisted cracking and embrittlement if the combination of tensile stress and diffusible hydrogen concentration in the material are high enough.

The availability of hydrogen in marine applications arises from a combination of sources. The sequence of cracking leading to failure involves hydrogen production, adsorption, subsequent diffusion of adsorbed hydrogen, and hydrogen accumulation in a fracture process zone often associated with the microstructure.

Little non-proprietary work has been reported regarding fully characterized subsea bolting material failure modes using state-of-the-art sophisticated failure analysis methods. Further, there is little evidence that most failure analyses have evaluated failure modes beyond metallurgical assessment of failed components

Even though hydrogen embrittlement has been found to be the primary cause of recent bolt failures, there is insufficient quantitative understanding of other controlling variables such as the actual loads and the extent of materials degradation by mechanisms such as hydrogen embrittlement in field deployment. Consequently, progress has been hindered towards developing mitigation strategies, including best practices, standards, industry alerts, probabilistic assessments of risk, etc.

The failure of a single bolt on an undersea flanged connector is cause for concern, but would not pose an immediate risk of hydrocarbon leakage because the numerous bolts in a typical subsea connector flange provide redundancy. However, redundancy is lost when a "cluster failure" occurs. A cluster failure is defined as the failure of multiple bolts in a single undersea flanged connector. A cluster failure can potentially cause a catastrophic cascade failure in which all remaining fasteners

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[11] R.P. Gangloff, "A Review and Analysis of the. Threshold for Hydrogen Environment Embrittlement of Steel," in *Corrosion Prevention and Control, Proceedings of the 33rd Sagamore Army Materials Research Conference* (M. Levy and S. Isserow, ed.), U.S. Army Materials Tech Laboratory, Watertown, Mass., 1986.

[12] Personal communication, Tom Goin, president U.S. Bolt Manufacturing, Inc., August 15, 2017.

become overloaded and fracture precipitating a complete loss of the well pressure boundary.

Since 2012, four cluster failures have been publicly reported. While these failures, which are discussed in Chapter 2, appear to occur much less frequently than single bolt failures, the lack of knowledge regarding the root cause of these failures is cause for concern. The first three cluster failures had a common thread—they were from the same series of connectors and part-numbered bolts. The failure was attributed to inadequate post electroplating heat treatment—that is, failing to bake out hydrogen that may have diffused into the material during the electroplating process. However, in the fourth cluster failure, the failed studs exhibited virtually the same failure mode and features observed in the three previous cluster failures while some of the studs possessed *none* of the attributes that were supposedly the cause of the earlier failures. The committee believes that the root cause of these cluster failures, possessing very different hardness, heat treating, and ingot creation is better explained by consideration of the various factors (e.g., coatings, impressed current systems, sacrificial anodes, etc.) which potentially contribute to the electrochemical nature of environmentally assisted cracking. Experiments with a full-scale simulation in the laboratory would provide definitive information relative to the root cause.

There is a keen interest in improving the reliability of offshore equipment and structures, and in reducing safety and environmental risks of damage to the environment to as close to zero as possible. With many disparate views on the preferred approach, there must be a forum by which everyone has an opportunity to contribute their ideas and have them adequately investigated to enhance the development of offshore resources. Traditionally in engineering design, materials selection, manufacturing, installation and operation, this forum has been accomplished through the development and use of standards and specifications, The national significance of standards is depicted in Figure S.1, which is a quotation from the May 14, 1900, law establishing the National Bureau of Standards (now known as the National Institute for Standards and Technology [NIST]). This quotation is engraved in stone in the lobby of the NIST main administrative building (Building 101) in Gaithersburg, Maryland.

Bolt manufacturers must keep track of more than 1,000 specifications that address various aspects of high-quality bolt design and manufacturing, which includes more than 500 specifications and standards (American Section of the International Association for Testing Materials, American Petroleum Institute, American Society of Mechanical Engineers, American Society for Nondestructive Testing, etc.), plus well over 500 customer-specific standards and discrete part drawings.[13] Multiple changes to specifications and standards are often made

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[13] Personal communication, Tom Goin, president U.S. Bolt Manufacturing, Inc., August 15, 2017.

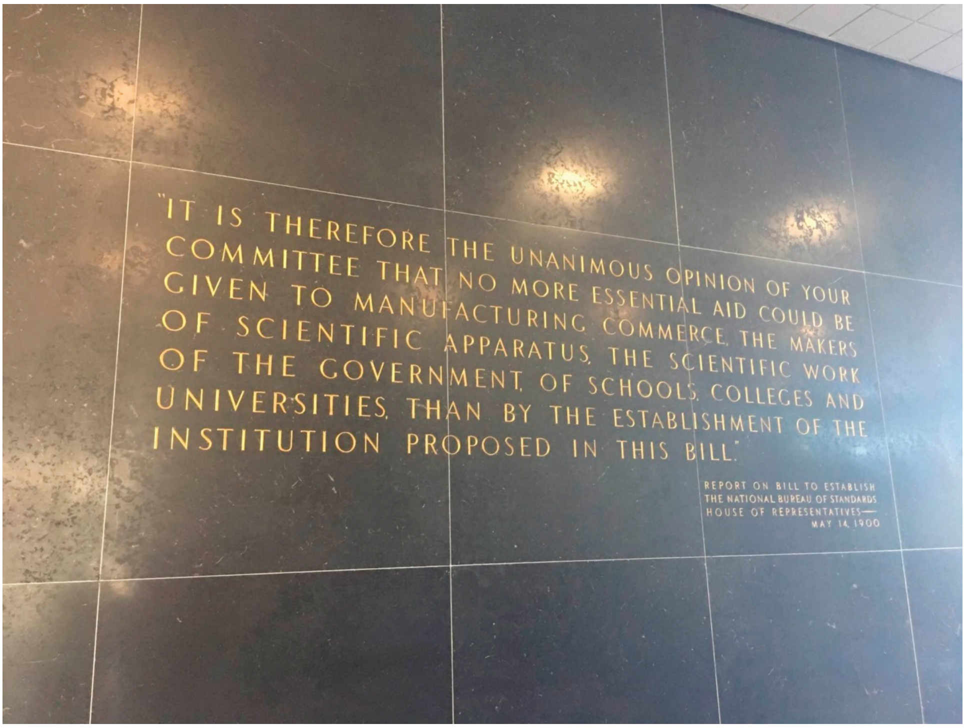

FIGURE S.1 Quote from the establishment of the National Institute of Standards and Technology (formerly the National Bureau of Standards).

in response to bolt failures or technology changes. Complicating the challenge is that applicable specifications commonly reference other specifications—thus, understanding the rationale and details of these changes, and then making the appropriate alterations to bolt manufacturing process sheets is a daunting process of change management throughout the supply chain.

The bolting industry has a multitude of proprietary standards that do not foster cooperation and shared expertise across the industry. Therefore, there is a need for leadership in harmonizing standards, using a balanced group of subject matter experts from industry, government, and trade organizations to provide uniformity and improved clarity for the supply chain.

Standards, as prepared today, will not totally solve the fastener reliability issues as they are reactive to known issues, usually do not address potential issues, and the enforcement process is not always clear-cut. Outside of standards committees themselves, there is no well-defined, proactive process for proposing areas/topics to develop new standards or improve current standards for other stakeholders, such as regulators and academia. Specification for allowable parameter limits (e.g., allowable hydrogen level, bolt pre-tensioning levels, cathodic protection, material characteristics, and system loads) are made independently, when in reality the definition of various parameter limits is in fact a complex multivariable problem. There has been no focused attempt to establish the relative importance of each variable and the interaction between them. An industrial research and development (R&D) program is required to provide much needed data and analysis.

It is clear that safety critical components, such as those maintaining the pressure boundary, require a more in-depth approach to quality assurance and quality control and the enforcement of materials specifications than is typically required by commonly used quality standards. Engineering firms often opt to have an in-depth internal process for qualifying a vendor and ensuring that those vendors maintain qualification.[14] These checks take the form of an initial audit of their quality management system and a full vetting of the product by the buyer's engineering team. This process should include analysis of the variability in outcomes of the manufacturing process and a determination that variability is within overall acceptable tolerances. Firms at all levels of the supply chain should be periodically audited by the end user (i.e., the operating company) to ensure that quality is maintained. A somewhat simpler approach might be a requirement that all companies involved in the design, manufacture, and assembly of equipment containing critical bolts have appropriate API or ISO certifications.

Best practices from other industrial sectors which have dealt with low-probability, high-impact events suggest opportunity areas for BSEE and the oil and gas industry to consider going forward. Two industrial segments were reviewed to offer insight into successful strategies—commercial aviation and Naval submarines. The commercial aviation industry is regulated by the Federal Aviation Administration (FAA), U.S. Department of Transportation, which has the mission to provide the safest, most efficient aerospace system in the world.[15] American commercial aviation has become the safest travel mode. In 2015, U.S. airlines flew 7.6 billion miles on airplanes with 10 or more seats with no fatalities, although there were close calls and accidents.

The FAA's Aviation Safety organization is responsible for the certification, production approval, and continued airworthiness of aircraft; and certification of pilots, mechanics, and others in safety-related positions.[16] This organization promotes safe flight through standards for design, material construction, quality work and performance of aircraft and aircraft engines. FAA Aviation Safety establishes

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[14] One example was presented during the committee visit to Schlumberger on March 23, 2017.

[15] Federal Aviation Administration (FAA), "About FAA," https://www.faa.gov/about/, accessed June 2, 2017.

[16] FAA, "Aviation Safety (AVS)," https://www.faa.gov/about/office_org/headquarters_offices/avs/, accessed June 2, 2017.

requirements for comprehensive aviation safety and oversees compliance through a variety of means. The FAA also employs Designated Engineering Representatives (DER) who typically work for an aerospace firm, including an OEM, but who have a responsibility to the FAA.[17] The DER system enables the FAA to supplement its skill base by employing qualified technical people to perform certain examinations, testing, and inspections necessary to comply with applicable airworthiness standards.

Under FAA leadership, this regulatory approach effectively engages all stakeholders in the aviation industry to continuously improve aviation safety. An example of the FAA's proactive response to a low-probability but high-impact accident is the establishment of the Jet Engine Titanium Quality Committee (JETQC). In response to an accident caused by a failed titanium fan disk which led to loss of life, the FAA formed JETQC to provide the industry an early warning system of potential problems in the manufacturing of critical titanium components.[18] The JETQC includes membership from all premium quality titanium alloy suppliers and engine manufacturers. Under the direction of the FAA, the consortium has established a metric (i.e., identified metallurgical inclusions arising from processing), harnessed the efforts of the global industrial base to address the root cause of these inclusions, and measured and reported progress against the metric. The JETQC has established detailed specifications for reporting inclusions at all stages of the processes used for manufacturing premium quality titanium alloys. As a result of this initiative the number of identified melt inclusions in premium quality titanium material, which was already low, has been reduced by a factor of one to two orders of magnitude.

The U.S. Navy operates a fleet of more than 270 ships and 3,700 aircraft and is the largest Navy in the world. These assets have highly demanding operational requirements ranging from submarines operating at depth, to high-speed surface vessels, to aircraft designed for both aerial combat and carrier landings. The material requirements needed in these severe operational environments are high and require a stringent approach to design, qualification, inspection, and maintenance to meet safety and reliability standards. The Navy has established effective controls and processes to manage both standard and specialized processes and controls to meet high-performance requirements while mitigating risk.

On April 10, 1963, a Navy submarine, the USS *Thresher*, was lost at sea, along with all 129 crew and shipyard personnel aboard. Although the exact cause of this low-probability, high-impact event is not known because the USS *Thresher* has not

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[17] FAA, *8110.37E—Designated Engineering Representative (DER) Guidance Handbook*, https://www.faa.gov/regulations_policies/orders_notices/index.cfm/go/document.information/documentID/1018533.

[18] FAA, "FAA Engine Titanium Consortium," FAA William J. Hughes Technical Center, http://www.tc.faa.gov/its/cmd/visitors/data/AAR-430/engtitan.pdf, accessed June 2, 2017.

been recovered, the inquiry found deficient specifications, deficient shipbuilding practices, deficient maintenance, and deficient operational procedures. As a result, the nuclear submarine fleet established the SUBSAFE program to ensure safety across the submarine fleet even as new designs are implemented. Since the loss of the USS *Thresher*, there have been no losses of SUBSAFE certified submarines.

In 1985 an independent organization was established within the Naval Sea Systems Command to strengthen and review compliance with the requirements of the SUBSAFE. These audits identified critical lessons learned: (1) mandatory disciplined compliance with standards and requirements; (2) a formalized engineering review system that resolves technical problems and issues; (3) safety and quality programs that support operations; and (4) safety and quality organizations that have sufficient authority and freedom to operate independently.

The human system is integral to the bolt landscape and the processes involved in the life cycle of a bolt in subsea service. A significant portion of the processes involved in the bolt life cycle is not fully automated. However, human systems have historically been neglected in developing strategies to improve bolt safety and reliability. It is critical that the complex human system at all levels be considered within all tasks that impinge on the bolt system, and that interventions to reduce bolt failures consider reducing human system failures. The human should be considered as a complex system component. For instance, explaining a failure as caused by "human error" will not improve safety and reliability unless the reasons why the human followed the wrong procedure or performed an incorrect action are identified and mitigated.

Individuals rarely work alone. Multiple disciplines must coordinate design, manufacturing, operation, and maintenance. Further, these processes are coordinated across multiple organizations encompassing all stakeholders. Communication across multidisciplinary teams and between scientists and field workers can be challenging throughout the bolt life cycle. Sharing information about bolt performance, failures, and near misses across different disciplines and organizations is critical to promote the safety culture required by oil and gas operations. Silos of information tend to be a barrier to a strong safety culture.

There are also issues that arise at the organizational level that impact human performance and ultimately system performance. Work and management processes vary by company and often conflict across companies. Companies may be hesitant to share information related to fastener failure because of liability concerns. However, the necessary direction regarding the sharing of critical pertinent information needs to be provided. The overarching rationale for information sharing is to promote an enhanced safety culture required to maintain a sustainable oil and gas industry.

The committee also identified multiple innovation opportunities that have the potential to significantly advance subsea fastener performance and reliability. These opportunities are in the areas of: testing protocols, in-situ measurements, improving the hydrogen assisted cracking resistance of bolt alloys, coating technologies, new fastener designs, and human systems integration. Some of these ideas have the potential to pay off in the relatively near term, whereas others will need a much longer time horizon to fully develop and implement. The path ahead will require a dedicated R&D effort that follows a structured development process so that implementation can quickly follow successfully completed efforts.

An overarching finding of this study is that both BSEE and the oil and gas industry has made important advances in improving bolting reliability for deep sea drilling operations. The recent highlights are summarized in Appendix F. However, there are multiple opportunities for the industry and BSEE to work together to enhance the safety culture and further increase fastener reliability. Prudent risk management necessitates the continuous reduction of the potential for fastener failures. A meaningful comprehensive government-industry initiative could be constructed, aimed primarily at improving fastener reliability for the most critical subsea applications. The challenge is to reduce the probability of a subsea fastener failure, which is already low, by another 1 to 2 orders of magnitude over a defined period of time, such as the next 10 years. A resulting multi-faceted roadmap could contain key objectives and priorities that could be executed and implemented by the industry, much as was done in the FAA's JETQC and the Navy's SUBSAFE efforts. Industry should have a large role in determining the priority for addressing potential improvements. As an example, the roadmap for improving durability could address four phases of the life cycle of a bolt: New Equipment, In-service Subsea, On Deck on the Rig, and 5-year Full Inspection. The improvement opportunities could be divided into short-term actions (could be implemented within a year or two), intermediate-term actions (may require up to 5 years to develop and qualify), and long-term actions (development and qualification extending beyond 5 years).

Initially organizing an industry-wide effort to construct a comprehensive roadmap is likely beyond the purview of industry, if for no other reason to avoid the appearance of unlawful collusion. Thus, there is an opportunity for BSEE to undertake the proactive role of establishing a consortium to construct a comprehensive roadmap that could advance the safety of threaded fasteners. The multi-faceted roadmap could contain key objectives and priorities that could be executed and implemented by the industry, much as was done in the FAA's JETQC and the Navy's SUBSAFE efforts. Industry should have a large role in determining the priority for addressing potential improvements.

Summary Option 6.1 is a synthesis of suggestions in the report that deal with actions that BSEE could take to guide the oil and gas industry in constructing a multi-faceted roadmap for actions that could lead to improvements in subsea bolting reliability. New regulatory action would be guided by the statutory requirement to determine which *best available and safest technology* options meet an economic feasibility hurdle.[19]

Summary Options 6.1: BSEE could undertake the proactive role of working with the oil and gas industry to construct a comprehensive roadmap that could advance the safety of threaded subsea fasteners. The multi-faceted roadmap would contain key objectives and priorities that could be executed and implemented by the industry, much as was done in the FAA's JETQC and the U.S. Navy's SUBSAFE efforts. Industry should have a large role in determining the priority for addressing potential improvements. The roadmap could be divided into several sections:

- Investigate bolting cluster failures using a large-scale fully instrumented flange test rig that simulates subsea conditions on fasteners in bolted joints including structural loads, environmental conditions and cathodic protection. [Option 2.9]
- Research and development of specific innovation opportunities that have the potential to significantly advance the reliability of offshore fasteners in critical service. [Options 2.2, 2.4, 5.1]
- Identification of gaps in current standards and obtaining the necessary data to guide updating the standards. [Options 2.5, 3.1, 3.2, 3.3]
- Promotion of a strategic vision for the safety culture throughout the oil and gas industry. This would include collecting and disseminating information about fastener performance, failures, and near misses across different disciplines and organizations, and using this information to guide roadmap priorities. [Options 2.1, 2.3,2.6, 3.4, 3.5]

Summary Recommendation 6.2 is a synthesis of the recommendations in the report that address actions which the oil and gas industry should take in concert to improve subsea bolting reliability. The activities to implement these recommendations could be incorporated into the comprehensive roadmap activity mentioned in Summary Option 6.1.

Summary Recommendation 6.2: Actions that the oil and gas industry should take to improve subsea bolting reliability include the following:

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[19] BSEE, *Statutory Requirements of OCSLA Regarding the Use of BAST*, https://www.bsee.gov/what-we-do/regulatory-safety-programs/statutory-requirements, accessed November 13, 2017.

- Establish a comprehensive methodology/program to optimize the cathodic protection (CP) practice for critical assets containing fastener metallic materials. [Recommendation 2.7]
- Review the usage of materials in contact with fasteners that are known to poison the chemical reaction of atomic hydrogen converting to hydrogen gas. [Recommendation 2.8]
- Establish a standard accepted laboratory standard test method to assess the susceptibility to environmentally assisted cracking/hydrogen embrittlement of bolting materials and their coatings used in offshore applications [Recommendation 2.10]
- Conduct systematic studies to assess effect of bolt designs on hydrogen embrittlement susceptibility. [Recommendation 2.11]
- Review the standards relating to bolt tensioning, both in terms of loading as a percent of yield strength and in terms of preloading technique, to minimize the probability for excessive stress on bolts operating in subsea environments. [Recommendation 2.12]
- The oil and gas industry should promote an enhanced safety culture across organizations and disciplines that is reflected in work rules and that involves encouragement at all levels of the organization to improve the reliability of subsea bolts. [Recommendation 4.1]
- Support activities related to Summary Options 6.1

1

The Challenges of Subsea Fastener Reliability Improvement

This report presents research strategies aimed at improving the reliability of bolting connections used in offshore subsea oil exploration equipment. The focus is on those fasteners employed in the most critical applications maintaining the pressure boundary of the well, such as blowout preventers (BOPs) which are an essential piece of safety equipment bolted to the wellhead. The overarching objective of the recommendations contained in this report is to reduce the probability of a bolting failure that could lead to a safety issue or cause an unintended release into the ocean environment. To date, even though there have been fasteners failures, (a summary of recent failures is compiled in Appendix E), and near miss failures, no major oil spills have resulted; the overall bolting failure rate is estimated to be in the range of 10^{-4} to 10^{-5} based on the total reported failures divided by the number of all fasteners employed in subsea service.[1] This "service record" is highly incomplete as there is no industry wide program to find bolts that are failing, or have failed and are just held in place by gravity. What record we have is clearly the result of fortuitously discovered bolt failures during an inspection on the rig, prior to any pressure test, **before a major loss of well control event occurred**. There is no industry-wide standard or practice that examines systematically and continuously the condition of in-service unfailed bolts. They are discovered when they fail.

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[1] K. Armagost, Anadarko Petroleum Corp., "Root Cause Failure Analysis In Support of Improved System Reliability," presented at Connector Reliability for Offshore Oil and Natural Gas Operations Workshop, National Academy of Sciences, Washington, D.C., April 11, 2017.

Complete bolting failures have been historically rare events, but how many near misses and incipient failures remain undiscovered is unknown.

The committee found multiple opportunities for improvement in the engineering design, specification, manufacture, application of these fasteners, and "womb to tomb" oversight of the fasteners. The overall strategy recommended in this report is one of risk management by continued improvement based on analyzing field conditions and fastener performance, and then acting on the results, such as devising roadmaps to conduct and implement research and development in areas that have the potential to improve the reliability of bolts, enhance the safety culture throughout the entire oil and gas industry, increase human factor performance, and institute wide-spread communication of best practices related to bolts throughout the industry, including its supply chain.

IMPORTANCE OF FASTENERS

A significant amount of crude oil lies under the continental shelf of the United States. Oil is recovered by drilling and transported to shore using barges, ships and pipelines. Underwater drilling off the U.S. coast began in shallow water in 1896 and has progressed to ever greater depths as the underwater drilling technology has evolved.[2] The original underwater drilling placed the derrick resting directly on the seabed floor, but as exploration moved to water depths beyond 1,500 ft. (460 m), new high-technology deep-water drilling techniques were developed. Appendix D summarizes the more than 100-year history of subsea oil exploration in the United States.

The U.S. Department of the Interior began regulating the offshore energy and mineral extraction industry in the late 1940s; its jurisdiction was formalized by the Outer Continental Shelf Lands Act (OCSLA) of 1953. After the April 2010 *Deepwater Horizon* incident in the Gulf of Mexico, the regulatory structure was changed. The Bureau of Safety and Environment Enforcement (BSEE) was established to provide emphasis on safety, enforcement, prevention of oil releases into the environment, and rapid response in case an oil release does occur. Other agencies are charged with Outer Continental Shelf (OCS) oil and gas lease sales, marine safety, and revenue generation.[3]

Deep water drilling in the United States continental shelf now involves seawater depths of 1,000 ft. (305 m) to 10,000 ft. (3,048 m) and beyond. Figure 1.1 depicts the OCS.[4]

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[2] American Oil and Gas Historical Society, "Offshore Petroleum History," http://aoghs.org/offshore-history/offshore-oil-history/, accessed March 13, 2017.

[3] Bureau of Safety and Environmental Enforcement (BSEE), "History," https://www.bsee.gov/who-we-are/history, accessed August 2, 2017.

[4] Bureau of Ocean Energy Management, "Assessment of Undiscovered Oil and Gas Resources of the Nation's Outer Continental Shelf," 2016, https://www.boem.gov/2016-National-Assessment-Fact-Sheet.

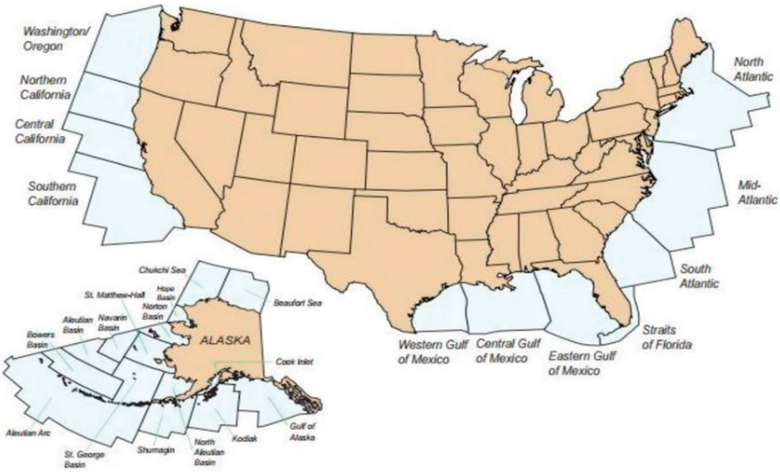

FIGURE 1.1 The U.S. outer continental shelf.

The preponderance of oil exploration in the OCS occurs in the Gulf of Mexico.

- In 2015, Gulf of Mexico oil production totaled 584 million barrels (9.3×10^7 m^3), accounting for 18 percent of total U.S. crude oil production.[5]
- In 2015 proved oil reserves[6] in the Gulf of Mexico were calculated to be 5 billion barrels (8×10^8 m^3) of the 40 billion barrels (6.4×10^9 m^3) of known reserves for the United States.[7]
- A 2016 analysis by the U.S. Bureau of Ocean Energy Management estimated undiscovered technically recoverable resources (UTRR) in OCS to be 90 billion barrels (1.4×10^{10} m^3) of oil. The UTRR estimate is generated stochastically based on certain assumptions; the values reported here are the mean of the various estimates. This calculation does not include known oil reserves. The offshore distribution of UTRR is shown in Figure 1.2.
- The Bureau of Ocean Energy Management also estimated the amount of undiscovered economically recoverable resources (UERR), which takes into account price-supply considerations. This analysis indicated that if oil were priced at $40/barrel, the UERR would be 40 billion barrels (6.4×10^9 m^3),

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[5] U.S. Energy Information Administration, "Gulf of Mexico Fact Sheet," https://www.eia.gov/special/gulf_of_mexico/ data.php#petroleum_fuel_facts, accessed April 7, 2018.

[6] *Proved reserves* are estimated volumes of hydrocarbon resources that analysis of geologic and engineering data demonstrates with reasonable certainty—that is, a probability of 90% or greater—are recoverable under existing economic and operating conditions.

[7] U.S. Energy Information Administration, "U.S. Crude Oil and Natural Gas Proved Reserves, Year-end 2015," https://www.eia.gov/naturalgas/crudeoilreserves/, accessed July 8, 2017.

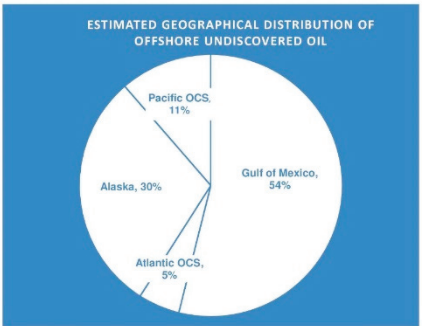

FIGURE 1.2 Estimated distribution of undiscovered oil in the United States.

and if oil were priced at $100/barrel, the UERR would be 70 billion barrels (1.1×10^{10} m^3).

There remains considerable potential for further exploration and recovery of oil in the OCS; the Gulf of Mexico will continue to be an important location for oil exploration and recovery into the future.

Access to these offshore oil and natural gas resources involves the possibility, however remote, of oil spills and subsequent environmental damage. The environmental consequences of an oil spill are more severe underwater than on land as oil from the leak that is almost impossible to immediately stop or capture, and the water eventually disperses the oil over a larger area. As the water depth increases, the water volume exposed increases. As a result, there is an increased consequence of an accidental oil release as the depth increases. Due to concern about the possibility of oil spills, state and federal governments have passed numerous laws restricting oil exploration.[8,9] Examples of recent laws passed by Congress include:

- Marine Protection, Research, and Sanctuaries Act, 1972, which prohibits oil and gas drilling in designated sanctuaries.
- North Carolina Outer Banks Protection Act, 1990, which prohibits oil exploration offshore from North Carolina
- Energy Policy Act of 2005 which prohibits drilling on the Great Lakes
- Gulf of Mexico Energy Security Act of 2006 which bans leasing of tracts for oil exploration until 2022 of portions of the eastern and central Gulf of Mexico.

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[8] R. Jervis, W.M. Welch, R. Wolf, and USA Today, "Worth the Risk? Debate on Offshore Drilling Heats Up," *ABCNews*, July 14, 2008, http://abcnews.go.com/Business/story?id=5367966.

[9] E. Kuhr, "To Drill Or Not to Drill—Debate Over Offshore Testing and Drilling in the Atlantic," *Time*, January 14, 2014, http://time.com/3249/to-drill-or-not-to-drill-debate-over-offshore-testing-and-drilling-in-the-atlantic/.

Bolted connections are an integral feature of deep-water wells. In any subsea wellhead and marine riser systems, there are thousands of large bolting components (threaded bolts, studs, and nuts), typically between 5 cm and 9 cm in diameter (between 2.0 and 3.5 in.), used in a wide range of applications. Most fasteners in the subsea riser packages hold together components of the systems used daily to drill the well and transport drilling fluids. A relatively fewer number connectors are directly related to holding together critical well control components or maintaining the well pressure boundary mechanical integrity. Typically, up to two thousand bolts are in critical and non-critical applications on safety equipment, such as a BOP. Critical bolts, those that secure the pressure boundary, will number far less than two thousand.

RISK ASSESSMENT AND MANAGEMENT

No activity can be entirely risk-free, with risk defined as the product of likelihood of failure and the potential severity of the consequences.[10,11,12,13] Quantitative determination of both factors is required for accurate quantification of risk. For low-probability events, conducting risk assessments requires collecting and assessing a significant amount of data. The financial and environmental cost associated with the potential failure of connectors in off-shore petroleum exploration and production also remains to be quantified.[14] But the potential consequences of connector failure in some strategic locations could be extremely large: "Federal regulators . . . warned subsea oil drillers and equipment makers that bolt failures in the Gulf of Mexico could result in an oil spill on the scale of the Deepwater Horizon disaster."[15] Thus, even with a low failure probably, the risk of failure for a least a subset of subsea connectors could be significant.

Fundamentally, a fastener failure results when its service load exceeds its remaining strength. Unfortunately, highly variable service loads and in-service material degradation processes that can reduce a fastener's strength remain to

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[10] R. Wilson and E.A.C. Crouch, *Risk-Benefit Analysis*, Harvard University Press, Cambridge, Mass., 2001.

[11] National Research Council, *Science and Judgment in Risk Assessment*, National Academy Press, Washington, D.C., 1994.

[12] D. Ropeik and G. Gray, *Risk: A Practical Guide for Deciding What' Really Safe and What's Really Dangerous in the World Around You*, Houghton Mifflin, New York, N.Y., 2002.

[13] Rudolph Frederick Stapelberg, *Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design*, Springer-Verlag, London, U.K., 2009, see pp. 3-21 and 529-545.

[14] Costs can always be quantified after the fact; the challenge is to have a realistic estimate before an incident occurs.

[15] T. Mann, "U.S. Regulators Warn Drillers to Find Solution to Subsea Bolt Failures," *Wall Street Journal*, August 29, 2016, http://www.wsj.com/articles/u-s-regulators-warn-drillers-to-find-solution-to-subsea-bolt-failures-1472490185.

be well understood. Of those subsea fasteners serving a critical role at a pressure boundary or well control device, the likelihood of failure is directly related to both the spectrum of the service stresses and the mechanical strengths in the given environment, neither of which remains constant over time. Even a poorly designed or manufactured fastener can provide decades of trouble free service if the in-service stresses are relatively low; conversely even a well-designed and properly manufactured fastener can suddenly fail if actual environmental conditions move outside the range anticipated by the design, manufacturing and installation, such as excessive cathodic protection voltage potential.

Qualitatively, to a first order, the risk associated with a pressure boundary connector failure is proportional to its distance from the well head. The most important fasteners attach the BOP stack to the wellhead; those next in importance lie in the BOP stack itself and hold together the components such as the blind shear ram necessary for critical functions in well control, and ultimately blowout prevention. The failure of connectors in the Lower Marine Riser Package (LMRP) could result in drilling fluid or hydrocarbon release, or result in loss of means of well control.

The challenges of doing quantitative risk analysis on subsea connectors are illustrated by the voluntary and proactive recall of more than 10,000 bolts after a failure occurred on a subsea hydraulic connector being used on a BOP. This failure led to a spill of approximately 400 barrels of synthetic drilling fluid in the Gulf of Mexico, in which relative minimal environmental damage occurred. This recall was initiated by the manufacturer, motivated by concern that a potentially impacted bolt could cause another release of drilling fluid. A rough estimate of the cost to the industry of this voluntary recall is in the tens of millions of dollars for the global fleet, with the cost of the bolts estimated to be on the order of $1 million to $2 million. Although post-incident analysis has produced some contributing causes, the root cause of the failure has not yet been definitively determined.[16,17,18] Industry-led changes to bolting specifications have been made, and a database containing BOP failure information has been established under the auspices of the International Association of Drilling Contractors (IADC)/International Association of Oil and Gas Producers (IOGP) at the urging of BSEE. This database is expected to provide necessary information to the database subscribers conducting failure analysis studies.

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[16] BSEE, *Evaluation of Connector and Bolt Failures—Summary of Findings*, QC-FIT Report #2014-01, Office of Offshore Regulatory Programs, August 2014, *https://www.bsee.gov/sites/bsee.gov/files/bolt_report_final_8-4-14.pdf.*

[17] BSEE, *Evaluation of Fasteners Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, February 2016, *https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf.*

[18] BSEE, *Evaluation of Fasteners Failures—Addendum II*, QC-FIT Report #006, Office of Offshore Regulatory Programs, July 2017, *https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf.*

Managing risk for low-probability, high-impact events is quite challenging. The root cause of these events is usually difficult to precisely determine and thus eliminate because they occur so infrequently, and measuring success requires large data samples over an extended period of time. The reality is that it is far more straightforward to count the number of failures than to account for the number of failures that have been avoided through proactive actions.

The management of the risk requires improvements in procedures, materials, controls, inspection and maintenance as well as sharing of best practices among/within the oil and gas industry and the government regulator. These actions require expenditure of time and effort that can be challenging to justify without taking the view that reducing low-probability but very-high-cost events is ultimately cost effective. Appendix F summarizes current proactive activities within the U.S. oil and gas industry to improve the reliability of bolting.

The Outer Continental Shelf Lands Act of 1953 was amended in 1978 to include Section 21(b), which states: "In exercising their respective responsibilities . . . the Secretary of the Department in which the Coast Guard is operating, shall require, on all new drilling and production operations and, wherever practicable, on existing operations, the use of the best available and safest technologies which the Secretary determines to be economically feasible, wherever failure of equipment would have a significant effect on safety, health, or the environment, except where the Secretary determines that the incremental benefits are clearly insufficient to justify the incremental costs of utilizing such technologies."[19] This statutory requirement for determining which *best available and safest technology* options pass an economic feasibility hurdle is a significant challenge for continually improving the reliability of fasteners.

REPORT CHAPTERS AND APPENDIXES

The remainder of this report reviews the critical aspects of fastener design and demonstrated in-service performance, discusses various strategies to further reduce fastener failures, and concludes with potential new approaches to address fastener design and regulatory strategies. Taken together, these recommendations could be used to construct an industry-government action roadmap, aimed at improving fastener reliability for the most critical subsea applications.

- Chapter 2, "Assessment of Critical Subsea Bolting System Design Elements," reviews the critical design factors and requirements for subsea fasteners

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[19] BSEE, *Statutory Requirements of OCSLA Regarding the Use of BAST*, https://www.bsee.gov/what-we-do/regulatory-safety-programs/statutory-requirements, accessed November 13, 2017.

and summarizes failure modes. The chapter covers fastener design, fastener material selection, variability in loads on fasteners, safety factors for bolting, lifecycle of a fastener, bolt failure modes, cathodic protection and hydrogen uptake, observed cluster failures of fasteners, and options for improving bolting material properties.

- Chapter 3, "Options for Improving Bolting Reliability," discusses existing fastener standards and specifications and quality assurance options, and presents options for improving government oversight of the fastener lifecycle.
- Chapter 4, "Safety Culture and Human Systems Integration," describes how human factors can significantly impact the safety culture in preventing fastener failures.
- Chapter 5, Innovation Opportunities," describes research and development opportunities that could advance fastener performance and reliability. These opportunities fall into the categories of testing protocols, in-situ measurements, hydrogen assisted cracking, coating technologies, new designs, and human systems integration.
- Chapter 6, "Summary of Recommendations," reiterates the key conclusions and recommendations contained in the report chapters.

In addition, the appendixes contain a significant amount of information that supplements the discussion in the report.

- Appendix A contains the statement of task from the study sponsor, BSEE, which precipitated the study that led to this report.
- Appendix B maps the statement of task to report chapters.
- Appendix C is a list of the acronyms that are used throughout the report.
- Appendix D is synopsis of the more than 100-year effort of subsea oil exploration in the United States.
- Appendix E is a summary of some subsea bolt failures that have occurred in the past.
- Appendix F summarizes recent activities by the oil and gas industry and BSEE to improve bolting reliability.
- Appendix G provides detail to the discussion of the subsea environmental factors that impact fastener design.
- Appendix H is a summary of bolting regulations and standards.
- Appendix I contains details on drilling riser design and describes the various forces that may eventually be places on connectors and bolts.
- Appendix J describes the many different factors that affect bolting preload and the associated conditions of safety factor analysis.
- Appendix K presents the different failure modes experienced by threaded fasteners.

2

Assessment of Critical Subsea Bolting System Design Elements

For purposes of this study, only bolted flange connectors are considered—more specifically, the connectors for closure bolting of pressure containing flanged connections or assemblies which will also be subjected to mechanical loads such as tension and bending. Figure 2.1 shows bolted connections used on a typical subsea blowout preventer (BOP) stack assembly. Bolting is used on the flanged connections between BOP rams, the flanged connectors between the lower BOP stack and the Lower Marine Riser Package (LMRP), and the flanged connectors between LMRP and the flexible ball joint and riser. Bolting is also used on the rams, such as the blind shear ram housing (on which, as stated elsewhere in this report, failures have occurred). Based on the limited data and general information that the committee has reviewed, the committee has seen little or no evidence of any bolt failures attributable to cyclic loading or fatigue.

A critical connection is defined as one which if it failed would result in the release of hydrocarbons and drilling fluids to the environment. Similarly, critical bolting, in this context, is a bolt, stud, nut or fastener used on a critical connection. There are approximately 850 critical bolts, studs, and nuts on a deepwater 7-ram BOP stack; this includes both the LMRP and lower BOP stack assemblies. A flanged drilling riser deployed in 6,000 ft. of water has an estimated 450 bolts plus 450 inserts (nuts)."[1]

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[1] K. Armagost, Anadarko Petroleum Company, "Root Cause Failure Analysis, In Support of Improved System Reliability," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

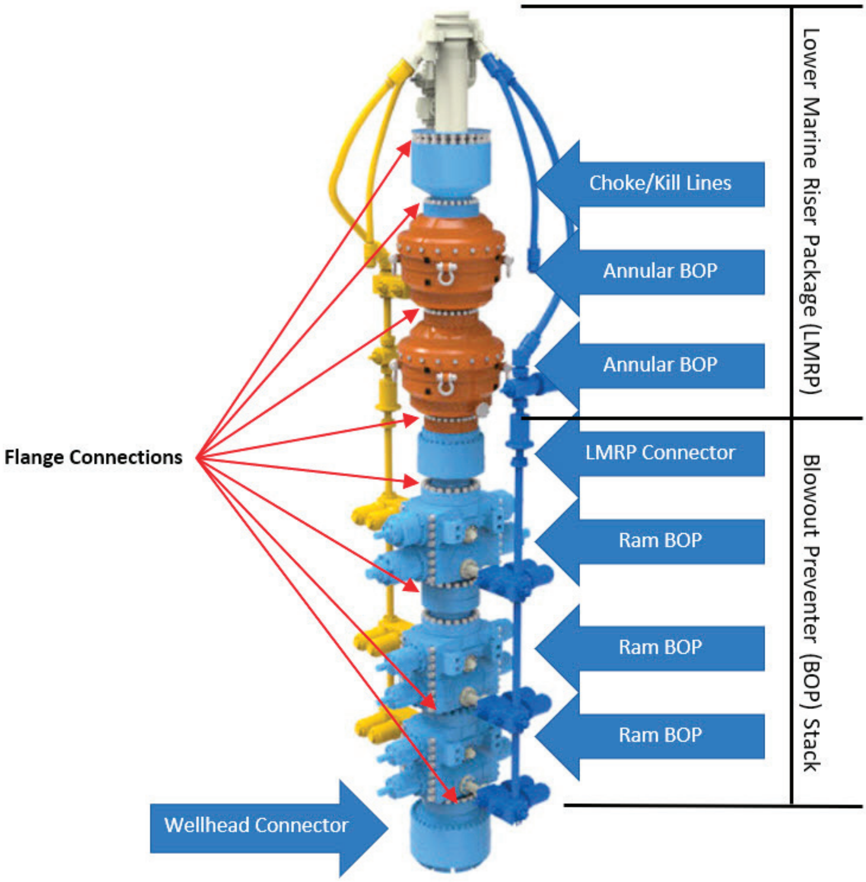

FIGURE 2.1 Typical deepwater subsea blowout preventer (BOP) system showing rams and bolted connections. SOURCE: GrabCAD, "Blow Out Preventer (BOP) (renders only)," November 23, 2012, https://grabcad.com/library/blow-out-preventer-bop, modified by committee.

Throughout this chapter, drilling risers are mentioned since they protect the drill string which is part of the pressure boundary, and employ fasteners in many applications. Appendix I is a tutorial on the design of a drilling riser. It begins with a discussion of the many forces that act on a drill riser system, and supplements the discussion in Appendix G, "Subsea Environmental Factors for Fastener Design." The appendix reviews the drilling riser system design process, operational analysis, failure (weak point) analysis and fatigue analysis. This appendix is intended as background and context to this chapter's discussion and analyses.

FASTENER DESIGN

Nomenclature

A simplified schematic depiction of a section of a subsea BOP, exhibiting a bolted flange connector and shear ram actuator housing is shown in Figure 2.2. The assembly includes among other components: flanges, ring gaskets, and multiple flange bolts, studs and nuts. The number of flange bolts and the size and strength of the bolts, studs, and nuts depends primarily on the flange size, seawater depth, and drilling or production fluid pressures and temperatures. Note that the threaded fasteners on the flanges and ram housing are of a variety of types, sizes, materials, and strengths. The threaded fasteners also require different makeup torques and possibly assembly tools.

Figure 2.3(a) shows a sketch of an LMRP hydraulic connector from the Bureau of Safety and Environmental Enforcement (BSEE) *QC-FIT Evaluation of Fastener Failures—Addendum* report. During assembly, torque is applied to the bolt head, or nuts, to compress the flanges faces and generate compressive stress on the seal

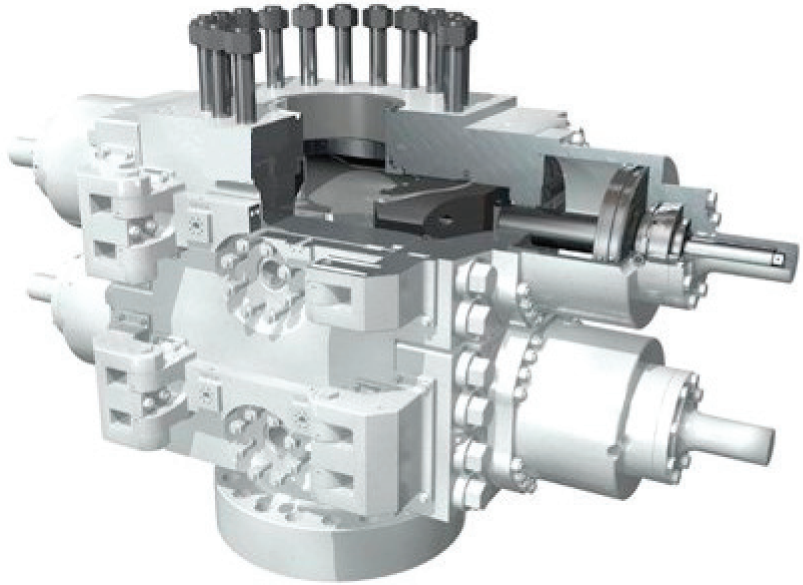

FIGURE 2.2 Typical bolted flange connector showing two flanges, a ring gasket, and bolting. This is a typical component of a blowout preventer (BOP) stack. Threaded fasteners on the flanges and ram housing are of a variety of types, sizes, materials, and strengths. SOURCE: T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017; see GE Oil & Gas, "Drilling Systems: Reliable to the Extremes," 2009, http://geoilandgas.ge.com.cn/sites/default/files/ueditor/upload/file/101966.pdf.

FIGURE 2.3 (a) Sketch of a lower marine riser package (LMRP) connector. (b) Photograph of actual. SOURCE: Bureau of Safety and Environmental Enforcement, *Evaluation of Fasteners Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, February 2016, https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf, pp. 15-16.

ring faces. As the flange and seal ring faces are compressed, the bolts are stretched, resulting in longitudinal tensile stresses in the bolts. As is well known, the thread roots create a stress concentration, with the first engaged thread root generally having the largest local tensile stress. It can be clearly seen in Figure 2.3(b) that threads failed at the first engaged thread at the flange face. As can also be seen in the photo of the failed connector, a cluster of bolts failed, but not all of them.

Operational Loads on Flange Bolts

Because of the subsea environment, varied and dynamic forces act on the flanged connections in the subsea riser equipment and the threaded fasteners therein. Basic design considerations for bolted connection (i.e., flanges and housing) design include the following:[2]

- Flange and seal ring compressive stress
- Bolting preload tension stress (currently based on torque)
- Flange stiffness or rigidity under load
- Bolt spacing
- Material selection for strength and environmental compatibility
- Service loading during drilling, production, installation (running)
- Environmental loading (sea states, currents, storms, etc.)
- Corrosion resistance through coatings, impressed voltage,
- Fatigue

Bolted flange connectors used in a subsea riser system, including the BOP/LMRP and wellhead connector, are subjected to several types of loads:

- Compression loads due to the net buoyant weight of the BOP stack and riser.
- Tension forces due to the loads transmitted by the drilling riser and floating platform, drilling operations, or during the running or retrieval of drill pipe.
- Bending loads due to lateral movement of the rig and riser and ocean currents.
  - — Bending on the LMRP and BOP are reduced by the upper and lower flex joints (discussed further in Appendix I).
  - — The bending loads transmitted to the subsea BOP system, however, will impart tension (on the high side) and compression (on the low side) on the flange and bolting.

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[2] Ramón I San Pedro, PE, "Bolted Flange Joints in Offshore: Basic Principles and Applications," presentation to the committee on March 22, 2017.

The design of American Petroleum Institute (API) wellhead and BOP flange connectors could, in theory, sustain its rated pressure, despite a limited number of bolt failures. The committee does not know if this theory has ever been verified by modelling or testing a flange connection with one or more bolts failed. However, the failure of any one bolt reduces the inherent reliability of the flange since the service loads are transferred to adjacent bolts, leading to the potential for subsequent bolt failure on the flange. This could lead to cascading bolt failures.

The committee found a general lack of concern by the industry about single bolt failures, as evidenced by the lack of any industry wide tracking of these failures until mandated by BSEE. This apparent lack of concern is troublesome, since the committee had no access to statistical data or engineering studies regarding the effect of single bolt failures on overall flange connector reliability under a variety of loading and environmental conditions. As discussed later in this report, considering the past occurrence of multiple bolt failures in the same connector, the failure of any bolt in critical service warrants a full root cause analysis to reduce the potential for future failures. It is important not to risk a false sense of security by the bolt redundancy designed into bolted connectors, particularly when they have demonstrated an ability fail in clusters or groups.

Bolt preload considerations are important and are discussed in greater detail in Chapter 3 and in Appendix J.

Bolt Preloading

Flange bolts are "preloaded" during flange assembly. Bolt heads or nuts are torqued to apply tension on the bolts which then compresses the flange faces to attain structural integrity and pressure containment which the preload should maintain in the face of all other loading. The preloading of bolts is a critical operation because of the high stresses placed on the bolts and the requirement for the bolts to accommodate any additional operational loads imparted on the connector.

Current oil and gas industry practice or preloading flange bolts using torque has been shown to have an accuracy preload variability of ±25 percent to 30 percent.[3,4,5] To the best of the committee's knowledge, bolt preload variability is not accounted for in bolt and connector design; this is of concern to the commit-

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[3] K.H. Brown, C. Morrow, S. Durbin, and A. Baca, *Guideline for Bolted Joint Design and Analysis: Version 1.0*, SAND2008-0371, Sandia National Laboratories, Albuquerque, N.M., January 2008.

[4] L. Burgess, discussions with Nancy Cooke and Bill Capdevielle on May 31, 2017, presented to the committee on August 28, 2017.

[5] J.H. Bickford, *An Introduction to the Design and Behavior of Bolted Joints*, Third Edition, Marcel Dekker, Inc., New York, N.Y., 1995.

tee. Bolt preload is a critical design parameter, and is discussed in greater detail in Appendix J.

Fastener Material Selection

Material and quality specifications are an important part of any design process. Threaded fasteners for offshore applications are manufactured according to specifications[6,7] including API Spec 20E, "Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries," and API Spec 20F, "Corrosion Resistant Bolting for Use in the Petroleum and Natural Gas Industries."[8,9] Each of these API specifications details the requirements for materials, properties, manufacturing, testing, inspection, and recording keeping. Three quality levels, referred to as bolting specification levels (BSLs) are identified in API Specs 20E and 20F. The higher-grade levels, particularly BSL-3, are of primary interest for connectors in critical offshore applications. Each specification also references American Section of the International Association for Testing Materials (ASTM) and API documents that identify material compositions and grades covered by each standard. As examples, common steels produced according to API Spec 20E include heat treated, nominally 0.4 weight percent carbon steels such as American Iron and Steel Institute (AISI) standards 4140 and 4340. Examples of corrosion resistant alloys (CRAs) produced according to API Spec 20F include the high nickel superalloy, Alloy 718, and selected alloys similar to stainless steels.[10,11] As the majority of the threaded connectors in service are heat treated medium carbon steels, the comments below concentrate on those types of steels. Selected comments specific to nickel base and CRAs are also presented.

The types of threaded steel connectors of interest for offshore applications are contained in Section 3.1.1 of API Spec 20E and include the following: all-thread

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[6] Det Norske Veritas (DNV), *JIP—Guideline for Specification, Design, and Assembly of Offshore Bolted Joints*, Report No./DNV Reg No. 2008-1656/1201FBR-56, Rev, 1 2012-06-11, Høvik, Norway.

[7] B. Lillebø, "Bolting Materials Subsea," presentation at the Materials in Offshore Constructions, Esbjerg, June 2, 2006, Det Norske Veritas, Bergen, Norway, http://www.offshorecenter.dk/log/filer/1_7%20DNV.pdf.

[8] American Petroleum Institute (API), *Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries*, API Specification 20E, Second Edition, Washington, D.C., February 2017.

[9] API, *Corrosion Resistant Bolting for Use in the Petroleum and Natural Gas Industries*, API Specification 20F, First Edition, Washington, D.C., June 2015.

[10] API, *Age-Hardened Nickel-Based Alloys for Oil and Gas Drilling and Production Equipment*, API Standard 6A718, Draft Copy of Third Edition, April 2013, Washington, D.C.

[11] ASTM International, *Standard Specification for High-Temperature Bolting, with Expansion Coefficients Comparable to Austenitic Stainless Steels*, ASTM Standard A453, West Conshohocken, Pa., 2017.

studs, tap-end studs, double-ended studs, headed bolts, cap screws, screws, and nuts.

VARIABILITY OF BOLTING LOADS

The dynamic loading on the drilling riser systems, which includes the LMRP/BOP systems and critical bolting, has been an active area of research. Since the riser system can impart tensile, compressive and bending loads on the BOP system and its critical bolts, riser dynamic loading should not be ignored or its importance minimized. Real-time measurement and analysis of stresses and deflections of risers was presented in, for example, Tognarelli et al., 2008.[12] In addition, Fleece presented sea current profiles and resulting bending moments on an API 18-3/4" LMRP connector flange in the workshop on April 11, 2017.[13]

The potential for sea states to cause fatigue due to dynamic loading of risers is an important subject of interest to the deepwater drilling and production industry. The committee has not been provided with any data that provides evidence of failures attributable to cyclic loading and fatigue. However, QC-FIT evaluations have shown that industry understands very little about the impact of cyclic fatigue on riser components such as bolts. For example, fatigue loading does not appear to have been responsible for reported failures summarized in Appendix E.

Rather, the evidence of the several cases presented to the committee appear to be environmentally assisted intergranular brittle failure of bolting in flanged connections, and a few cases of what appeared to be ductile overload failures on a blind shear ram actuator housing. To be clear, the committee notes that concurrent presence of static tensile load and low frequency cyclic loading can produce hydrogen-assisted intergranular cracking at reduced static threshold stress intensities below those observed in purely static loading. This only occurs as long as hydrogen was present from the gas phase or aqueous charging of hydrogen. The committee wishes to note that this differs from dry fatigue in the absence of charged hydrogen and is due to enhanced hydrogen uptake and hydrogen dislocation, or fracture process zone interactions, which enhance susceptibility to hydrogen-assisted cracking (HAC).

API Specification 17D, "Specification for Subsea Wellhead and Christmas Tree Equipment" which also applies to subsea BOPs, specifies bolt loading limits as a percentage of yield stress (not ultimate tensile strength), because plastic deforma-

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[12] M.A. Tognarelli, S. Taggart, and M. Campbell, "Actual VIV Fatigue Response of Full Scale Drilling Risers: With and Without Suppression Devices," Paper OMAE2008-57046, *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE2008)*, American Society of Mechanical Engineers, New York, N.Y., 2008.

[13] T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017, p. 17.

tion of bolts is as undesirable an event as an actual bolt failure if it leads to failure of the connector to maintain the pressure boundary of the well.

The yield margin of safety for flange bolts can be derived from the working stress limitations specified in API Spec 17D, which recommends the following:

- For bolt preload (the initial "tightening of a flange bolt to achieve flange face closure force), the bolt should be placed in a tensile loading state of 67 percent to 73 percent of the yield stress.[14]
- For bolt in-service loading (the bold preload plus any additional working loads such as pressure, externally applied tension, or bending moments on the connector) the tensile loading on the bolt shall not exceed 83 percent of the yield stress.[15] Assuming that the torque values are ±30 percent, the yield margin of safety is .205; Appendix J contains more details on yield margin of safety and margin of safety.

Subsea wellhead and Christmas tree bolts suffer additional and greater integrity risks, including:

- Service in high-pressure salt water—sometimes hypersaline
- Exposure to H_2S, CO_2, hydrogen, and cathodic protection
- Potential tensile forces coming from the rig through the riser
- Potential bending moments caused by deep water currents

The above four factors place significant and often uncertain environmental stress and loading on subsea bolts. This operating environment of subsea critical bolts raises questions about the appropriateness of the yield margin of safety implied by API Spec 17D even though no failures due to inadequate yield margin of safety were reported to the committee.

More information on flange bolt loading can be found in Appendix J.

FASTENER LIFE CYCLE

Bolt Manufacturing

The manufacture of threaded fasteners begins with the production of cylindrical rods (typical diameters of 25 to 150 mm). This section highlights details of the production processes followed by assessments of installation and service life considerations.

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[14] API, API Specification 17D, ISO 1 3628-4, 2nd Edition, May 2011, Section 5.1.3.5, p. 19.

[15] API, API Specification 6A, ISO 10423:2009 (Modified), 20th Edition, October 2010, Section 4.3.4, p. 28.

Multiple different processing routes are available to produce heat-treatable steel alloys, nickel-based superalloys, and other CRAs as wrought bar products for use in the production of offshore industry connectors. As reviewed previously,[16] steel alloys are first synthesized in liquid form and solidified in either ingot or continuous casting form. As a direct consequence of solidification, alloy elements redistribute during the cooling process to form regions of micro-segregation within the solidified microstructure producing alternating zones of high and low alloy content. As a result of shrinkage associated with solidification, internal porosity can also develop. The integrity and properties of steel bars which are the feed stock for the manufacture of finished connectors depend on multiple variables including initial alloy content and cleanliness along with thermal and deformation history. Production of defect-free steel bars with homogeneous chemical composition and microstructures is ideal.

In ingot casting facilities, individual ingots with cross sections in excess of 1 m^2 are typically produced. Prior to rolling or forging, ingots are heat soaked (i.e., heated and held at an elevated temperature for a long period of time) to facilitate alloy homogenization by diffusion and to produce ingots with a uniform temperature throughout the cross sections. Depending on the facility, the ingot cross sectional area is first reduced in a blooming mill ("bloom" refers to an intermediate semi-finished bar) prior to further reduction by rolling to a form a billet (note that the difference between a bloom and billet is somewhat arbitrary and relates to size).[17] In continuous casting facilities, steel is solidified directly as a continuously moving billet with typical section sizes up to about 18 cm × 18 cm square.[18] Recently continuous casting systems have been developed which produce jumbo blooms with larger section sizes up to about 45 cm × 61 cm[19] and these systems may include an in-line forging system prior to rolling to billets. However, API 20E currently prohibits the use of continuous cast product in the production of BSL-3 connectors.[20]

Round bars are produced by hot rolling billets through multi-stand bar mills with reductions per pass and pass geometries carefully selected to produce the de-

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[16] G. Krauss, "Solidification, Segregation and Banding in Carbon and Alloy Steels," presented at the Howe Memorial Lecture, ISS, April 2003, and published in *Metallurgical and Materials Transactions B* 34B:781-792, 2003; also published in *AIST Transactions, Iron and Steel Technology* 1(3):145-157, 2004.

[17] W.T. Lankford, N.L. Samways, R.F. Craven, and H.E. McGannon, eds., *The Making, Shaping, and Treating of Steel*, 10th edition, Association of Iron and Steel Engineers, Pittsburgh, Pa., 1985.

[18] B. Kozak and J. Dzierzawski, "Continuous Casting of Steel: Basic Principles," http://www.steel.org/making-steel/how-its-made/processes/processes-info/continuous-casting-of-steel---basic-principles.aspx, accessed May 2017.

[19] P. Anderson, "Forging Quality in Steel Ingot Manufacturing & Conversion," presentation at Forge Fair 2015, April 15, 2015, TimkenSteel, Ohio, http://www.timkensteel.com/what-we-know/resource-library.

[20] API Spec 20E.

sired final diameter bars required for connector manufacture. For threaded studs machined from as-supplied rolled rod, often the final rod is provided in the cold rolled or an intermediate heat-treated condition, where cold finished bars have a higher dimensional tolerance than hot rolled products. In contrast to the production routes summarized above for heat treatable medium carbon steels, high alloy materials (e.g., austenitic nickel based alloys and CRAs) often are melted in vacuum furnaces, cast to ingots, and reduced by radial forging to rounds for use as finished products or as feed to subsequent rolling operations.

During hot working (i.e., forging or rolling), internal porosity present after casting is eliminated and regions where micro-segregation is present, are deformed and aligned with the rolling direction producing compositional bands. On cooling or during subsequent thermal processing, the composition bands may lead to microstructural variations with wavelengths on the order of microns. The resulting microstructural variations lead to a feature referred to as "banding."[21] Significant improvements in steel making technology have evolved to produce cleaner (i.e., low residual and low inclusion content) steels with more homogeneous microstructures (i.e., minimal banding).

Historically, one of the primary ways to characterize the extent of hot working and the ability of hot working to produce bars with as close to homogeneous microstructures as possible is to calculate the reduction ratio—that is, the ratio of the initial cast cross section area to the final wrought cross-section area. For selected applications, minimum reduction ratios to identify characteristic transitions from cast to wrought microstructures have been identified.[22] For example, API 20E indicates that for the heat treatable medium carbon steels, a minimum reduction ratio of 4:1 is required for steels that meet BSL-1 or BSL-2 while a minimum 10:1 is required for BSL-3. For the CRAs considered in API 20F, a minimum 4:1 reduction ratio must be achieved. More recently, and in-line with advanced steel making technologies, it has been suggested that material soundness (e.g., as potentially assessed via ultrasonic testing) is a better measure of the effects of hot working than calculated reduction ratios and should be considered in future evaluations of materials for specific applications.

Hex head flange bolts and related connectors are produced by hot forging where control of thermal history (i.e., temperature and time) and forging parameters are critical to ensure the production of high quality, dimensionally accurate forgings. After forging, bolt blanks are heat treated with the times, temperatures, cooling rates (e.g., quenching), and tempering conditions selected to produce the

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[21] ASTM International, *Standard Practice for Assessing the Degree of Banding or Orientation of Microstructures*, ASTM Standard E1268-02, West Conshohocken, Pa., 2017.

[22] C.V. White, G. Krauss, and D.K. Matlock, Solidification structure and the effects of hot reduction in continuously cast steels for bar and forgings, *Iron and Steelmaker* 25(9):73-79, 1998.

specified hardness for the selected alloys.[23] During heat treating, bolts are typically loaded into special carriers that ensue all bolts in a batch receive the same thermal history. Depending on the application and processing history, the bolts may be cleaned chemically or mechanically at some stage in the production process. As stated in API 20E, the resulting microstructure should be predominately tempered martensite with a maximum hardness of HRC34. For high nickel superalloys, strengths are achieved by aging heat treatments after solutionizing.

Threads are produced either by machining or metal forming. Machining operations may include single point cutting on a lathe or cutting with a die.[24] In machining, the major diameter of the thread is essentially the same as the part diameter prior to threading. Alternately, thread rolling is used to mechanically form the threads. In thread rolling, the deformation process mechanically moves material from the thread roots to form the threads and as a result the major diameter of the threads is generally larger than the bar diameter prior to threading. Control of thread root geometry is also important to minimize local stress concentrations.[25] In comparison to machined threads, the thread roots produced by rolling exhibit an increase in strength due to the local cold work and a residual stress state which includes compressive stresses parallel to the bolt axis at the thread root, a consequence of the non-uniform strain applied to form the threads. An additional difference in the two thread forming processes is the susceptibility to preloading variances after torqueing, and implied by Figure J.1 in Appendix J.

Different criteria are indicated for the sequence of heat treating and threading. With Alloy 718 for example, ASTM 453A indicates "threads may be formed after precipitation heat treatment or after solution anneal but prior to precipitation heat treatment." and states that "for fasteners exposed to fatigue loads, external threads shall be rolled after final heat treatment." After completion of the threading operation, the bolts may be coated for corrosion control or modification of thread friction.

Heat treated steels and CRAs of current use in offshore applications are based on proven technologies with the ability to produce final products at specified hardness levels.

There has been increased success in the ability to design new bolting materials which can be produced to the required hardness levels for use in offshore

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[23] G. Krauss, *Steels: Processing, Structure, Performance*, ASM International, Materials Park, Ohio, 2005.

[24] L. Burgess, "Bolt Manufacturing—A Look at Critical Operations," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

[25] ASTM International, *Standard Specification for Heavy Hex Structural Bolt/Nut/Washer Assemblies, Alloy Steel, Heat Treated, 200 ksi Minimum Tensile Strength*, ASTM F3111-16, West Conshohocken, Pa., 2016.

environments but which incorporate alternate strategies to mitigate corrosion and susceptibility to hydrogen-assisted cracking (HAC; see discussion below). Several alternate alloying and processing strategies have been identified.[26,27,28,29]

Current specifications for offshore fastener steels prohibit the use of continuous cast products, primarily because the existence of banding has been observed in steels which also failed in service by what was identified as hydrogen embrittlement (HE). However, as a result of recent advances in steel making casting technologies, significant advances in product quality have been realized. A recent root cause analysis of continuously cast bolt failures showed no direct relationship between crack initiation or growth by HE and the presence of banding.[30]

While banding typically is concentrated in the center part of rolled bars, hydrogen induced fractures typically initiate near surface in regions where banding is essentially absent. Advances in steel making casting technologies suggest that metrics other than reduction ratios would provide improved assessments of product quality. Recent data suggests that prohibition of banding may not be necessary to maintain product quality for subsea bolting applications.

These threaded connectors for offshore applications, however, must be manufactured with the specified dimensions, dimensional tolerances, and material properties to meet system design requirements and applicable specifications. If the connector dimensions are correct, the critical requirement for connector installation is to ensure that sufficient tension is created within the connector to safely maintain required compressive contact forces between mating surfaces.[31]

Chapter 2 and Appendix J provide more detail on methods for achieving flange bolt preloading and the concerns the committee has regarding current industry practice.

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[26] D. Hirakami, T. Chida, and T. Tarui, "High Strength Steel and High Strength Bolt Excellent in Delayed Fracture Resistance and Methods of production of Same," U.S. Patent #0298262 A1, November 29, 2012.

[27] M. Kubota, T. Tarui, S. Yamasaki, and T. Ochi, *Development of High-Strength Steels for Bolts*, Nippon Steel Technical Report, No. 91, January 2005, pp. 62-66.

[28] H.K.D.H. Bhadeshia, Prevention of hydrogen embrittlement in steels, *ISIJ International* 56:24-36, 2016.

[29] H.K.D.H. Bhadeshia, "Extremely Strong Steels—The Mechanism and Prevention of Hydrogen Embrittlement," *AISTech 2017 Proceedings*, Association for Iron and Steel Technology, Warrendale, Pa., 2017, pp, 1-9.

[30] Stress Engineering Services, Inc., *Metallurgical Failure Analysis of HC Connector Studs from West Capricorn Facility, Houston, Texas*, Report No. 1253345-FA-RP-01, October 6, 2014.

[31] Energy Institute, *Guidelines for the Management of the Integrity of Bolted Joints for Pressurized Systems*, London, U.K., May 2007.

Service Life

During service, flange bolts must function to sustain the required clamping force on the connector. Pressure-induced and externally applied tensile loads applied during field operations must be restricted to prevent the failure of any flange bolt. Robust operating procedures are in place to minimize this possibility.

There are two main failure modes relevant to this study of critical bolting in subsea BOP systems:

- Ductile failure due to overload
- Brittle failure modes, including intergranular failure due to environmentally assisted cracking or embrittlement

Notwithstanding bolt failure, instances of loading beyond yield, or plastic deformation, can go unnoticed by visual inspections. Severe yielding may be noticed visually or by loose nuts. Without a systematic effort to measure every bolt when new and when removed from service to check any change in the length of each bolt, minor yielding may go unnoticed. This can lead to re-use of plastically deformed bolts and can lead the industry to under-count failure rates. The lack of an industry wide program to assess bolts removed from service has been discussed elsewhere in this report. Given the low margin between the currently inaccurate bolt preloading methods and operational loads, it is highly likely there have been instances of plastic deformation of connectors in Gulf of Mexico deepwater drilling operations. The committee has not seen evidence of any inspection program that would capture plastic deformation of critical flange bolts if they did not fracture.

Detailed documentation on all bolts put into service, and a thorough inspection of all critical bolts removed from service, and not just those that failed, would be necessary to accurately assess the risk of in service critical connector failure. Companion tests should be made for those that did not fail. Critical information is dimensional deformation, quantitative fractography, mechanical and fracture toughness tests, and critical chemistry measurements. Cross sectional metallography should be included to understand if elements of the microstructure were particularly susceptible to cracking. Clear, traceable documentation of all steps is required.

Damage-induced modifications to connectors which reduce effective clamping forces include corrosion, fatigue crack nucleation and growth, and crack nucleation and growth by intergranular mechanisms, including HE and stress corrosion cracking. If a connector bolt develops a partial through-diameter crack (e.g., by fatigue or embrittlement), the effective stiffness of the fastener decreases (i.e., the compliance increases). Thus, for a given imposed total connector displacement determined by the geometry of the clamped components, the load carried by the connector decreases. Because of the decrease in load carrying capacity by one fastener, service loads carried by adjacent connectors increase potentially leading to increased failure rates. Similarly, general corrosion which can change connector geometry can also alter the load bearing capacity of a given connector.

Damage-induced failures are more likely to result in catastrophic failure of the bolt, but can usually be identified during inspection of "un-failed" bolts.

In-Service Inspection

BSEE currently requires a visual inspection by a remotely operated underwater vehicle (ROV) of a marine riser, wellhead and BOP system every 3 days if weather and sea conditions permit.[32] This visual inspection cannot evaluate insipient bolt failures. It may identify actual bolt failures. In all likelihood a ROV visual inspection will only detect gross connector failures, or worse yet, significant hydrocarbon leakage resulting from connector failure.

BOPs are either sent to shore every 5 years for recertification or they are part of a Continuous Certification Program (CCP) in which the BOP stack is inspected, maintained, tested, and certified by the original equipment manufacturer (OEM) onboard the vessel/rig on a set frequency/schedule, thus eliminating the need to send it to shore every 5 years for recertification. It is the committee's understanding that most drilling contractors will perform a closer, more thorough visual inspection of studs and nuts. Nondestructive testing (NDT) of bolts is performed by some drilling contractors,[33] but is not required by law.

Subsea BOPs must be disassembled for inspection and maintenance every 5 years. Each OEM recommends an inspection program to the drilling contractor. Flange bolts may be removed and visually inspected for flaws. There is no requirement to perform NDT on bolts, studs, and nuts; no requirement to measure them for dimensional change, nor is there a requirement to replace bolts, studs, and nuts that pass visual inspection. It is certain that not all drilling contractors change connector bolts during the BOP inspection every 5 years.[34]

There are technologies and opportunities for more effective NDT inspection of bolts in situ (see Chapter 5), on the deck, and in the shop. Given the high operational cost of critical bolt failures and the extremely high cost of riser system failures, it would seem in industry's best interest to exploit every opportunity to identify incipient bolt failure. Some experts who perform risk-based designs (load

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[32] 30 CFR Chapter II §250.739(c).

[33] P. Bennett, "A Deepwater Drilling Contractors Perspective," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

[34] Comments made by Peter Bennett with Pacific Drilling at the BSEE Bolt Workshop, August 29, 2016.

and resistance factor design, LRFD), consider "inspectability" to be a very important parameter in LRFD design analysis.[35]

BOLT FAILURE MODES

There are two failure modes relevant to this study: ductile fracture and brittle fracture. Ductile failure typically occurs when the bolt is overloaded due to excessively large tensile forces. With no evidence of fatigue brittle failure occurs when the bolt material exhibits cracking due to environmentally assisted effects, sometimes the result of excessively high hardness, such as HE. Details of the metallurgical aspects of these failure modes are described in Appendix K. As stated previously, the committee has found that the vast majority of failures in critical bolts reported to BSEE have been due to HAC, with only a few instances of ductile failure.

CATHODIC PROTECTION AND HYDROGEN UPTAKE

In considering the corrosion[36,37] and cathodic protection of fasteners in deep-water (very low oxygen concentration) conditions, the reduction reaction is water reduction producing hydroxide and hydrogen gas according to the reaction: $2H_2O + 2e^- >> 2OH^- + H_2$.

Note that for this discussion, it is assumed that the oxygen concentration is low enough that oxygen reduction can be neglected.[38] The water reduction rate on a metal surface is primarily a function of the electrode potential[39] of the surface. Parameters that affect the reaction rate include type of metal (hydrogen overpotential), temperature, surface films (oxides), surface finish, and environment chemistry. The electrode potential of the metal surface is the parameter that is controlled during cathodic protection and the reduction reaction rate is related to the potential by the Tafel constant, which is in turn controlled by the type of metal and environment. A reasonable value for water reduction is an increase of an order

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[35] B. Healey, Ph.D., and P. Sharma, DNV GL, discussions with Bill Capdevielle on July 7, 2017, presented to the committee on September 28, 2017.

[36] D.A. Jones, *Principles and Prevention of Corrosion*, 2nd edition, Prentice Hall, Upper Saddle River, N.J., 1996.

[37] E. McCafferty, *Introduction to Corrosion Science*, Springer-Verlag New York, N.Y.

[38] Also note that temperature and pressure affect both the thermodynamics and kinetics of the reduction of water reaction. The thermodynamic shift in Nernst potential for water reduction is not to be ignored but not the decisive difference or decisive factor.

[39] Electrode potential: the applied potential of a subsea structure including a bolt or fastener relative to a reference half-cell potential. Its value depends on thermodynamic and kinetic considerations and may vary across submerged surfaces. This phenomenon is known as a potential distribution which is readily understood since the potential is not in the metal but across the metal-electrolyte interface.

of magnitude in reaction rate for each −120 mV of potential change. Therefore, when cathodic protection is applied, a cathodic polarization of even 50 to 100 mV can produce a significant increase in reaction rate. Coatings can have a significant effect on reaction rates, especially metallic coatings where the underlying fastener material is exposed (scratch or void in the coating). For example, zinc coatings act as a sacrificial anode when the steel fastener is exposed driving the potential of the steel surface to more negative potentials and increasing reduction reaction rates (another form of cathodic protection where the zinc coating is acting as a local cathodic protection system). Other coatings also can affect the potential of the metal surface when the coating is damaged.

The water reduction reaction rate is critical, since it controls the hydrogen production on the fastener surface, which in turns leads to hydrogen uptake into the fastener. Hydrogen uptake occurs prior to the atomic hydrogen combining on the metal surface to form hydrogen gas, which is released into the environment. Other parameters that are critical to the amount of hydrogen uptake into the metal surface are those that affect the concentration of atomic hydrogen on the metal surface. For example, it is known that sulfide poisons the combination reaction of atomic hydrogen to hydrogen gas, thereby increasing the atomic hydrogen concentration of the metal surface and increasing the hydrogen uptake into the metal;[40] discontinuing use of sulfide-containing lubricants on fasteners should be considered. Additionally, an oxide or organic coating can function as a barrier to the reduction reaction and subsequent hydrogen uptake.

Hydrogen uptake, the diffusible hydrogen concentration, follows a relationship where hydrogen concentration is proportional to the cathodic current density raised to some power such as one-half power.[41] Thus, a 10-fold increase in current density produces a 3.5 increase in hydrogen concentration. As discussed above, this concentration can be affected by parameters that influence the atomic hydrogen concentration on the metal surface, such as sulfides.

It should be noted that hydrogen is produced during corrosion and its generation does not necessarily require the presence of cathodic protection (CP) currents. For example, hydrogen uptake due to pitting can be significant.[42] However, CP increases the rate of hydrogen production by increasing the water reduction reaction

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[40] H.G. Nelson, "Hydrogen Embrittlement," p. 275 in *Embrittlement of Engineering Alloys* (C.L. Briant and S.K. Banerji, eds.), Academic Press, New York, N.Y., 1983; J.F. Gabitto and C. Tsouris, Sulfur poisoning of metal membranes for hydrogen separation, *International Review of Chemical Engineering* 1:394-411, 2009.

[41] D. Li, R.P. Gangloff, and J.R. Scully, Hydrogen trap states in ultrahigh-strength AERMET 100 steel, *Metallurgical and Materials Transactions A* 35(3):849-864, 2004.

[42] R.F. Schaller and J.R. Scully, Spatial determination of diffusible hydrogen concentrations proximate to pits in a Fe-Cr-Ni-Mo steel using the Scanning Kelvin Probe, *Electrochemistry Communications* 63:5-9, 2016.

on the metal surface and, therefore is a focus of this discussion. There is a range of complicating factors that affect the electrode potential and, thereby, affect the rate of hydrogen production. First, the CP current and potential distribution vary with macro position on a structure and micro position in a crevice, thread root or crack as a function of the local potential and chemistry. In general, cathodically polarized confined spaces absorb less hydrogen while anodically polarized confined spaces may absorb more.[43] As another example, over time the reduction reactions on a cathodic surface increases the local pH and calcareous deposits form on the surface modestly reducing hydrogen uptake.[44] Ultimately the critical factor for a given environment, temperature, depth, flow and cathodic protection level is the cathodic current on the fastener.[45] The hydrogen content varies critically with this factor and both the local and overall conditions are equally important. Proposed innovations are presented in Chapter 5 that would provide much needed data about the hydrogen concentration in fasteners.

The cathodic protection system must be designed in parallel with material choices. Legacy decisions that have worked with legacy materials, may not work as effectively with different materials or production processes. The intrinsic behavior of critical materials in the electrochemical environment must be understood. As design requirements necessitate high performance materials these considerations become increasingly important.

One example of designing a cathodic protection system was a recent change in the U.S. Navy. Until recently sacrificial cathodic protection on U.S. Navy vessels has been achieved by Zn-based sacrificial anodes, similar to that used in various marine structures. Under typical service conditions these apply a protection potential of −1.05 V versus Ag/AgCl.

As high strength alloys became more prevalent, the concern for HAC increased and as a result, both the U.S. Navy and the French Navy have begun to utilize “low voltage” aluminum anodes with a protection potential of −0.8 V versus Ag/AgCl.[46] The alloys in use by the U.S. Navy, MIL-DTL-24779D, contain additional minor alloying of gallium, indium, or tin to cause corrosion initiation at more positive

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[43] B.A. Kehler and J.R. Scully, Predicting the effect of applied potential on crack tip hydrogen concentration in low-alloy martensitic steels, *Corrosion* 64(5):465-477, 2008.

[44] A. Neville and A.P. Morizot, Calcareous scales formed by cathodic protection—An assessment of characteristics and kinetics, *Journal of Crystal Growth* 243.3:490-502, 2002.

[45] How critical the variability with temperature and the effect of pressure is not well known. Lower temperature and higher pressure may inhibit hydrogen recombination and recombinative H desorption such that hydrogen is channeled into the absorption reaction. However, this is more of an issue for future studies and not the root cause of rare failures.

[46] E.J. Lemieux, E.A. Hogan, K.E. Lucas, and A.M. Grolleau, “Performance Evaluation of Low Voltage Anodes for Cathodic Protection,” CORROSION 2002 Conference Paper NACE-02016, NACE International, Houston, Tex., 2002.

potentials.[47] *The reduced cathodic polarization relative to either zinc or traditional aluminum anodes decreases the production of hydrogen on protected surfaces, which thereby reduces the risk of HE.*

CLUSTER FAILURES

The failure of a single bolt on an undersea flanged connector would certainly be cause for concern, but would not pose an immediate risk of hydrocarbon leakage. The numerous bolts in a typical subsea connector flange provide redundancy. However, redundancy is lost when a "cluster failure" occurs. A cluster failure is defined as the failure of multiple bolts in a single undersea flanged connector. A cluster failure can precipitate a complete pressure boundary loss of the well.

The cluster failure that appears to have motivated a serious and detailed examination of undersea connector failures in general involved the Transocean *Discoverer India*. In December 2012, all 36 H4 connector bolts made from alloy AISI 4340 failed approximately 4 to 5 years after their manufacture[48]: "the rig's lower marine riser package (LMRP) separated from the blowout preventer (BOP) stack resulting in the release of approximately 432 barrels of synthetic-based drilling fluids into the Gulf of Mexico."[49]

The failures were attributed to "hydrogen stress cracking"[50] or "stress corrosion cracking (SCC) due to hydrogen embrittlement"[51] in "faulty" bolts that, due to the use of an outdated standard, "the bolts did not receive the required post electroplating treatment."[52] As a result of this omission the conclusion was reached "it is likely that atomic hydrogen present in the bolts due to the plating process (and not removed via a subsequent bake-out) played a major role in the failures."[53]

Fortunately, while the *Discoverer India* investigation was in progress, in early 2013 "SES received fractured bolts from two other rigs, the *Discoverer Americas* (DAS) and *Petrobras 10,000* (PB10K), both of which use the same series of connectors and part-numbered bolts."[54] Unfortunately the heat numbers for these

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[47] N. Idusuyi and O.O. Oluwole, Aluminium anode activation research: A review, *International Journal of Science and Technology* 2.8:561-566, 2012.

[48] Stress Engineering Services, Inc. (Stress), *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis of Discover India LMRP*, Report No. PN1252494, February 27, 2013, Houston, Tex., p. iv.

[49] Bureau of Safety and Environmental Enforcement (BSEE), *QC-FIT Evaluation of Connector and Bolt Failures—Summary of Findings*, QC_FIT Report #2014-01, Office of Offshore Regulatory Programs, August 2014, p. 1.

[50] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage*, 2013, p. v.

[51] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 7.

[52] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 2.

[53] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, p. v.

[54] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, p. v.

bolts were not reported so their age remains unknown. It was not reported how many bolts were involved in these latter cluster failures, only that four fractured bolts were received from DAS and five fractured bolts were received from PB10K.[55] Acquisition of the additional bolts from DAS and PB10K, along with those from *Discoverer India*, permitted failed bolts from three different cluster failures to be examined by the same experts.

The failures of all the H4 connector bolts from the three rigs resulted in a massive recall campaign in which "a total of 10,982 replacement bolts were provided by GE Oil and Gas for the 361 LMRP connectors worldwide."[56] A rough estimate of the cost to the industry of this voluntary recall is in the tens of millions of dollars for the global fleet, with the cost of the bolts themselves estimated to be on the order of $1 million to $2 million.[57]

The investigation into these cluster failures produced remarkably similar descriptions of the failures. Generally, each bolt exhibited multiple, evidently more or less simultaneous intergranular crack initiation points circumferentially first in the most highly loaded thread root around the bolt. The fracture surfaces of all of the bolts exhibited "predominantly intergranular fracture features" with some areas of micro-void coalescence. There was no evidence of fatigue or overload noted on the fracture surface of any failed bolt from any cluster failure.[58,59]

Unfortunately, since there were only failed bolts, most of significant age, involved in the investigation of these three cluster failures, no unfailed or exemplar H4 bolts for these three connectors were apparently available or examined for the presence of cracking that has not yet progressed to the conditions that enable complete fracture. Perhaps even more unfortunate, of the at least 1,318 H4 bolts returned during the GE recall campaign (and perhaps as many 3,000 reported to the committee anecdotally in the April 2017 workshop) there appears to have been no organized reported expertise examining these bolts for cracks or incipient failures, although here again it has been reported anecdotally they were examined and no cracks were found; the crack detection limits were not specified to the committee.

What is not disputed is that no report of an organized investigation of these returned H4 bolts has been provided to the committee or mentioned in any BSEE report.

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[55] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, Appendix C.

[56] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 6.

[57] BSEE, *Evaluation of Fasteners Failures—Addendum II*, QC-FIT Report #006, Office of Offshore Regulatory Programs, July 2017, *https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf.*

[58] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, Appendix C.

[59] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, p. 25.

The nine studs that fractured on the Seadrill's West Capricorn (WC) in June 2014 after being in service for only six months came as a complete surprise and were only discovered when a "subsea engineer . . . grabbed the top of one of the HC collet connector flange studs and noticed that it moved."[60] As a result of the nine fractured studs on the Seadrill's WC rig, examination and inspection of exemplar unfailed studs from other sources were reported as planned,[61] but again, remain unreported to this committee and the results are nowhere mentioned in any BSEE report.

This serendipitous discovery of nine completely failed studs, along with four more that exhibited thread root cracks identified by magnetic particle inspection during the root cause analysis raises disturbing questions about the surveillance and monitoring systems currently used to assess the integrity of in-service subsea bolts. Had the subsea engineer *not* grabbed the top of one of these studs during this stack pull, would the BOP stack have been subsequently returned to service with nine failed studs still in place? This issue does not appear to be addressed in the subsequent BSEE report or the industry root cause analysis (RCA). Presumably this stack was the subject of multiple ROV inspections while undersea, and obviously had multiple failed connectors, with no notice.

The WC stud cluster failures motivated a reconsideration of the conclusions of the earlier investigations, if for no other reason than some studs exhibited virtually the same failure mode and features observed in the three previous cluster failures while possessing *none* of the attributes that were supposedly the cause of the earlier failures.

The supposedly inadequate post electroplating heat treatment of the *Discoverer India* bolts, by an unmonitored lower tier subcontractor, was extensively discussed in the BSEE reports and the industry RCA for its "major role" in the three cluster failures mentioned previously. Indeed, Table 1 in ASTM B850, "Standard Guide for Post-Coating Treatments of Steel for Reducing Risk of Hydrogen Embrittlement," specifies a bake out of at least 10 hours at 190°C to 220°C.[62] In direct contrast to the *Discoverer India* bolts, for the Seadrill WC studs their "corresponding certificate of compliance indicated that the studs were pre-baked at approximately 400°F [204°C] for 4 hours and post-baked (after coating) at approximately 400°F for slightly over 20 hours." In other words, the WC studs were documented to have received *twice* the required post-bake heat treatment.

The hardness of some (but not all) of the *Discoverer India* bolts were measured, and those measured were found to be in the range of 35.5 to 37.5 HRC.[63] "The GE H4 connector bolt is made with AISI 4340 grade alloy metal with material hard-

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[60] *BOP Stud Failure Investigation*, Author Redacted, Report Version 4, February 9, 2015, p. 3.

[61] Stress, *Metallurgical Failure Analysis of HC Connector Studs from West Capricorn Facility—Final Report*, No. 1253345-FA-RP-01 (Rev 0), October 6, 2014, Houston, Tex., p. v.

[62] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, Appendix M.

[63] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, p. 29.

ness of Class 145 yield strength (145 ksi) and a minimum hardness of 34 Rockwell Hardness Scale C (HRC) and a maximum hardness of 38 HRC."[64] In spite of the fact that the *Discoverer India* bolts appeared to be within specification, BSEE reported "The QC-FIT found that bolt-hardness values above 34 HRC in a subsea environment remain an issue and should be the subject of additional testing."[65] In contrast the Seadrill WC studs, which had a Cameron specification of 31-35 HRC, and thus more reflective of BSEE's concern, were found to have actual average hardness values that ranged from 30 to 41 HRC, with a majority below 35 HRC.[66] It was further observed that "Some studs exhibited a variation in hardness across the section that ranged in some cases up to 8 HRC points…. This type of variation is indicative of a nonuniform heat treatment."[67]

Regardless of the hardness, all failed Seadrill studs exhibited remarkably similar fracture features—that is, multiple IG initiation cracks around the perimeter of the root of the first loaded thread. These features were essentially identical to those observed in the failures from the *Discoverer India*, DAS, and PB10K rigs. Figure 2.4 (Figure 7 of the Stress Engineering Services report) has been annotated to include the average HRC stud hardness values for each bolt to illustrate the independence of hardness and fracture origin patterns and to highlight that bolts with hardness values significantly less than the industry-accepted value of 34 HRC also failed.

As with the case of the *Discoverer India* bolts, the report on the Seadrill WC rig indicated that the industry "RCA also determined that the subcontracted vendor's non-compliance to the QA/QC processes led to deviations from the OEMs manufacturing specification."[68] And, again, the industry "RCA investigation attributed the failure to non-conformances to the manufacturer's heat treatment material specifications, raw material specification, and quality control compliance impacting the fastener material properties."[69] This time BSEE appeared to be less convinced and determined the RCA to exhibit "inconclusiveness" and stated "BSEE recommends that a more detailed investigation be performed by an independent third-party testing laboratory on behalf of the operator to determine the specific damage mechanism."[70]

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[64] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 10.

[65] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 10.

[66] Stress, *Metallurgical Failure Analysis—Final Report*, 2014, p. 18.

[67] Stress, *Metallurgical Failure Analysis—Final Report*, 2014, p. 16.

[68] BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, Washington, D.C., February 2016, https://www.bsee.gov/sites/bsee_prod.opengov.ibmcloud.com/files/memos/public-engagement/qc-fit-bp-bolts-report-final.pdf, p. 5.

[69] BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, 2016, p. 4.

[70] BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, 2016, p. 5.

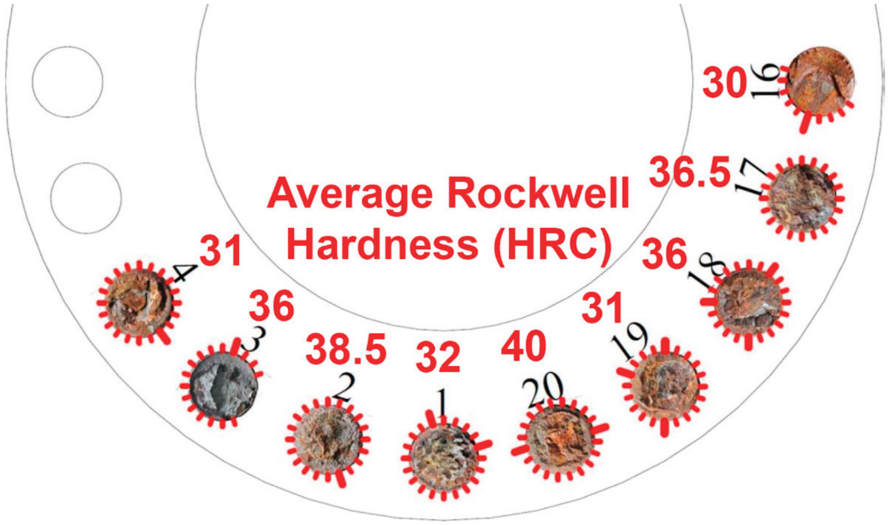

FIGURE 2.4 Schematic showing flange bolt circle with fractured studs from the Seadrill West Capricorn rig. The red lines indicate that there are multiple fracture origins at thread roots. The broad red tick marks indicate more dominant crack propagation/loading directions. SOURCE: Figure was adapted from the Stress Engineering Services report by adding the hardness numbers of the failed bolts.

The industry RCA for the Seadrill WC failures specifically found "banding" in the stud microstructures that was attributed to using rolled bar from continuously cast ingots for the stud steel instead of the specified ingot cast material, "which can result in areas of localized high hardness and unexpected mechanical properties." However, based on metallographic cross sections of multiple secondary cracks which emanated from primary cracks and short cracks at thread roots indicating crack nucleation there does not appear to be any evidence in the micrographs of the cracks that the banding played any role in crack nucleation or propagation. Specifically, the micrographs showed that the cracks that exhibited irregular crack paths characteristic of intergranular fracture by HE "independent of the hard/soft banded regions." The report confirmed that the cracks progressed through or across the banded regions and showed no preference to propagate within these regions. In other words, the crack did not turn to follow the band along its long axis (and parallel to the major tensile stress axis) which is often seen in stress corrosion of alloys with susceptibility dependent on an undesirable metallurgical condition that creates an easily environmental fracture path. In such materials, even though the tensile stress is lower in a radial direction for a longitudinal crack, the metallurgical susceptibility becomes a dominant factor.

Prior to installation, the failed studs for both the *Discoverer India* and Seadrill WC rigs were coated with a protective zinc-chromate conversion coating.[71,72,73] It was noted that this type of coating is designed to help prevent "corrosion during storage of the fasteners and to a certain degree acts as a corrosion protection layer, along with cathodic protection, in subsea application." The potential contribution to the observed failures by the presence of the coating appears to have been overlooked as analyses of the *Discoverer India* failures by Stress Engineering Services indicated that "The zinc-chromate coating . . . appeared to have been consumed during service. Distinct white-colored deposits were observed throughout most of the bolt shank to varying extents. In every case, the fractures were coincident with areas where the coating had been compromised."[74] For the bolt failures from the Seadrill WC it was observed that "in every case, it was apparent that the coating was absent at the locations where fractures had occurred." As discussed in the below, the committee believes a common mode of failure exhibited by all the *Discoverer India* bolts and Seadrill WC studs, of very different hardness, heat treating, and ingot creation is better explained by consideration of the various factors (e.g., coatings, impressed current systems, sacrificial anodes, etc.) which potentially contribute to the electrochemical nature of HE as discussed in the following paragraphs.

External cathodic protection can drive surface and circumferential cracks at a higher rate than deep radial cracks. Under cathodic polarization a negative electrode potential and subsequent high hydrogen overpotential is applied to exposed metallic surfaces which produces hydrogen and OH^- in service. Any confined spaces such as crevices or cracks become increasingly alkaline relative to the bulk as a result of proton discharge and water reduction. In these situations, the crack tip potential is not as negative or in other words experiences somewhat more positive potentials due to ohmic voltage drop. Therefore, the overpotential for hydrogen production may be smaller at deeper radial crack tips than on the boldly exposed surfaces in the cathodic case, and the pH is higher. Taken together, hydrogen uptake may be slightly lower. However, visual inspection of the fracture surfaces of all the *Discoverer India* bolts and Seadrill studs revealed calcareous deposits in the cracks which serve as a positive indicator of cathodic polarization into growing cracks. When the overpotential for hydrogen production is greater on the bulk surfaces than at the crack tip, the diffusible hydrogen concentration may be larger near the most exposed surfaces and consequently the crack grows faster on the sample edges and around the circumference and penetrates radially towards the mid-thickness at a slower rate. That is, the circumferential edge of the first thread corresponds

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[71] BSEE, *QC-FIT—Summary of Findings*, 2014, p. 11.

[72] Stress, *Metallurgical Failure Analysis—Final Report*, 2014, p. v.

[73] BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, 2016, p. 6.

[74] Stress, *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis*, 2013, p. v.

to higher values of $C_{H,diff}$, while the sample center in the radial direction would correspond to lower $C_{H,diff}$ values. Therefore, cathodic polarization may lead to greater hydrogen uptake at less occluded sites, and subsequent faster near surface cracking even though the stress intensity and hydrostatic stress may be lower at such locations.

However, the increased stress intensity at a deep radial crack tip and associated triaxial stress state there will eventually concentrate the hydrogen that is produced and absorbed there and at some point lead to a much higher local concentration at the surface than would be found throughout the material. Thus it is quite reasonable to expect the ring of intergranular fracture that was observed around the root of the thread, which in all cases was the primary location of the fracture. It is also reasonable to expect that some dominant radial cracks grow as indicated in Figure 2.4 growing radially from a limited number of circumferential cracks. The root of the thread would concentrate hydrogen in the material in that location, making it a preferred initiation site. In contrast, internal HE due to improper baking and resident internal hydrogen as a result of improper baking would not occur at the surface and spread circumferentially but occur at the peak stress under the notch. Moreover, calcareous deposits would not have been observed on cracks produced as a result of coatings and improper baking as this is an indicator of cathodic protection in seawater.

The immediate implication of this analysis is the *Discoverer India* bolts and Seadrill studs failure mechanism appears to have been misunderstood in the previous RCA efforts. The analysis suggest hydrogen-assisted SCC due to cathodic polarization occurred and the committee's analysis does not support an argument towards banding microstructure, a specific hardness value nor zinc plating/and baking status as the cause of HE.

The question that must be answered is why these few cluster failures occurred, and no others. Most fasteners used undersea have an anodic coating, and if they were the root cause, failures would be more prevalent. Unfortunately, because there is no regular inspection of bolts removed from service that have not failed, or monitoring for incipient cracks of bolts in service that have not failed, we are left with only the evidence of these few cluster failures. Something about their specific application caused the service cathodic polarization to enable fasteners to experience high hydrogen overpotentials and high enough stress states to enable HAC (i.e., brittle failure modes) and ultimately resulted in HAC of the bolts, whereas in most flange connections this mechanism does not appear. This analysis makes it more imperative that BSEE call for greater industry research as cited elsewhere in this report.

A related unresolved issue is the observation of clusters of bolt failures all located in one flange by HAC given a possibly random set of bolts with respect to heat or lot origin and a range of hardness levels and processing conditions. It should be mentioned that while the cluster of bolt failures all contained circumferential cracks that formed more or less over the same period of time, they may have followed some sequence where the rate of cracking varied over time for each fastener. Suppose that the first bolt to crack by HAC progressed to complete failure. This process would become evident in the fractography by ductile overload of a small remaining ligament of material near the center. When this is the case, it indicates that pre-load stresses in the bolt remained high enough during crack growth that the applied stress intensity reached fracture toughness in the material when the radial HE cracks were sufficiently long but before preload was bled off or lowered sufficiently to arrest the crack (crack growth relieves displacement controlled stresses).

The question then becomes how the failure of a single bolt changes the situation of remaining nearby bolts such that HE is more likely in these bolts. Cathodic protection and the environment would not change and neither did the anodic coatings. Metallurgy and hardness does change bolt to bolt, but not in a consistent pattern, and not in a pattern that seem to correlate with the failures. Preload does not transfer to adjacent bolts sufficient to cause ductile overload. Moreover, in the flanges associated with the failed bolts being evaluated, the combined effect of a correctly selected bolt preload of all the bolts should "insulate" the remaining bolts from the bulk of the operational load cycles with the failure of a single bolt, or perhaps two. However, with the loss of a few bolts, the operational bending loads on a bolted connection might now begin to exceed the effect of the remaining bolt preload, particularly for bolts immediately adjacent to those that have failed. While none of the failed bolts were reported to have exhibited any fatigue striations, the transfer of operational loading to the adjacent remaining bolts would lead to higher stresses and potentially accelerate the hydrogen cracking in those bolts in comparison to the other remaining bolts in the fixture further from the zone of failed bolts. As the following example illustrates, this mechanism would explain why all the failure WC studs were on one side of the connector and the absence of ductile overload or fatigue.

It should be noted from Figure 2.5 and literature that HAC is very sensitive to small changes in stress intensity, applied especially during what is known as stage I cracking. In this regime, crack velocity is affected significantly by small changes in stress intensity factor (SIF) and could essentially turn on or off, or significantly change the crack velocity. For instance, a change in bolt stress from just 60 percent of yield strength to 75 percent of yield strength for a fixed crack length can change the applied SIF by up to 5 MPa $(m)^{1/2}$ which could enable the threshold stress intensity for HEC growth to be reached or exceeded and for the crack growth rate to increase by an order of magnitude or more. This situation would enable HEC in adjacent bolts but critically would never raise the applied SIF enough to induce ductile overload in a pristine hydrogen free fastener. This is consistent with the absence of ductile overload failure or fatigue on regions of the failed surface beneath intergranular cracks.

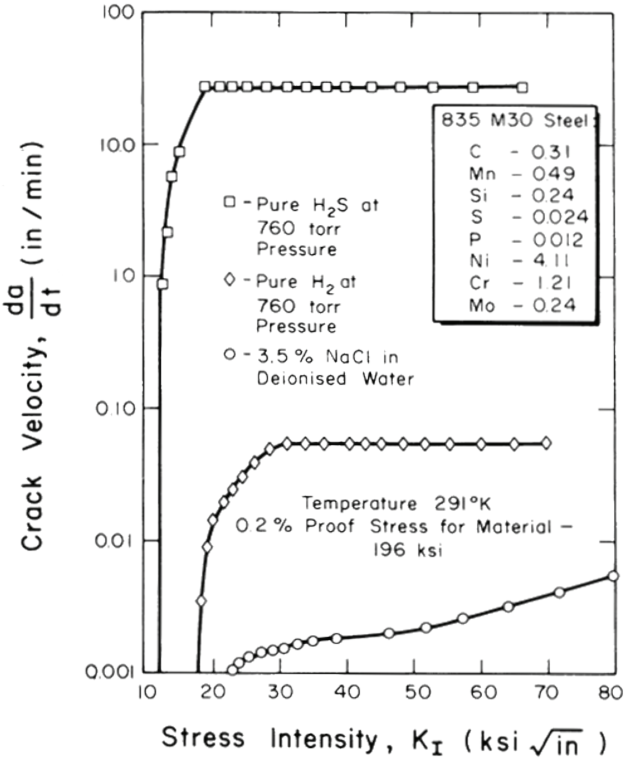

FIGURE 2.5 The stress intensity dependence of subcritical crack growth rate produced in a tempered martensitic steel exposed in three separate environments that produce atomic hydrogen at the crack tip during stressing under slow rising crack mouth opening displacement (CMOD). SOURCE: G.E. Kerns, M.T. Wang, and R.W. Staehle, "Stress Corrosion Cracking and Hydrogen Embrittlement in High Strength Steels," pp. 700-735 in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys* (R.W. Staehle, ed.), NACE International, Houston, Tex., 1973. © NACE International 2012.

The committee is aware of other bolting failures in flanged connectors exhibiting the "cluster" phenomenon. But for various reasons, detailed information on these particular failures is not publicly available and cannot be explicitly identified in this report. The application conditions differed from those considered in this report—the flange had a large internal pressure load and few bolts, while the drilling riser system has no pressure and many bolts. Interestingly for these particular cases, the root cause of the bolt failures was determined to be HAC. Bolts failed on several flanges over a period of time.[75] Some flanges, but not all, exhibited cluster failures. Loading of the flanges was not uniform along the structure, and loads on the flanges was

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[75] The committee was not able to gain any information on the exact timing of bolt failures.

believed to be relatively low. While the preload torque on bolts may not have been carefully documented or tracked, bolt preload was believed not to be a contributor to the bolt failures. If bolt preload tension was excessive, then bolts would have failed almost immediately. Rather, it appears that bolt failures occurred well after preloading during flange assembly. Bolt failure clusters are believed to have occurred in flanged connections which were loaded nonuniformly around the circumference of the flange. Some bolts may have had higher tensile loading than others, such as would be the case with bending loads. The sensitivity to the bolts to HAC resulted in initiation of brittle failure of a single bolt at a relatively low tension stress, and then the load transfer of service load to neighboring bolts could result in accelerated HAC failure of that neighboring bolt, and so on. It should be noted that the sensitivity of

BOX 2.1
The San Francisco Oakland Bay Bridge

In 2013, the San Francisco Oakland Bay Bridge (SOBB) experienced hydrogen embrittlement (HE) failure of some steel "anchor" rods during bridge construction. The "Pier E2 rods" were 3-4 in. in diameter (76-102 mm) steel components that provided a clamping friction between the bridge deck and bridge pier structures. They were designed to prevent lateral displacements such as during seismic events. The rods were constructed from ASTM A354 Grade BD steel (HRC 31-38 allowed range) which was coated with a sacrificial metallic coating by a hot dip galvanizing process prior to installation. These rods failed by a brittle fracture mode when loaded after exposure to the outdoor elements such as rain and a marine atmosphere for a period of time. Rods tested in air after processing did not fail. Hydrogen production and entry was enabled when water collected in the rod pipe sleeves which were not grouted and sealed prior to tensioning. These sites allowed water collection and the hot dip galvanizing provide the electrochemical cell that produced a high hydrogen overpotential on the steel. The failures occurred over a period of time after the tie rods were loaded to design loads in tension by tightening to 70 percent of their minimum tensile strength. 32 of the 96 rods failed within 14 days of load application. The failure was interpreted to be due to external HE, which was well supported by a number of factors including brittle fracture appearance, delay time from load application until cracking and failure, high material hardness albeit within the ASTM A354 specification, a source capable of enabling significant levels of hydrogen production (i.e., a hot dip galvanized sacrificial anodic coating, which enable hydrogen production from the reduction of water when galvanically coupled to steel), time for entry and diffusion of hydrogen to the fracture process zone at the root of threads, elevated applied stresses from loading, and, consequently, high tri-axial tensile stresses at thread roots. Thus, all three of the common factors required for HE were present: a detrimental stress (i.e., high-stress intensity at threads when loaded), a detrimental "environment" because of the chemical and electrochemical conditions (i.e., hot dip galvanizing as well as environment hydrogen production), and "material susceptibility" brought about by presence of a detrimental metallurgical condition when combined with hydrogen concentrations above a critical threshold (i.e., susceptible interfaces and hydrogen traps). Lastly, time was available as well for hydrogen ingress and accumulation.

It was interpreted that this set of Pier E2 rods were stressed above their HE threshold and failed by delayed fracture when stress to 70 percent of the minimum tensile strength over a the bolts to HAC may result in brittle fracture at low tensile loads, virtually always at the first exposed thread root. That is, the bolt stresses due to bending or tensile loads did not need to be large to cause HAC brittle fracture. The relatively low threshold stress intensity for HAC in these steels at finite diffusible hydrogen concentrations enable by cathodic protection makes this scenario possible. Gross overload leading to ductile fracture over the entire bolt cross sections was not observed.

Therefore, even though cluster failures are rare events, the potential consequence is very significant, and the root cause of this type of failure should be determined so that mitigating actions can be instituted.

Note that the committee choose to standardize the language in this report to HAC. However, this term is not meant to imply that existing cracking must be

period of time due to external HE. The specific batch of materials used in rods which failed is believed to have a reduced starting fracture toughness and ductility due to a more susceptible microstructure as result of processing and fabrication methods. As such, these fasteners should not have been galvanized and exposed to water in this condition. Other rods and fasteners were judged to be loaded below their external HE threshold owing to both lower applied loads and greater thresholds.

The SFOBB scenario has several similarities and many distinct differences with oil and gas fasteners subjected to marine exposure.

The similarities to oil and gas fasteners are that the three commonly held requirements for HE were present in both cases, albeit brought about in different ways. Regarding susceptible materials—in both cases the ferrous alloy used are in a microstructural condition required to produce the strength desired and are, consequently, relatively susceptible to HE already in a classic material science trade off. Moreover, this susceptibility is furthermore very sensitive to material and component specific processing details. A design challenge in both applications is the need for high strength (which makes a steel relatively more susceptible to HE), the lack of intrinsic corrosion resistance in high-strength steels (necessitating zinc sacrificial coatings or some other means of cathodic protection) and design considerations as well as physical circumstances which lead to or avoid a high state of stress. In both cases, the level of applied stress can be an issue. In other bridges and other rods on the SFOBB, one major difference was implementation of a much lower fastening load with ASTM A354BD grade rods. The fastener was coated with a hot-dip galvanized sacrificial coating in the SFOBB case and often some zinc-rich is also often used in the case in oil and gas; however, is not always the case. Failures are in both cases attributed to external HE. Internal HE due to hydrogen introduced during processing and remaining after baking is in general regarded as being insignificant or secondary. In both cases a myriad or details and interdependencies (a higher strength and hardness creates more susceptibility conditions where a lower hydrogen concentration to reach the embrittlement threshold is typically seen) confound the ability to identify a single factor controlling failure. Finally, the use of standards comes into play in both applications where failure of rods within specification is an issue. Moreover, in both cases standard revision may be part of any discussion on prevention.

SOURCE: *San Francisco Oakland Bay Bridge Self-Anchored Suspension Bridge: Evaluation of the ASTM A354 Grade BD Rods*, September 30, 2014, http://baybridgeinfo.org/sites/default/files/pdf/SFOBB-SAS%20Evaluation%20of%20the%20A354BD%20Rods%20Final%20Report.pdf.

present to be enhanced by the uptake of hydrogen. Other terms used by different authors to describe the phenomenon include HE, hydrogen environment-assisted cracking (HEAC), hydrogen-enhanced cracking (HEC), hydrogen-induced cracking (HIC), hydrogen-enhanced decohesion (HEDE), and hydrogen-enhanced local plasticity (HELP).

OPTIONS FOR IMPROVING THE SELECTION OF BOLTING MATERIAL PROPERTIES

Currently material specifications for steels and CRAs used in the manufacture of threaded connectors are primarily detailed in the relevant API specifications (e.g., 20E or 20F). The specified properties of interest are composition and mechanical properties (as per the relevant ASTM standard), processing history (to include melt practice and hot rolling details), casting history (continuous or ingot cast), inclusion content, grain size, degree of banding and microstructure. The only assessment of mechanical properties in the final heat-treated parts explicitly required in API Specs 20E and 20F is hardness. However, API Specs 20E and 20F incorporate by reference ASTM Specs A193, A194, A320, A453, and A540, which require additional mechanical testing. It is important that connector meet these normative ASTM specifications for the following reasons. Steels with the same hardness often exhibit microstructure-dependent yielding and strain hardening behaviors (as evidenced by the shapes of tensile stress-strain curves) that differ from traditional martensitic quenched and tempered steels. With the identification of alloys and microstructures which exhibit improved resistance to failure by HAC in comparison to currently available quenched and tempered martensitic steels or thermally processed (e.g., precipitation hardened) CRAs, more extensive quantification of mechanical properties via complete stress-strain curves and fracture toughness data will be required. One option will be to modify the standards to expand the specifications on mechanical properties, to include yield strengths, ductility, and ultimate tensile strengths. In addition, fracture testing by Charpy impact tests or fracture toughness tests with crack planes oriented to mirror observed fracture planes in threaded connectors also will provide essential information to further characterize and identify mechanical properties to guide material selection.

In addition to improved cleanliness brought about by modern steel making processes, multiple alloying and processing approaches are currently under investigation to produce steels with improved resistance to HAC. As summarized in Chapter 5, strategies employed in ongoing studies include alloy designs to resist hydrogen production and uptake, development of microstructures with constituents such as vanadium carbides which act as traps to sequester hydrogen away from fracture sites, and development of microstructures with inherently higher resistance to fracture. Approaches to the latter strategy include the use of interface or grain boundary engineering, such as achieved by adding specific elements (e.g., rare earth elements) to control segregation of specific alloying elements (e.g., sulfur) often found on hydrogen-embrittled fracture surfaces. Assessments of potential new steels with improved resistance to HAC are also being aided by rapid advances in computational tools available to the alloy designer.

As the critical failures observed to date have been associated with environmentally assisted cracking (primarily identified as hydrogen embrittlement), incorporation of standard laboratory test methods to assess the susceptibility of candidate steels to hydrogen embrittlement and/or stress corrosion cracking should be required and the results would provide additional criteria for incorporation in standards for material selection and manufacture. It is recognized that several laboratory test methods currently exist[76,77,78] to assess the relative susceptibility of HAC of different materials. However, these existing tests do not provide information on lifetimes under service loads/environments or establish windows of susceptibility using these methods alone. Thus one option will also be to establish a program to develop such a standard applicable to connector materials for offshore applications. It is also important to note that susceptibility is environment specific and standards developed for one set of environmental conditions—for example, sour service may not be directly applicable to seawater environments.[79]

Paralleling the option to consider new materials, coatings designed to mitigate the susceptibility of manufactured connectors to HAC, particularly when installed where active impressed current corrosion protection systems are operative, need to be assessed and potentially incorporated in standard modifications. Also, bolt designs as currently specified utilize standard well-accepted thread designs applicable to most all industries. To date, assessment of the selected thread design for offshore applications to ensure that the design exhibits the maximum resistance to environmentally assisted fracture has not been undertaken. Since the bolt design (including the tread geometry) is a "critical parameter," systematic studies to assess effect of bolt design on HAC susceptibility would also be required for the various

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[76] ASTM International, *Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials*, ASTM E1681-03, West Conshohocken, Pa., 2013.

[77] ASTM International, *Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique*, ASTM F1624-12, West Conshohocken, Pa., 2012.

[78] ASTM International, *Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking*, ASTM G129-00, West Conshohocken, Pa., 2013.

[79] NACE MR0175 gives requirements and recommendations for H2S containing environments and does not cover subsea applications. See NACE International, NACE Standard ANSI/NACE MR0175/ISO 15156, 2015, https://store.nace.org/ansi-nace-mr0175-iso-15156-2.

candidate materials identified in this option. For the additional property data, coatings, and bolt designs identified in this option, specific acceptable property levels would need to be identified to be incorporated in the standards. These property levels should include data in air and in an appropriate controlled environment to assess susceptibility to environmentally assisted cracking.

SUMMARY AND RECOMMENDATIONS

The design of a subsea drilling system and, its components, is a challenging engineering task requiring numerous technical disciplines at multiple companies. The bolted flange connectors within the subsea system are deceptively simple pieces of equipment. But because of the varied and dynamic forces acting on a bolted flange connector in subsea drilling applications, the design of a flange connector is complex. Of particular importance are the assumptions related to the operating environment, installation, operation, and maintenance practices that occur in shops and on rigs that affect the loads on the riser/BOP system. The challenge for the design engineer is to integrate the various levels of uncertainty to arrive at the appropriately conservative design for each mechanically fastened connection, and then for each individual fastener/bolt. Because bolts are subject to multiple time-dependent failure modes in addition to mechanical overloads, all potential failure modes must be identified and the risks must be mitigated during the design process.

Out of all this complexity, there are a few conclusions the committee has made: (1) The environment in which these subsea connectors operate (salinity, temperature, pressure, water chemistry, cathodic protection) is a design variable over which the design engineers have no control; (2) there are certainly urgent changes that should be made regarding the highly loaded bolts on subsea systems, however there are also innovation opportunities to reduce the high stress loading on these bolts and threads that should be undertaken; (3) the documented failures appear to be caused by environmentally assisted intergranular brittle failure of bolting in flanged connections, plus a few cases of what appeared to be ductile overload failures on the blind shear ram actuator housing; and (4) the most likely and immediate means of mitigating bolt failures lies in material science, material specifications, and quality control.

Finding: Oil and gas industry specifications and practice use torque as the value to be measured in tightening flange bolts. Torqueing, as currently specified in the oil and gas industry, is an inaccurate method of preloading flange bolts.

Finding: As operations have moved deeper offshore and bolts experience more demanding service, the use of torque as a bolt/stud/nut tightening criteria to establish a connector tensile preload has outlived its usefulness. There is sufficient evidence that the practice of demanding increasingly accurate bolt torqueing equipment is non-optimal. Furthermore, it carries the risk of believing that the accuracy of torqueing reflects the accuracy of the desired design parameter-bolt preloading.

Option 2.1: BSEE could convene an industry study group to investigate flange bolt design and installation standards. Options which could be considered include:

- Put a hold on requirements for industry to use more accurate torqueing equipment.
- API Spec 17D could be revised to "require" rather than "recommend" that bolts be accurately preloaded.
- Eliminate the term "torque" as torque has been determined to be inherently inaccurate. Suggest the use of a more accurate bolt pre-tensioning method for critical flange bolt preloading on all new equipment fabrication and at five yearly inspections. (Appendix J lists some alternative bolt pre-tensioning methods.)
- Consider commissioning engineering design studies to determine realistic tension loading safety margins for flange bolts. Such a study could initially concentrate on the preload variability that results from torqueing, however assessments of operational loading uncertainty and in-service material degradation could also be considered.
- Consider commissioning a study to evaluate the impact of a single bolt failure on overall connector reliability. This study could cover a range of flange sizes (i.e., number of flange bolts).
- Consider new and revised specifications, standards and recommended practices to be incorporated into Code of Federal Regulations (CFR) 30 section 250 based on proactive assessment of risk areas.

Finding: Current specifications for offshore fastener steels prohibit the use of continuous cast products, primarily because the existence of banding has been observed in steels which also failed in service by hydrogen embrittlement. However, as a result of recent advances in steel making casting technologies, significant advances in product quality have been realized.

Finding: A recent root cause analysis of bolt failures showed no direct relationship between crack initiation or growth by HAC and the presence of banding.[80]

> **Option 2.2:** BSEE could request an industry-led consortium with academic participants to initiate systematic studies to investigate and evaluate the environmentally assisted cracking/hydrogen embrittlement susceptibility of continuous cast and ingot cast steels. The results on continuous cast steels could also include "modern" product produced in newer facilities and characterized with non-destructive testing techniques to assess soundness. The consortium could also evaluate alternate steel alloys and processing histories leading to improved in-service performance. The prohibition of banding to maintain product quality for subsea bolting could also be reviewed.

Finding: Instances of "plastic deformation" and incipient HAC damage can go unnoticed by visual inspections of unbroken fasteners; such fasteners would be categorized as "failed" if properly identified and would not be re-used.

> **Option 2.3:** Under the oversight of BSEE, the industry could collect data on the service conditions and performance of bolting in all critical riser/BOP applications for every deepwater drilling operation. This would include subjecting all fasteners, failed and un-failed, in these critical applications to a thorough post-operational inspection—requiring a full dimensional check and metallurgic post-mortem, with root-cause analysis being performed when the equipment did not perform according to design.

Finding: BSEE currently requires a visual inspection by ROV of a drilling riser and BOP every 3 days.[81]

Finding: BOPs are either sent to shore every 5 years for recertification or they are part of a Continuous Certification Program (CCP) in which the BOP Stack is inspected, maintained, tested, and certified by the OEM onboard the vessel/rig on a set frequency/schedule, thus eliminating the need to send it to shore every 5 years for recertification. Each OEM recommends an inspection program to the

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[80] Stress, *Metallurgical Failure Analysis—Final Report*, 2014.

[81] 30 CFR Chapter II, §250.739(c).

drilling contractor. All bolts are likely to be removed and visually inspected for flaws. During this inspection there is no requirement to perform NDT on bolts, studs, and nuts; nor is there a requirement to replace bolts, studs, and nuts that pass visual inspection.

Option 2.4: The oil and gas industry could pursue technologies that offer more effective NDT inspection of bolts in-situ, on the deck, and in the shop. Employment of these technologies could be made mandatory by BSEE as they have been qualified in other industries.

Option 2.5: BSEE could establish inspection requirements for un-failed bolts during the five-year shop inspection, or could require that all critical bolts be replaced during this inspection. BSEE should also establish / require serial numbers on all critical bolts so that inspections of any specific bolt could be documented and catalogued. The results from inspections should be reported as determined by mutual agreement between BSEE and the organization performing the five-year shop inspection.

Finding: There are several API documents that provide excellent techniques and guidance on various aspects of marine riser design, operations, inspection, and riser. These are:

- API Spec 16F, “Specification for Marine Drilling Riser Equipment”
- API RP 17G, “Recommended Practice for Completion/Worker Risers”
- API RP 16Q, “Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems”

In particular, API RP 16Q, Chapter 6 (Riser Operations) and Chapter 7 ((Riser Integrity) provide excellent guidance relevant to bolt integrity.[82]

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[82] API, *Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems*, API RP 16Q, Washington, D.C., Chapters 6 and 7.

Option 2.6: BSEE could take steps to incorporate the following API specifications and recommended practices, (in total or in part) into CFR 30 section 250 by reference to ensure that the best known maintenance practices are instituted:

- API Spec 16F, "Specification for Marine Drilling Riser Equipment"
- API RP 17G, "Recommended Practice for Completion/Worker Risers"
- API RP 16Q, "Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems"

Finding: Hydrogen is produced during corrosion and its generation does not necessarily require the presence of cathodic protection (CP) currents. However, CP increases the rate of hydrogen production by increasing the reduction reaction on the metal surface and, therefore is a focus of this discussion. There is a range of complicating factors that affect the electrode potential on the metal surface and, thereby, affect the rate of hydrogen production.[83]

Finding: The U.S. Navy and the French Navy have begun to utilize "low voltage" aluminum anodes to decrease anodic voltage, thus reducing the risk of HAC of their high-strength alloys.

Recommendation 2.7: The oil and gas industry should establish a comprehensive methodology and or program to optimize the cathodic protection (CP) practice for critical assets containing fastener metallic materials. For current structures, CP monitoring and assessment practice should be instituted. As new structures are designed, the industry should establish CP design requirements optimized for materials in use, based on electrochemical fundamentals. This project should evaluate the use of "low voltage" aluminum anodes currently being used by the U.S. Navy and the French Navy to reduce the risk of hydrogen-assisted cracking of their high-strength alloys.

Finding: Hydrogen uptake and the diffusible hydrogen concentration follows a relationship where hydrogen concentration is proportional to the cathodic current density raised to some power—such as the one-half power.[84] But hydrogen

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[83] Hydrogen is produced during corrosion and its generation does not necessarily require the presence of cathodic protection (CP) currents.

[84] D. Li, R.P. Gangloff, and J.R. Scully, Hydrogen trap states in ultrahigh-strength AERMET 100 steel, *Metallurgical and Materials Transactions A* 35(3):849-864, 2004.

concentration can be affected by parameters that influence the atomic hydrogen concentration on the metal surface, such as sulfides. It is known that sulfides poison the combination reaction of atomic hydrogen to hydrogen gas, thereby increasing the atomic hydrogen concentration of the metal surface and increasing the hydrogen uptake into the metal.

Recommendation 2.8:

- **The industry should review the usage of materials (e.g., lubricants containing sulfides) in contact with fasteners that are known to poison the chemical reaction of atomic hydrogen converting to molecular hydrogen (hydrogen gas), and identify substitute materials so that the concentration of atomic hydrogen at the metal surface is reduced.**
- **BSEE could consider immediately prohibiting the use of sulfide-containing lubricants until such a study indicated that they can be used without enabling hydrogen uptake.**

Finding: Cluster failures involve the failure of multiple bolts in a single undersea flanged connector. Three rigs experienced cluster failure of H4 bolts, of common heritage, that secure the lower marine riser package (LMRP) from the blowout preventer (BOP) stack. Subsequently, nine fractured studs were found on another rig. These studs exhibited virtually the same failure mode and features observed in the three previous cluster failures while possessing NONE of the attributes that were supposedly the cause of the earlier failures; that is, had very different hardness, heat treating, and ingot creation.

Option 2.9: The committee suggests that cluster failures be investigated by BSEE in large-scale fully instrumented flange test rig that simulates subsea conditions on fasteners in bolted joints including structural loads, environmental conditions, and cathodic polarization cathodic polarization. This equipment set-up could be used to reproduce cluster failures under various conditions. These investigations are necessary to definitively establish the origins of these cluster failures and to prove the effectiveness of mitigation strategies.

Finding: Many of the critical failures observed to date have been associated with environmentally assisted cracking (primarily identified as hydrogen embrittlement). Standard laboratory test methods to assess the susceptibility of candidate steels to hydrogen embrittlement and/or stress corrosion cracking are not adequate to determine the likelihood of HAC in the off shore environment.

Finding: There is not an accepted laboratory standard test method within the industry to assess the susceptibility HAC for bolting materials used in offshore applications.[85,86]

Recommendation 2.10: The oil and gas industry should establish through adequate research an accepted laboratory standard test method to assess the susceptibility to hydrogen assisted cracking of bolting materials and their coatings used in offshore applications.

Finding: Bolt designs, as currently specified in the oil and gas industry, utilize standard well-accepted thread designs. These thread designs can result in extremely high stress concentrations at the thread roots—especially on the first thread root. Other industries have utilized innovative designs to alleviate this problem.

Finding: Threads are generated by either machining or rolling. To date, assessment of the selected thread design and method of manufacture used for offshore applications to ensure that the design exhibits the maximum resistance to environmentally assisted fracture has not been undertaken.

Recommendation 2.11: The oil and gas industry should:

- **Assess various thread designs and manufacturing methods for maximum resistance to environmentally assisted fracture.**
- **Conduct systematic studies to assess effect of bolt designs (including the tread geometry) on hydrogen assisted cracking susceptibility.**
- **Pursue research into thread designs which could reduce the stress concentration in bolt threads.**

Recommendation 2.12: The oil and gas industry should review the standards relating to bolt tensioning, both in terms of loading as a percent of yield strength and in terms of preloading technique, to minimize the probability for under- or over-tensioning bolts operating in subsea environments.

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[85] General guidelines can be found in ISO 7539 Part 11 (Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking) at https://www.iso.org/standard/43440.html, accessed January 2, 2018.

[86] For example, NACE MRO175 does not cover subsea applications. See NACE International, NACE Standard ANSI/NACE MR0175/ISO 15156, 2015, https://store.nace.org/ansi-nace-mr0175-iso-15156-2.

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Options for Improving Bolting Reliability

There is a keen interest in improving the reliability of offshore equipment and structures and in reducing the risk of damage to the environment to as close zero as possible. With many disparate views on the preferred approach, there should be a forum by which all stakeholders have an opportunity to contribute their ideas and have them adequately investigated to enhance the development of offshore resources. Traditionally in engineering design, materials selection, manufacturing, installation and operation, this has been accomplished through the development and use of standards and specifications.

Indeed, the inscription in the lobby of the National Institute of Science and Technology (NIST) main administration building (Building 101) (formerly the National Bureau of Standards) in Gaithersburg, Maryland, graphically makes the case for the importance of standards to modern society: "It is therefore the unanimous opinion of your committee that no more essential aid could be given to manufacturing, commerce, the makers of scientific apparatus, the scientific work of the government, of schools, colleges, and universities than by the establishment of the institution proposed in this bill."[1]

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[1] Report on the bill to establish the National Bureau of Standards, House of Representatives, HR1452, 56th Congress, 1st Session, May 14, 1900 (U.S. House Reports, Serial 4026, Volume 6, 1899-1900).

SPECIFICATIONS AND STANDARDS

A complex challenge in improving the reliability of bolted connections in the oil and gas industry is the multitude of specifications and standards that currently exist that can be read to apply to one or more elements of these connections in some manner. One bolt manufacturer reported that their library contains approximately 1,000 specifications and standards that address various aspects of bolt design and bolt manufacture. This includes more than 500 specifications and standards of trade organizations (American Section of the International Association for Testing Materials [ASTM], American Petroleum Institute [API], American Society of Mechanical Engineers, American Society for Nondestructive Testing, etc.), plus well over 500 customer-specific standards.[2] Appendix H contains a summary and brief explanation of the most commonly used bolting regulations and standards, including the pertinent federal regulations; industry standards, specifications, and recommended practices from API and ASTM; NACE Materials Requirements; NORSOK materials standard; and API flange bolt design specifications.

This multitude of requirements, many of which are overlapping, contradictory or lack consistency, is an unnecessary burden on the industry, and counterproductive to safety. Design engineers with the major oil companies and original equipment manufacturers (OEMs), along with their sourcing experts, can readily manage this multitude of standards and specifications. But within the lower vendor tiers, this multiplicity, overlap, and contradictory standards and specifications can lead to confusion and application of the wrong standard or specification. Therefore, there is a need for leadership in consolidating standards, using a balanced group of subject matter experts from industry, government, and trade organizations to provide uniformity and simplicity the supply chain. For instance, the process used to produce the 2nd Edition (issued February 1, 2017) of API SPEC 20E, "Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries," appears to be a step in the right direction since there was wide participation in its development, and the standard is written in clear, unambiguous language.

In addition to the multiplicity of standards previous mentioned, the bolting industry itself has a multitude of proprietary internal standards that do not foster cooperation and shared expertise across the industry.

Development of specifications and standards should be based on science and be informed by history, shared data and experience. There are numerous industries and organizations that have developed effective means of collating this information into specifications and standards. Discussion later in this chapter describes specific examples from the Aviation Industry and the U.S. Navy, but others can be found

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[2] Personal communication, Tom Goin, president U.S. Bolt Manufacturing, Inc., August 15, 2017.

in diverse industries such as the nuclear power industry,[3] construction industry, automotive industry, communications industry, food industry and the pressure vessel industry. The USS *Thresher* disaster was a wake-up call for the U.S. Navy to develop a preeminent safety culture in submarine design and construction, and the Northridge earthquake was a wake-up call for the construction industry to include greater attention to seismic design. Similarly the Deepwater Horizon incident must continue its progress as a wake-up call for the further improvement of specifications and standards in the offshore oil and gas industry.

An overly prescriptive regulatory environment can have a suffocating effect on new technological developments and applications. The preferred alternative is a move toward a performance or goal-oriented regulatory system such as is practiced by Norway and the United Kingdom. The authoring committee for the National Academy of Engineering/National Research Council report *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety* also believed in the advantages of goal-oriented regulations. Contained in their report is Summary Recommendation 6.1 "The United States should fully implement a hybrid regulatory system that incorporates a limited number of prescriptive elements into a proactive, goal-oriented risk management system for health, safety, and the environment."[4] This regulatory system will prevent any firm from gaining a competitive cost advantage through cutting corners on safety, by forcing everyone to bear the associated cost increases of safety measures as a part of doing business.

A National Academies of Sciences, Engineering, and Medicine committee recently assessed various considerations for designing a safety regulatory approach for high-hazard industries. Its report, as two of its case studies, examined the offshore regulatory regime in the United States.[5] Among other findings, it states,

> While BSEE has relied increasingly on regulations that require management programs to fill gaps in its regulatory content and coverage, the regulatory regime within which offshore oil and gas development takes place remains one that is oriented toward micro-level, technical regulations. Keeping these regulations current and compatible with advances in practice and technology is a continuing challenge, especially as more advanced drilling and

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[3] Some sense of the regulations can be found in Regulatory Guide 1.65, "Materials and Inspection for Reactor Vessel Closure Studs" and references therein. Some indication of issue resolution in this context can be found in R.E. Johnson, *Resolution of Generic Safety Issue 29: Bolting Degradation or Failure in Nuclear Power Plants*, NUREG-1339, U.S. Nuclear Regulatory Commission, Washington, D.C., 1990.

[4] National Academy of Engineering and National Research Council, *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*, The National Academies Press, Washington, D.C., 2012.

[5] National Academies of Sciences, Engineering, and Medicine, *Designing Safety Regulations for High-Hazard Industries*, Transportation Research Board, Special Report 324, 2018, The National Academies Press, Washington, D.C., doi:10.17226/24907.

> production systems allow for the development of deepwater fields. Because the regulations incorporate many consensus standards by reference, BSEE staff must have subject matter experts who can participate on API standards committees addressing offshore matters.[6]

Outside of standards committees themselves, there is no well-defined, proactive process for proposing areas/topics to develop new standards or improve current standards for other stakeholders, such as regulators and academia.

Standards will not totally solve the fastener reliability concerns, as these standards cannot mandate judgment and insight, and do not address the enforcement process. In some instances safety critical standards are not incorporated into current federal regulations—for example, Part 250 of the U.S. Code, and as a result are not directly enforceable. Additionally, regulations are only enforced at the operator level of the oil and gas industry and thus do not directly impact the complex tiers of vendor systems of manufacturing and operation. Unless incorporated into the Code of Federal Regulations (CFR), the industry standards do not have force of law. Industry will take an active interest in development of safety standards if it is understood that these standards will be incorporated in the CFR. Standards drafted by industry stakeholders alone, creates an incentive to withhold industry expertise to maintain a competitive advantage. Safety critical standards must be owned or monitored by an independent stakeholder that is charged with responsibility for safety and reliability.

BSEE reported to the committee that they were sponsoring a project through Argonne National Laboratory (ANL) that had the goal of evaluating fastener standards used by the oil and gas, refining, aerospace, aviation, nuclear, military, naval, and automotive industries to identify differences in manufacturing, material property requirements, and cathodic protection systems between these documents and provide recommendations on harmonizing the information into a consistent set of material property and manufacturing requirements for subsea application.[7] ANL is also tasked to make recommendations to BSEE on how to proceed to oversee use of these fasteners on the OCS. Presumably this report will be publicly available when completed.

QUALITY ASSURANCE OPTIONS

Quality assurance (QA) is the process by which industries verify that a product conforms to specifications and avoids mistakes and defects. Quality control (QC)

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[6] Ibid., p. 68.

[7] Bureau of Safety and Environmental Enforcement (BSEE) presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 10-11, 2017. Note: The contract was originally with Lawrence Berkeley National Laboratory, but at some point during 2017, the contract shifted over to Argonne National Laboratory.

pertains to insuring the product fulfills its quality requirements.[8] The fastener manufacturing industry for oil and gas typically uses API Specification Q1 or ISO 9001 for quality management. These standards cover areas such contract review, design controls, management process, documentation, and inspection. The overall objective is to ensure that critical components are fit for service. Unfortunately all quality control can do is reduce the probability of a substandard manufactured part to an acceptable level. No part of a quality control process addresses the correctness of the design specification for the component. In the case of fasteners, the QC process would establish checks aimed to ensure that each step in the bolt manufacturing process from original casting to thread cutting or rolling meets specifications and purchase requirements.

Managing the supply chain is a difficult endeavor. There are many tiers of subcontracted suppliers that continually change due to costs and schedule demands. QA/QC issues have been cited as a contributory cause by even RCA provided to the committee.[9] Typically, there is a QA/QC specific team within each organization, and the final buyer has oversight of the entire supply chain. It should be incumbent on operating companies to ensure there are no lower tier supply chain issues and critical components are fit for service, and incumbent on the buyer to ensure that the parts purchased have the correct and verifiable pedigree.

Safety critical components require a more in-depth approach to QA/QC and the enforcement of material specifications than is typically required for common components. The U.S. Nuclear Regulatory Agency addresses some of these issues in their QA regulation which holds all levels of the supply chain to the same standard.[10] Equipment manufacturers often opt to have an in-depth internal process for qualifying a vendor and ensuring that those vendors maintain qualification.[11] These checks take the form of an initial audit of their quality management system and a full vetting of the product by the buyer's engineering team. This process should involve analysis of the variability in outcomes of the manufacturing process and a determination that variability is within overall acceptable tolerances. Firms at all

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[8] Note that *quality control* is reactive in nature and is used to identify and respond to nonconformities. *Quality assurance* is proactive in its approach to quality planning and instituting system improvements to prevent defects and maintain reliability while maintaining after-the-fact quality control and audit functions.

[9] BSEE, "QC-FIT Connector and Bolts Failure," https://www.bsee.gov/what-we-do/regulatory-safety-programs/systems-reliability-section/findings-recommendations. See, for example, BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, Washington, D.C., February 2016, https://www.bsee.gov/sites/bsee_prod.opengov.ibmcloud.com/files/memos/public-engagement/qc-fit-bp-bolts-report-final.pdf.

[10] U.S. Nuclear Regulatory Commission, "Appendix B to Part 50: Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," NRC 10 CFR, last reviewed/updated August 29, 2017.

[11] One example was presented during the committee visit to Schlumberger visit on March 23, 2017.

levels of the supply chain should be periodically audited to ensure that quality is maintained, which does not appear to be currently the practice.

Quality issues arise for the following reasons:

- While subject matter experts are often involved in initial vetting of suppliers, they are not directly involved in ongoing maintenance of the QA program. Subject matter experts should be involved in audits and inspections.
- Small QA inspections sample sizes can result in a statistically unacceptably large possibility of critical component failures. The level of acceptable risk of a component not meeting specifications should determine the frequency and scope of inspections. A similar logic should determine if quality standards are sufficient or if there should be increased oversight to reduce risk.
- Clear, traceable documentation of all steps is required. Relying on undocumented individual expertise that makes continuity and reproducibility in the process difficult to maintain, particularly when there is a change in lower tier vendors
- The entire fastener process from manufacturing through installation and maintenance should be subjected to audits for quality. The organizations performing audits must be free from external influence.

The multiple layers of QA inherent in the procurement and manufacture of bolts for critical service is an organizational challenge for the oil & gas industry. This is evidenced in the past by substandard bolts finding their way into critical service in deepwater drilling equipment.

REGULATORY EXAMPLES FROM OTHER INDUSTRIES

Across industries, engineering best practices and regulations are often identified because of significant critical failures. While this process is inherently reactionary, it has a proven track record of preventing failures similar to past failures, but naturally falls short at preventing other "new" failure types. Failure events also provide an opportunity to determine the gaps and limitations in the overall approach to safety and reliability that extends beyond the cause of the failure event.

This section presents lessons learned by the Federal Aviation Administration (FAA) and the U.S. Navy and how regulatory practices were changed in response to low-probability, high-consequence events. Both the FAA Aviation Safety organization and U.S. Navy SUBSAFE regulatory approaches, and their governing authorities, have elements that BSEE could tailor for their field of interest. These focus on the core areas of empowered centralized engineering oversight of critical areas, industry-wide engineering to identify risk reduction solutions, and promulgate institutional culture to reduce risk. In some cases, to ensure the newly identified best practices were implemented throughout the industry, additional statutory authority may be necessary and would have to be pursued.

Federal Aviation Administration

The FAA, U.S. Department of Transportation, has the mission to provide the safest, most efficient aerospace system in the world.[12] The FAA was established in 1958, by the Federal Aviation Act, after aviation safety's wake up call, the DC-7/F100 collision near Las Vegas, Nevada, which transferred functions from the Civil Aeronautics Authority to provide a focus on civil aviation safety.[13]

The FAA, working with the aerospace industry and its supply chain and the airline operators, including flight crews, have dramatically improved flight safety. American commercial aviation has become the safest travel mode. Scheduled airlines operate under the stringent rules of Federal Aviation Regulation (FAR) Part 121. The last fatal accident involving a scheduled U.S. airline was in 2009. In 2015, U.S. airlines flew 7.6 billion miles on airplanes with 10 or more seats. Even thought there were no fatalities, there were close calls and accidents. The accident rate was low: 0.155 per 100,000 aircraft flight hours. That's down by half from 2004, when there were 0.302 accidents per 100,000 flight hours. In 1960, at the beginning of the jet age, U.S.-certificated air carriers had 7.9 accidents per 100 million aircraft miles flown.[14]

The FAA's Aviation Safety organization is responsible for the certification, production approval, and continued airworthiness of aircraft; and certification of pilots, mechanics, and others in safety-related positions.[15] This organization promotes safe flight through standards for design, material construction, quality work and performance of aircraft and aircraft engines. FAA Aviation Safety establishes requirements for aviation safety including:

1. Regulations, orders and advisory circulars;
2. Requirements for quality systems, design, manufacturing and maintenance of operating organizations;

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[12] Federal Aviation Administration (FAA), "About FAA," https://www.faa.gov/about/, accessed June 2, 2017.

[13] FAA, "A Brief History of the FAA," https://www.faa.gov/about/history/brief_history, accessed June 2, 2017.

[14] D. Reed, "In A Dangerous World, U.S. Commercial Aviation Is On A Remarkable Safety Streak," *Forbes.com*, December 28, 2016, https://www.forbes.com/sites/danielreed/2016/12/28/in-the-last-7-years-you-were-more-likely-to-be-run-over-by-a-car-than-to-die-in-an-airline-crash/#39af873d428a.

[15] FAA, "Aviation Safety (AVS)," https://www.faa.gov/about/office_org/headquarters_offices/avs/, accessed June 2, 2017.

3. Certificates and approvals for design and design changes, production and manufacturing, maintenance and operations;
4. Production approvals with a detailed fifteen element check list to ensure quality production of products and articles
5. FAA oversight and control of Production Approval Holders (PHA) including guidance for surveillance, and FAA authority to act in the interest of safety at any time.
6. FAA use of certificate management to ensure that each PHA remains in compliance with manufacturing regulations through inspections, audits, accident investigations, and evaluation of suspected unapproved parts. Further audits are conducted at multiple points including at PHA supplier facilities and/or its' suppliers;
7. FAA initial and annual risk assessments of all PHAs are used to determine certificate management audit responsibilities. Even with these extensive regulations and processes the industry has experienced defective parts in critical applications and they have ongoing efforts with the industry to find and eliminate them.

While the FAA monitors and interacts closely with the aviation industry, it allows for the use of standard parts (e.g., nuts and bolts) Such parts can be manufactured by anyone if the parts meet government and industry standards. The responsibility for the quality of such parts lies with the installers with some FAA oversight. However, the parts used under these criteria are defined by the FAA as non-critical.

The FAA also employs designated engineering representatives (DERs) who typically work for an aerospace firm, including OEMs, but who have a responsibility to the FAA. The DER system enables the FAA to use qualified technical people to perform certain examinations, testing, and inspections necessary to determine compliance with applicable airworthiness standards. A DER offers state-of-the-art technical expertise. FAA interaction with DERs is highly interdependent, building on the mutual interests that the FAA, manufacturers, and operators have in achieving the highest level of safety.[16] BSEE could easily adopt a similar approach by requiring Professional Engineers to be involved during critical design, manufacturing, assembly and testing activities.

An example of the FAA's proactive response to an accident is establishment of the Jet Engine Titanium Quality Committee (JETQC). In 1989, a titanium fan disk failed in the center engine of a DC-10 airplane; shrapnel from the disk severed

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[16] FAA, *8110.37E—Designated Engineering Representative (DER) Guidance Handbook*, https://www.faa.gov/regulations_policies/orders_notices/index.cfm/go/document.information/documentID/1018533.

the lines of the three hydraulic systems that powered the airplane's flight controls. The flight crew had difficulty controlling the airplane for landing, and it crashed on landing at Sioux Gateway Airport, Iowa, leading to loss of 111 passengers and crew. The root cause of the disk failure was determined to be metallurgical inclusion located in a high-stress region of the disk that led to an undetected fatigue crack.[17]

The objective of the JETQC is to provide the industry an early warning system of potential problems in the manufacturing of titanium components. The JETQC included membership from all premium quality titanium alloy suppliers and engine manufacturers. The JETQC established detailed specifications for reporting inclusions at all stages for the processes used for manufacturing premium-quality titanium.

Because of the proactive industrial initiative to improve inspection and processing technologies, educate the workforce, and share information among all consortium members, there has been a one to two order of magnitude reduction in identified melt inclusions in titanium components and no reported component failures.[18]

The JETQC incorporated the following strategies:

1. Membership is comprised of the FAA, engine OEMs, and the titanium suppliers of premium-quality material; membership is global
2. Regulations require mandatory reporting of all inclusions, and regular reporting to all consortium members of the statistics
3. Continuous process improvements in the processing and inspection of premium-quality titanium
4. Proactive cooperative industry initiatives to enhance reliability of premium-quality titanium rotating-part components

The FAA regulatory approach has effectively worked with all stakeholders in the aviation industry to continuously improve aviation safety. The formation of JETQC is an example of the proactive leadership role the FAA has taken to address the root cause of an accident: Establish a metric (i.e., identified metallurgical defects),

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[17] National Transportation Safety Board, *United Airlines Flight 232 McDonnell Douglas DC-10-10*, November 1, 1991, https://www.ntsb.gov/investigations/accidentreports/pages/AAR9006.aspx; FAA, "Manufacturing Process of Premium Quality Titanium Alloy Rotating Engine Components," Advisory Circular 33.15-1, September 22, 1998; FAA, "FAA Engine Titanium Consortium," FAA William J. Hughes Technical Center, http://www.tc.faa.gov/its/cmd/visitors/data/AAR-430/engtitan.pdf, accessed June 2, 2017.

[18] See Figure 5.4, courtesy of Andy Woodfield, GE Aviation, in National Academies of Sciences, Engineering, and Medicine, *Bolting Reliability for Offshore Oil and Natural Gas Operations: Proceedings of a Workshop*, The National Academies Press, Washington, D.C.

harness the efforts of the entire industrial base to provide continued improvements, and measure and report progress against the metric.

U.S. Navy Practices

The U.S. Navy operates a fleet of more than 270 ships and 3,700 aircraft and is by a significant margin is the largest Navy in the world and its air force is second in size only to the U.S. Air Force. These assets have highly demanding operational requirements ranging from submarines operating at depth, to high-speed surface vessels, to aircraft designed for both aerial combat and carrier landings. The performance, material requirements, and complexity needed in these operational environments is high and requires a stringent approach to design, qualification, inspection, and maintenance to meet safety and reliability standards. For example, the critical fasteners attaching a controllable pitch propeller blade on DDG 51 destroyer required critical evaluation of the fastener design, an in situ study to determine the operational conditions, fastener material and specialized installation practices.[19] The Navy has established the proper controls and processes to manage both standard and specialized processes and controls to meet high-performance requirements while mitigating risk.

The nuclear submarine fleet has successfully established the institutional structure through the SUBSAFE program to ensure safety across the submarine fleet even as new designs are implemented. The following summarizes Rear Admiral Paul E. Sullivan's statement on the inception of the SUBSAFE design practices and lessons learned during intervening reviews of the SUBSAFE program as presented to the House Science Committee, on October 29, 2003.[20]

On April 10, 1963, the USS *Thresher* was lost at sea. The USS *Thresher* inquiry led to 166 findings of fact, 55 opinions, and 19 recommendations. While the exact cause is not known, the inquiry found deficient specifications, deficient shipbuilding, deficient maintenance, and deficient operational procedures. This report formed the basis of the Navy's SUBSAFE design and operational requirements and were codified into the Submarine Safety Requirements Manual (NAVSEA 0024-062-0010) in 1974. Since the loss of the USS *Thresher*, there have been no SUBSAFE certified submarines lost. In 1985, an independent organization was established

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[19] H. Stefansson, Rolls-Royce Naval Marine, "Controllable Pitch Propeller Blade Bolt Design," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations on April 11, 2017.

[20] Statement of Rear Admiral Paul E. Sullivan, U.S. Navy Deputy Commander for Ship Design, Integration and Engineering, Naval Sea Systems Command, before the House Science Committee on the Subsafe Program October 29, 2003, http://www.navy.mil/navydata/testimony/safety/sullivan031029.txt.

within the Naval Sea Systems Command (NAVSEA) to strengthen and review compliance with SUBSEA requirements. Theses audits found critical lessons learned:

- Disciplined compliance with standards and requirements is mandatory.
- There must be an engineering review system in place to resolve technical problems and issues.
- There must be a safety and quality programs in place to support operation.
- Safety and quality organizations must have sufficient authority and freedom to operate without external pressure.

The SUBSAFE program has a clearly defined objective to provide maximum reasonable assurance of maintaining watertight integrity and recovery capability. To maintain the safety culture, clear, concise non-negotiable requirements are enforced through multiple structured audits that hold personnel at all levels accountable for safety and annual training that emphases strong emotional lessons learned from past failures.

There is a single submarine program manager who manages and ultimately approves all aspects of construction, maintenance and life cycle management and ensure compliance with SUBSAFE requirements. There is a single technical authority that overseas each specific technical area of the SUBSAFE program such as subject matter experts to support the submarine program managers. These technical authorities are warranted and have the responsibility and accountability to establish, monitor and approve technical products to ensure conformance to requirements. They must ensure that a full technical discussion is held prior to making designs. When technical products are not in conformance with policy, the technical authority must evaluate risk.

The certification process covers design, material, fabrication, and testing and is implemented through three critical areas: work discipline, material control, and documentation. Work discipline is conveying the knowledge of the requirements and compliance with those requirements to everyone who works with submarines. Material control ensures that the correct material is purchased on procurement contract, receipt inspection, storage handling, and installation on the submarine. Documentation begins at the design phase of the submarine when a drawing is established and maintained through the life of the ship for every component and includes system diagrams and manuals.

The overall objective is to generate an identifiable accountable and auditable record of work performed within the SUBSAFE boundary. For each component there is a comprehensive record of the quality of any work performed on a component—for example, nondestructive testing of a material, weld records, and work orders. Documentation of quality evidence proves the materials and work were performed to specification and allow for any deviations or nonconformity to be adjudicated by the appropriate authority. All organizations and contractors performing SUBSAFE work must be evaluated, subject to routine audits and certified by NAVSEA that these requirements are met.

The fastener technical warrant holder is empowered to make design decisions related to fastener use and nonconformity in the fleet.[21] Common issues encountered include the following:

- Requirements set before consulting fastener engineer or environment. Were requirements based on an engineering need or a business decision?
- Be proactive regarding design changes. Retrofitting is often significantly more expensive
- Quality such as ISO17025 must be built into both the contract and design

An important component of the decision process is determining risk. Each risk is assigned a both a probability and a criticality or severity of consequence. The ultimate responsibility for determining the risk and severity lies with the technical warrant holder who has the responsibility to approve all designs and design modifications and communicate that risk to other stakeholders.

The SUBSAFE program established procedures to ensure the most critical components related to operational safety are maintained through design, implementation and maintenance and are carried over to new designs. It established a centralized empowered authority to oversee each technical area individually and the system as whole. The culture of safety was established and emphasized to every level of personnel. Routine accreditation and standards compliance audits of both internal and external organizations are routinely made. A comprehensive set of documentation is tracked for each critical component to ensure quality.

A bolting reliability improvement roadmap—a meaningful comprehensive government-industry initiative—could be constructed and aimed primarily at improving fastener reliability for the most critical subsea applications. The challenge is to reduce the probability of a subsea fastener failure, which is already low, by another 1 to 2 orders of magnitude over a defined period of time, such as the next 10 years.

Initially organizing an industry-wide effort to construct a comprehensive roadmap is likely beyond the purview of industry, if for no other reason to avoid the appearance of unlawful collusion. Thus, it is likely that BSEE will need to undertake the proactive role of establishing a consortium to construct a comprehensive

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[21] See the presentation summary for Frederick Kachele, Acting NAVSEA Fastener Technical Warrant Holder, in National Academies of Sciences, Engineering, and Medicine, *Bolting Reliability for Offshore Oil and Natural Gas Operations: Proceedings of a Workshop*, The National Academies Press, Washington, D.C., 2017, pp. 89-92.

roadmap that could advance the safety of threaded fasteners. Statutory changes to oil industry anti-trust requirements may be needed. The multi-faceted roadmap could contain key objectives and priorities that could be executed and implemented by the industry, much as was done in the FAA's JETQC and the Navy's SUBSAFE efforts. Industry should have large role in determining the priority for addressing potential improvements. The roadmap could be divided into the following sections:

- Clearing and legal obstacles to having multiple companies working closely and sharing data.
- Research and development of specific innovation opportunities that have the potential to significantly advance the reliability of offshore fasteners in critical service. Specific opportunities are suggested in Chapter 5 of this report.
- Collection of necessary statistical data for key operational environment design parameters; this would allow a statistically based probabilistic risk assessment (PRA) to be performed to quantify the safety factors to use in the design.
- Identification of gaps in current standards and obtaining the necessary data to guide updating the standards.
- Promotion of a strategic vision for the safety culture required by oil and gas operations. This would include collecting and disseminating information about fastener performance, failures, and near misses across different disciplines and organizations, and quite importantly, assessing how this information would affect roadmap priorities.

SUMMARY AND RECOMMENDATIONS

There is a keen interest in improving the reliability of offshore engineering structures and in reducing the risk of damage to the environment to as close zero as possible. With many disparate views on the preferred approach, there should be a forum by which stakeholders have an opportunity to contribute their ideas and have them adequately investigated to enhance the development of offshore resources. Traditionally in engineering design, materials selection, manufacturing, installation and operation, this forum has been accomplished through the development and use of standards and specifications.

Finding: A challenge in improving the reliability of bolted connections in the oil and gas industry is the multitude of specifications and standards that currently exist. Bolt manufacturers must deal with more than 1,000 specifications that address various aspects of bolt design and bolt manufacture. This includes more than 500 specifications and standards of trade organizations (ASTM, API, Mil, AS, ASME, ASNT, etc.), plus well over 500 customer-specific standards.[22]

Option 3.1: BSEE could leverage the results of the study at Argonne National Laboratory that is evaluating fastener standards to bring industry together in addressing detailed standards and best practices in design, materials, manufacture and operation of offshore structures.

Finding: An overly prescriptive regulatory environment can impede newer technological developments and applications. A 2012 report on the Macondo Well Deepwater Horizon Blowout by the National Academies of Sciences, Engineering, and Medicine stated, "The United States should fully implement a hybrid regulatory system that incorporates a limited number of prescriptive elements into a proactive, goal-oriented risk management system for health, safety, and the environment."[23]

Option 3.2: The committee endorses the Summary Recommendation 6.1 contained in the National Academies of Sciences, Engineering, and Medicine 2012 report on the Macondo Well Deepwater Horizon Blowout:[24] "The United States should fully implement a hybrid regulatory system that incorporates a limited number of prescriptive elements into a proactive, goal-oriented risk management system for health, safety, and the environment." BSEE could implement this Summary Recommendation.

Finding: Standards will not totally solve the fastener reliability concern. For instance, current standards do not address the enforcement process. They are not incorporated into current federal regulations, e.g., Part 250 of the U.S. Code, and as a result are not directly enforceable. Regulations are also only enforced at the operator level of the oil and gas industry and do not directly apply to the complex systems of manufacturing and operation.

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[22] Personal communication, Tom Goin, president U.S. Bolt Manufacturing, Inc., August 15, 2017.

[23] National Academy of Engineering and National Research Council, *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*, The National Academies Press, Washington, D.C., 2012.

[24] Ibid.

Option 3.3: Safety critical standards and specifications could be enforced by BSEE throughout the supply chain by incorporation of such standards into the Code of Federal Regulations.

Finding: Managing the supply chain is a difficult endeavor. There are many tiers of subcontracted suppliers that continually change due to costs and schedule demands. QA/QC issues are often cited as contributory causes in failure analyses.[25]

Option 3.4: The committee agrees with the BSEE 2016 QC-FIT report, Evaluation of Fastener Failures Addendum that recommended that all bolts used in critical service in US OCS waters shall be manufactured by organizations that maintain sufficient quality certifications.[26] BSEE could consider fully implementing this recommendation.

Finding: Across industries, engineering best practices and regulations are often the result of lessons learned from a critical failure of significance. While this process is inherently reactionary, it has a proven track record of preventing failures similar to those of past failures. The FAA and the U.S. Navy, in response to low-probability, high-consequence failures, have successfully implemented long-term programs that have dramatically increased safety.

Option 3.5: The FAA and U.S. Navy regulatory approach and governing authorities have elements that BSEE could tailor for their domain of interest. In some cases, additional statutory authority may be necessary.

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[25] BSEE, "QC-FIT Connector and Bolts Failure," https://www.bsee.gov/what-we-do/regulatory-safety-programs/systems-reliability-section/findings-recommendations. See, for example, BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, 2016.

[26] BSEE, *QC-FIT Evaluation of Fastener Failures—Addendum*, 2016.

4

Safety Culture and Human Systems Integration

HUMAN SYSTEMS INTEGRATION AND SAFETY CULTURE

Human-Systems Integration (HSI) is a framework in which human capabilities and limitations across various dimensions are considered in the context of a dynamic system of people, technology, environment, tasks, and other systems with the goal of achieving system resilience and adaptation, approaching joint optimization.[1,2] HSI considers human factors at the levels of the individual, team and organization.

Safety culture exists at the organizational level and is the cumulative values and attitudes of all of those in the organization. The organization reinforces specific values and attitudes through behaviors such as work rules, processes, management practices, supervision rewards, and communication. HSI takes into account various dimensions of the human system that include manpower, personnel, training, safety, human factors, survivability, and habitability. Thus, the HSI framework includes considerations of safety and at the organizational level, produces the safety culture. HSI, when done properly, can lead to an improved safety culture, but has the additional benefits of improving worker productivity and job satisfaction. This is critical because often organizations treat safety considerations as a cost of doing

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[1] National Research Council, *Human-System Integration in the System Development Process: A New Look* (R.W. Pew and A.S. Mavor, eds.), The National Academies Press, Washington, D.C., 2007.

[2] D.A. Boehm-Davis, F.T. Durso, and J.D. Lee, *APA Handbook of Human Systems Integration*, American Psychological Association, Washington, D.C., 2015.

business; however, by doing good HSI, an organization can achieve a safer organizational culture and a more effective and satisfied workforce.

HUMAN SYSTEMS INTEGRATION AND FASTENERS

Human capabilities and limitations need to be considered in the context of the complex landscape of subsea fasteners and their employment. Humans impact and are impacted by all aspects of the system. For instance, the human who is executing the torqueing process can directly impact the integrity of the subsea installation. In addition, the size, strength, position and material composition of a fastener or stud affects the required torqueing process. Different coatings and lubricants also change the torque specified, and they do affect the ultimate fastener preload, which is in turn related to stress and the operating environment. In addition, there are also organizational impacts on torqueing stemming from the equipment, training, guidance and quality control system of the company. All of these interactions that can be affected by human variability should be taken into account when intervening to improve the human system and ultimately the entire fastener system.

Considerations of selection, training, safety, skill development, and work processes are relevant to the processes involved in manufacturing, installing, maintaining, and inspecting subsea fasteners. Personnel must be qualified to perform the job and trained to carry out processes according to defined standards and specifications. Human expertise associated with various processes and best practices need to guide the training content. Attention to these various human dimensions cannot only improve safety culture, but productivity and effectiveness of the entire system. Examples of fastener solutions that take these human dimensions into account can be found in Chapter 5.

But standards and specifications, are not sufficient. Human error is often associated with failure to follow correct procedures. However, this begs the question of whether the procedures can be followed—often people use work arounds because the procedures are flawed in some way; some procedures can doom a person to fail. Understanding the rationale for procedures and the consequences of not following procedures are also important for safety. At the same time, there may be no procedures for some critical tasks. Optimization of the work process itself to reduce the risk of unsuccessful outcomes is critical and often overlooked. Standard operating procedures regarding design, production, application, and serviceability of critical fasteners may not exist to the extent required to completely avoid fastener Failure to consider HSI issues early in system design can result in safety issues, poor system performance, and increased costs of re-design. And every system that does not check the quality of every human performed task is doomed to the irreducible error rate of humans.

HUMAN SYSTEMS INTEGRATION IN OTHER INDUSTRIES AND COUNTRIES

Most of the HSI research and development in the oil and gas offshore industry has taken place within the European oil industry, especially Norway and Great Britain.[3] Flin and Slaven report research primarily conducted in the North Sea and Irish Sea, focusing on the development of the workforce (selection, training, health, management, stress, and error) with less attention to work process, larger organizational issues, and human interactions with tools and technology. Much of this work is a direct result of the Piper Alpha disaster in July of 1988 that killed 167 workers in the world's deadliest offshore oil industry disaster.[4]

Human Systems Integration is not new and has been standard practice in multiple agencies and organizations including the Department of Defense, the Federal Aviation Administration (FAA), the Department of Energy, and NASA. The U.S. military has practiced human-centered design since safety issues became apparent with World War II aircraft. The U.S. Army, for instance, has a director-level position responsible for HSI and a service-level policy document. Of importance is the consideration of HSI in the acquisition process because changes made later in the lifecycle can be expensive as the organization becomes hampered by legacy equipment.

The nuclear industry began to consider human systems integration after Three Mile Island and its human factors implications. The Nuclear Regulatory Commission (NRC) has a Human Factors Information System which is a database that collects and stores reports on human performance issues in the industry. Reports are submitted by licensees (licensee event reports) and by NRC inspection. This information is used to focus efforts to improve human-system interfaces, organizational processes, training programs, procedures and inspections at each plant.

The FAA has a Human Factors Division which by FAA Order 9550.8A is a "multidisciplinary effort to generate and compile information about human capabilities and limitations and apply that information to equipment, systems, facilities, procedures, jobs, environments, training, staffing, and personnel management for safe, comfortable, and effective human performance." Though labeled "human factors division," the FAA considers systems and systems of systems in line with the tenets of human systems integration with the aim of supporting human performance across various aviation domains.

NASA has a Human Systems Integration Division that targets improved crew performance, safety and health in spacecraft as well as aircraft. Like the National

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[3] R. Flin and G. Slaven, "Introduction," pp. 1-6 in *Managing the Offshore Installation Workforce* (R. Flin and G. Slaven, eds.), PennWell Books, Tulsa, Okla., 1996.

[4] NASA, "The Case for Safety: The North Sea Piper Alpha Disaster," NASA Safety Center Case Study, May 2013, Volume 7, Issue 4, https://sma.nasa.gov/docs/default-source/safety-messages/safetymessage-2013-05-06-piperalpha.pdf?sfvrsn=6.

Airspace System, military systems, and the nuclear industry, NASA is responsible for a complex system of systems of humans and machines in an environment that is often challenging to human performance and survival. Like the FAA, NASA not only oversees that human systems policies are enacted in new and existing systems, but conducts research to inform policies and decisions.

HSI is a reaction to issues identified in major disasters such as the Piper Alpha, Three Mile Island, or the *Challenger* explosion. Despite a spotty history for oil and gas in the United States including the Macondo blowout, there continues to be a gap in HSI in this industry.

GAPS IN U.S. HUMAN SYSTEMS INTEGRATION IN THE OIL AND GAS INDUSTRY

According to Flin and Slaven[5] there had been little attention paid to HSI in oil and gas outside of Europe and apparently, the situation has not radically changed. Although safety drills are practiced broadly, there is little attention paid to HSI or human factors in U.S. standards. According to a report by the Ocean Energy Safety Institute (OESI) "the American Petroleum Institute (API) recently mandated Recommended Practice 75 (API, 2004) which incorporates directives that Human Factors should be considered, but gives no specific guidance on the appropriate steps or directions for implementation."[6]

Also, the same OESI report states that "Currently there are few, if any, frameworks that can integrate human-centered design concepts throughout the rig design process and can identify crucial elements specific to design stages. There are also gaps in establishing examples of successful implementation and identification of the key performance indicators (KPI) and return on investment (ROI) for all of the methods presented."[7]

The OESI report also notes gaps in the perception of risk among oil and gas workers and how workload and organization factors may affect risk perception and in turn worker performance and safety. In addition, quantitative risk assessment has failed to take into account human and organizational factors in the oil and gas industry (e.g., Macondo incident).

Given the minimal attention paid to HSI in the larger oil and gas industry, it should come as little surprise that there has been no attention paid to this aspect of subsea fasteners.

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[5] R. Flin and G. Slaven, "Introduction," pp. 1-6 in *Managing the Offshore Installation Workforce* (R. Flin and G. Slaven, eds.), PennWell Books, Tulsa, Okla., 1996.

[6] S.C. Peres, R. Bias, N. Quddus, W.S. Hoyle, L. Ahmed, J.C. Batarse, and M.S. Mannan, *Human Factors and Ergonomics in Offshore Drilling and Production: The Implications for Drilling Safety*, Technical Report, Ocean Energy Safety Institute, 2016, p. 8.

[7] Ibid., p. 7.

HUMAN INTERACTIONS WITH SUBSEA FASTENERS

The lifecycle of a fastener includes processes from manufacturing, testing, and validation to operations, monitoring, and maintenance that are often discussed with minimal to no reference to a human being.[8] For example, the significant GE H4 bolt recall was blamed on a failure of a lower tier subcontractor to use the correct standard requiring a post-electroplating bake-out procedure. But this failure was just a symptom of the fact that no process was in place to insure lower tier subcontractors were provided the information they needed, nor was any planning given to the critical need to monitor their human performance. Typical Venn diagrams[9] depicting the fastener landscape and potential failures include interactions between materials, stress, and the environment,[10] pointing out the complex interactions between these three systems, yet without reference to the complex human system that is involved in all processes throughout the life of a fastener (Figure 4.1b).

Notably, a very large portion of the processes involved in the fastener lifecycle are not automated, but are executed by humans. For instance, in the manufacturing process humans process the raw material, and carry out machining, heat treatment, quality control, and coating processes.

Although these processes may be associated with specifications and standards, it is the human who translates the standard to practice. It is also a human who makes decisions is areas where no specifications and standards apply. Finally, it always falls to a human to monitor, or fail to monitor, another human's conformance with the standards. Similarly, humans play a role in every fastener process (see Table 4.1).

These processes can be further subdivided into sub-processes as has been done in Tables 4.2 and 4.3 for the manufacturing processes of steel and fasteners. Each process and subprocess requires human intervention.

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[8] R. San Pedro, "Fastenered Flange Joints in Offshore: Basic Principles and Applications," presentation to committee on March 22, 2017.

[9] A Venn diagram is a diagram that shows all possible logical relations between a finite collection of different sets. A typical Venn diagram consists of multiple overlapping closed curves (often circles) each representing a set.

[10] F.C. Adamek, "A Historical View of Subsea Fastenering," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 10-11, 2017; see Figure 4.1a.

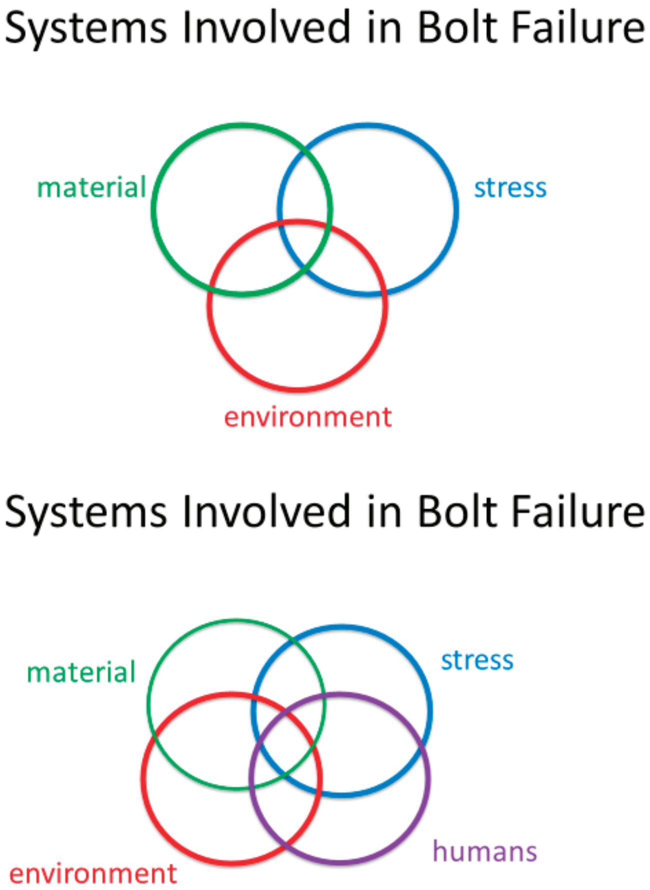

FIGURE 4.1 Systems involved in fastener failure: (a) A historical view of subsea bolting and (b) with the human system. SOURCE: F.C. Adamek, “A Historical View of Subsea Fastening,” presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations on April 11, 2017.

TABLE 4.1 Processes in a Fastener Life Cycle that Involve Humans

Fastener Manufacturing	Drilling Contractor Operations	Monitoring and Maintenance
Raw material processing	Assembly	Corrosion, integrity, voltage
Machining	Installation	Current
Heat treatment	Torqueing	Flex joint angle
Coating	Cathodic protection	Connector loading
Marking	In-service inspection	Monitoring environment

TABLE 4.2 Steel Manufacturing

			Casting					
Process Design	Chemistry Control	Melt/Re-melt	Ingot	Continuous	Hot Working	Heat Treat	Quality Control	Product Identification
• Interpret —Industry standards —Customer Specs —Contract/PO • Define process —Steps —Parameters —Resolve questions and conflicts • Prepare Mfg. procedures • Prepare QC program	• Prepare Material Input QC program • Review material documentation • Chemical verification • Properly mark materials • Track Heat/PO numbers • Properly sort materials • Send right materials to Mfg. process	• Heat to proper temperatures throughout ladle • Maintain temperature for correct times • Mix molten steel for proper time • Perform ladle treatments as applicable • Properly record all Mfg. parameters • Perform quality controls—ladle analysis • Track Heat/PO numbers	• Select correct size casting molds and prepare molds. • Make sure that metal is at the correct temperature • Pour ingots • Cool steel to right temperature at right cooldown rate • Properly record all Mfg. parameters • Track Heat/PO numbers	• Select correct size strand and number of strands. • Make sure that pouring temperature and rate as correct. • Cast the strand at proper rate • Cool steel to right temperature for subsequent processing • Properly record all Mfg. parameters • Track Heat/PO numbers	• Select appropriate working equipment (forge presses, rolling mills, etc.) • Select correct working forces, rates and times (amount of reduction in each pass, total reduction) • Work to correct dimensions • Properly record all Mfg. parameters • Track Heat/PO numbers	• Determine correct heat treatment procedure—times, temperatures, load size • Properly load material in furnace to ensure uniform heating and cooling) • Heat to correct temperature at right heating rate • Maintain temperature for correct amount of time • Cool steel to right temperature at right cooldown rate • Properly record all Mfg. parameters • Track Heat/PO numbers	• Ensure all measurement equipment is properly calibrated and qualified • Ensure all samples are correctly prepared • Properly perform tests according to written procedures • Interpret test results • Correctly document all results • Track Heat/PO numbers	• Understand marking requirements as per PO • Mark correctly—hard stamp, tags, labels as applicable • Gather all Mfg. documentation and records • Pack, preserve, and ship products and documentation

TABLE 4.3 Fastener Manufacturing

Preliminary Design	Input Material QA	Heat Treat	Cutting Lengths	Forming	Threading and Machining	Coating	Quality Control	Product Identification
• Interpret — Industry Standards — Customer Specs — Contract/PO — Resolve questions and conflicts • Design product manufacturing plan • Define process — Steps — Parameters • Prepare Mfg. procedures • Prepare QC program • Communicate information to the production function	• Procure material from a qualified supplier • Prepare material input QC program • Review material documentation • Properly sort materials • Dimensional & chemical verification • Track heat/lot/PO numbers • Send right material to Mfg. process	• Define heat treatment procedure—times, temperatures, load size • Properly load material in furnace • Heat to correct temperature at right heating rate • Maintain temperature for correct amount of time • Cool/quench steel at the right cooldown rate • Properly record all Mfg. parameters • Track Heat/Lot/PO numbers	• Determine cut lengths • Program/set-up cutting equipment • Monitor cut lengths to maintain dimensional quality • Track Heat/Lot/PO numbers	• Select proper forming dies • Program/set-up forming equipment—determine time and temperature • Ensure temperature monitors are working and calibrated • Ensure billets are fully heated before placing in forming machine. • Keep forming dies properly lubricated • Handle formed parts so avoid damage • Track Heat/Lot/PO numbers	• Determine starting diameter. • Machine or form to required diameter as necessary • Program/set-up threading equipment • Check proper dies or cutters are installed • Machine other dimensions to the part drawing as applicable • Monitor output quality and change dies or cutters to maintain dimensional quality • Properly record all Mfg. parameters • Track Heat/Lot/PO numbers	• Pre-quality coating vendors • Ensure coating vendor knows which coating to apply for PO and that all questions are answered • Visually inspect coating • Track Heat/Lot/PO numbers	• Ensure all measurement equipment is properly calibrated • Ensure all samples are correctly selected and prepared • Properly perform tests according to written procedures • Interpret test results • Correctly document all results • Track Heat/Lot/PO numbers	• Understand marking requirements as per PO • Mark correctly • Gather all Mfg. documentation and records • Pack, preserve, and ship products and documentation

THE HUMAN'S ROLE IN FASTENER FAILURES

Root cause analyses for fastener failures, if carried to the full root cause, will likely implicate the human. Armagost[11] reported five root cause categories associated with fastener failures:

1. *Maintenance:* Mistake, misuse or oversight during maintenance.
2. *Procedural:* Mistake, misuse or oversight during operation.
3. *Quality assurance/quality control (QA/QC) manufacturing:* Failure related to manufacturing.
4. *Wear and tear:* A component that has reached a point where it cannot perform its intended function as the result of use.
5. *Human error:* Errors in judgment and behavior

Clearly humans are involved in the fifth category, but are likely to also be involved in other categories as well. It is a human who is probably making the mistake or misusing equipment, or failing to provide adequate oversight. The fact that there is human involvement, however, does not justify the label "human error" as the root cause. Human errors come in many varieties. They have immediate effects (active errors) or latent with consequences are not experienced for some time.[12] They can also be characterized as slips, lapses, mistakes, and violations.[13] They can be errors of omission in which a critical step is omitted and errors of commission in which something extra is done that is not in the procedure. Errors of commission and those with latent consequences are challenging to address. Understanding the type of error can be instrumental in intervening to prevent additional errors.

Moreover, the human needs to be considered as a complex system component, on par with the fastener environment or materials. It would not be sufficient to identify environmental error or materials error as a root cause, just as the "human error" label is not sufficient. More importantly, the label, "human error" is not an explanation that can point to any interventions other than to remove humans from the system. It is necessary to identify why the human followed the wrong procedure or made an incorrect action. This needs to be done in the context of the complex human-fastener system.

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[11] K. Armagost, "Root Cause Failure Analysis in Support of Improved Systems Reliability," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 10-11, 2017.

[12] R. Gordon, "Contribution of Human Factors and Human Error to Accidents," pp. 149-176 in *Managing the Offshore Installation Workforce* (R. Flin and G. Slaven, eds.), PennWell Books, Tulsa, Okla., 1996.

[13] J. Reason, *Human Error*, Cambridge University Press, Cambridge, Mass., 1991.

For example, torqueing to preload a fastener or stud is a task that is particularly prone to "human error" for the following reasons:

1. Different coatings lubricants, and quality of thread surface finish all change the torque required to achieve the desired fastener preload, but the current specifications do not appear to account for these differences.
2. Torqueing of flange fasteners *must* be done following a rather complex procedure that specifies the order in which flange fasteners are torqued and the number of torqueing passes required to attain required torque.
3. Torqueing of flange fasteners *must* be done a number of times around the flange, in the proper order.
4. From a design perspective, torqueing is an inaccurate method for preloading fasteners due to:
    - i. Manufacturing tolerances of threads.
    - ii. Uncertainty about whether the actual friction during torqueing is accurately predicted by the friction factor assumed when calculating the required make-up torque.
    - iii. Absent observing the torqueing procedure directly, there appears to be little use of technologies that could be used to check if adequate preload on the bolt has been, in fact, obtained.

In tasks like this the human can be set up to fail to achieve the desired result. It may be, for instance, impossible to follow the established procedure that is poorly written or overly complex. In other words, other parts of the system are impacting human performance. For example, there is no standard torque training or competency assessment available for workers on the rig or the shop floor who perform torqueing. Or, better yet, a new method of measuring preload as discussed elsewhere in this report has yet to be instituted. Interestingly, the 2012 National Academy of Engineering (NAE)/National Research Council (NRC) report *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety* also notes that education and training of offshore drilling personnel needs to be expanded.[14] It is important to note that training alone will not eliminate human error in the face of distractions such as time pressure. Training is also not a solution for poor design. An API workgroup established a "Torque Action Plan" that reviewed the specification of the torqueing process (e.g., attending to the number of passes to final torque). Their recommendation to ensure torqueing was done correctly was to have a supervisor removed from his/her normal duties to verify

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[14] National Academy of Engineering (NAE)/National Research Council (NRC), *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*, The National Academies Press, Washington, D.C., 2012.

that any crew performing torqueing is doing it correctly.[15] Putting a second human on a task to supervise work that is too difficult for the first does not seem like the best solution to the problem. There is no assurance that a supervisor is any more competent (i.e., trained) to perform or oversee a torqueing operation. Additionally, what other risks will be introduced by removing the supervisor from his/her normal duties? Instead, directly addressing the issues associated with torqueing difficulty to improve the process would be more likely to succeed. Alternatively, some version of the installation quality technique recommended by the Research Council on Structural Connections (RCSC) should be considered. This technique required that an engineer of record approve the installation technique and the required installation quality steps. Additionally, a trained inspector is required onsite to perform torqueing calibrations and to monitor crews performing bolt torqueing.[16]

In general, in cases of human error, the "error" needs to be considered in light of the larger system including the larger human system. In all the processes involved in the fastener lifecycle there is also input from teams of humans and entire organizations. For example, industry standards, specifications, and recommended practices are developed from teams comprised of representatives from various types of companies in one or more industries. Their development is likely impacted by team dynamics as much as by technology.

TEAM ISSUES

Seldom do individuals work alone. Fastener processes are complex and require the work of multiple individuals. For instance, inspection of subsea fasteners on drilling risers is undertaken every 3 days by a crew of eight people who control a remotely operated vehicle. Teamwork can be highly effective. But can also be a contributor to systems failures when there are failed team processes such as poor communication and coordination, lack of shared knowledge, and role confusion.[17] There are some specific challenges for teamwork in the world of subsea fasteners. Multiple disciplines must coordinate design, manufacturing, operation, and maintenance. Additionally, these processes must be coordinated across multiple organizations, including operators, drilling contractors, BOP original equipment manufacturer (OEM), and fastener manufacturers. Communication across multidisciplinary teams can be difficult, but is especially challenging in the oil and gas industry due to contractual obligations and legal risk mitigation. Experienced field

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[15] T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

[16] Research Council on Structural Connections, *Specification for Structural Joints Using High Strength Bolts*, Chicago, Ill., August 1, 2014.

[17] E. Salas, N.J. Cooke, and M.A. Rosen, On teams, teamwork and team performance: Discoveries and developments, *Human Factors* 50:540-547, 2008.

workers may not share perspectives of scientists and engineers. On the other hand, sharing information about fastener performance, failures, and near misses across different disciplines and organizations is needed to promote a safety culture. Other team issues include handoffs (a shift handoff being the cause of the Piper Alpha disaster)[18] or crew changes that can result in significant risk of system failure. Work left incomplete by one crew could go unnoticed by the next if there is no formal procedure for handoffs.

ORGANIZATION ISSUES

There are also issues that occur at the organizational level that impact human performance and ultimately safety culture and system performance. Work and management processes vary by company and often differ across companies (rigs, operators, OEMs). Companies may be hesitant to share information related to fastener failure for liability reasons. Business decisions have been made to protect and optimize shareholder value (e.g. Deepwater Horizon) at the expense of safety, quality, and personnel. This can have a negative impact on the company's safety culture (Safety and Environmental Management Systems; SEMS; API RP76). There needs to be an adequate balance between competition that leads to resistance in taking responsibility for a failure or near miss and cooperation that enables steps to be taken to avoid future failures. Moreover, reporting on fastener failures and near misses should be encouraged and built into the work rules as part of the safety culture. This was also recommended in the 2012 NAE/NRC report and the 2014 and 2016 QC-FIT recommendations.

The move to deep water installations has resulted in a paradigm shift regarding the conditions surrounding the fasteners. Industry, however may not have fully shifted all parameters regarding oil and gas operations. Fasteners, which are seen as off-the-shelf commodities, may be one of the design elements that went unnoticed except by the bolting specialists. It should be mentioned, however, that the oil and gas industry, through the API, has responded to recent fastener failures with an outstanding effort.

Decision makers are driven by KPIs that are sometimes not well thought out. Laws and regulations hastily written responses to bad practices can make industry less competitive. An overly-prescriptive regulatory environment can suffocate newer technological developments and applications. An alternative that should be considered is a deliberate move toward a goal-oriented regulatory system such as is practiced by Norway and the United Kingdom. The study committee that authored the 2012 NAE/NRC *Macondo* report also believed in the advantages of goal-oriented regulations. Contained in its report is Summary Recommendation

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[18] Reference Lord Cullen's report.

6.1: "The United States should fully implement a hybrid regulatory system that incorporates a limited number of prescriptive elements into a proactive, goal-oriented risk management system for health, safety, and the environment."[19]

Organizations also need to adapt to changes in the workforce such as the "great crew change" of 1986 or the workforce decline that paralleled the declining price of oil. Students stop majoring in petroleum engineering in lean times resulting in an expertise gap in the workforce. In an industry in which skills are often learned on the job and passed down through generations, there is a serious lack of skilled crew and experienced mentors when the oil economy turns around.

SUMMARY AND RECOMMENDATION

Human systems integration has not been widely considered in the U.S. oil and gas industry or has been trivialized in the analysis of past fastener failures to explanations of "human error." Yet, the human system is integral to the fastener landscape and the processes involved in the lifecycle of a fastener. It is critical that the complex human system at all levels (i.e., individual operator, teams, and organizations) and across all dimensions (e.g., training, selection, safety) be considered within the fastener system and the interventions to reduce fastener failures and improve the safety culture. Considering fasteners within the larger system necessitates an enterprise-wide safety culture. A human systems integration perspective is required in considerations of fastener failures and the interventions to prevent failure. Examples of HSI solutions are presented in Chapter 5.

Finding: Virtually every root cause analysis of an undersea bolt or stud failure finds a human error at least as a contributing cause.

Finding: In general, human error or mistakes are often used as an explanation for failures without looking for deeper root causes or factors that lead to mistakes or worse yet, redesigning the system to insure they do not happen in the future.

Finding: There is insufficient attention to individual worker and skill development through selection, training, and work process design.

Finding: Information sharing and reporting in the oil and gas industry regarding fastener failure incidents and near misses is evolving; this is an essential activity in promoting a safety culture across the industry.

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[19] NAE/NRC, *Macondo Well Deepwater Horizon Blowout*, 2012.

Finding: Multiple organizations often have conflicting work processes and share minimal information (rigs, operators, OEMS)

Recommendation 4.1: The oil and gas industry should promote an enhanced safety culture across organizations and disciplines that is reflected in work rules and that involves encouragement at all levels of the organization to improve the reliability of subsea bolts. This would include the following:

- **The creation of a dedicated organizational human systems stakeholder;**
- **Attention to the individual worker and skill development through training, selection and work process sign;**
- **Company and industry-wide sharing of best practices for collecting and disseminating information about fastener performance, failures, and near misses; and**
- **Assessing gaps that could be mitigated by technology developments.**

5

Innovation Opportunities

Research and development of specific innovation opportunities have the potential to significantly advance the reliability of subsea fasteners in critical service. Opportunities are divided into various categories such as those that address the materials, the design, or the handling and usage of fastener materials and involve human factors. Specific opportunity areas include the following: new testing protocols (forensic evaluation of decommissioned fasteners, damage tolerant analysis using computational methods, and robust understanding of rare failure events), in situ fastener measurements during service (in situ bolt load measurement, in situ bolt defect identification, in situ assessment of hydrogen contents in steels, in situ analysis of hydrogen and hydrogen-assisted cracking (HAC) susceptibility using surrogate and "canary" materials, fatigue monitoring system, and monitoring of connector integrity), improvement of the hydrogen-assisted cracking resistance of bolt alloys (uncovering sources of embrittling hydrogen in fastener materials and 21st century metallurgical design of hydrogen resistant alloys), coating technologies for bolts (Nitrided 4130, 4340 bolts for improved corrosion resistance; multifunctional and smart coatings; coating design for blowout preventer (BOP) bolts; hydrophobic coatings; and nano-laminated metallic coatings), new fastener designs (alternative thread designs and other connector geometries), and enhanced human systems integration.

Some of these innovations can be investigated and qualified within a few years since they leverage work done in other industrial sectors. Other opportunities will require a long-term development effort. Key for each of these activities is the issue of qualification for subsea service.

TESTING PROTOCOL

Forensic Evaluation of Decommissioned Fasteners

Nondestructive testing of newly manufactured fasteners is an important quality assurance practice. Destructive testing of newly manufactured bolts to evaluate mechanical properties (e.g., tensile properties and hardness) and microstructure is a common quality assurance practice for selected samples before fasteners are put into service.

Some destructive testing has been done on failed fasteners and on adjacent intact fasteners used in applications where fasteners have failed. This has provided valuable information on the root cause of fastener failures and has given some insight into the breadth of problems that have led to failures in the past.

Another opportunity exists for destructive testing on fasteners removed from BOP stacks when they are reconditioned. Selected fasteners could be tested to determine if they have been weakened or otherwise damaged in use. To take into account environmentally assisted cracking (EAC) propensities, including hydrogen embrittlement, it will be necessary to hydrogenate parts before testing to reproduce conditions that might have occurred in service. Also, for maximum effectiveness, it will be necessary to institute rigorous bookkeeping on installed heat and lots to have traceability as might occur in aerospace, naval, or nuclear sectors. This rigorous bookkeeping could start with those fasteners securing the pressure boundary.

Decommissioned connector testing can occur in a number of ways, as a metallurgically based failure analysis centered investigation aimed at identifying root causes of failures, fracture assessment using fracture mechanics and damage tolerance approaches, or by better hydrogen analysis and re-creation of embrittlement conditions under known hydrogen levels above and below those in service.

Material is usually only tested to determine whether it meets specifications and failure analysis from field retrievals is rudimentary. There is no new systematic HAC test of the failed material to see whether it possesses enhanced susceptibility in a controlled lab test that mimics service. Near misses (or any alternate bolts) are never or rarely studied in comparison. Despite tens (if not hundreds) of millions of dollars spent by the industry recalling thousands of bolts in the Transocean *Discoverer India* failure discussed in Chapter 2, the postulated root cause failure mechanism was apparently never replicated a single time on a single bolt in the laboratory.

A purely fracture and damage tolerant approach is also of value (see below). In connection with this, the population of subcritical crack lengths in a population of bolts and hydrogen levels is a topic of keen interest but rarely assessed. Fasteners close to those that crack and those in similar applications could be removed and sectioned or otherwise examined for cracks. This information has tremendous value to find cracks and is well worth the modest costs of such high throughput studies. Given information on worst case and average crack lengths as well as geometry and combined loading, stress intensity factors in service can be estimated for various possible scenarios such as whether high torque, fit up, or bending would produce conditions for cracking. Rough indications of crack growth rate are also possible based on service life, crack length (if detected) and various possible scenarios regarding crack initiation time. First and foremost, this type of analysis settles the question of the presence or absence of more widespread slow cracking and the presence of small cracks in field retrievals in contrast with a complete lack of crack initiation claimed in unfailed fasteners. If there is no crack initiation in intrinsically susceptible high strength materials, one key question is what is keeping fasteners of known susceptibility from cracking in service and what can be done to ensure that such favorable conditions prevail for all fasteners? This guides an alternative way to think about the problem and mitigation strategies. If susceptibility is blocked effectively in most fasteners, this points to the need to understand measures that preserve this state. That could include low applied stresses and low stress intensity factors or lack of hydrogen production and uptake perhaps due to intact coatings that prevent hydrogen production and uptake or lack of wetting.

In one analysis reported to the committee by an oil company,[1] a population of bolts was allegedly assessed for existing cracks. It was declared that there was no cracking present in unfailed bolts based on strain gauge analysis of fasteners subjected to torque via assessment of their compliance, but typically this measure is only sensitive to significant cracks. It was unclear what the minimum crack length needed to be for detection and/or how many cracks needed to be present in order to detect a change in compliance. This conclusion and its veracity are important. Were small cracks missed based on the method of detection or were they absent? The conclusion that cracks were not present in unfailed bolts distinctly impacts the future directions to be taken. This would imply that worst case metallurgical conditions (mechanical, unusual event, or special environmental conditions) causes a small population of connectors to fail amongst generally somewhat benign conditions.

Alternatively, a fracture mechanics based assessment of crack initiation and growth could be conducted at various controlled hydrogen concentrations, and stress intensities in the lab. This would create a data base of hydrogen cracking data as a function of cathodic protection level, SIF, material, heat etc. that could be used to assess whether cracks will initiate and grow and the future crack length given certain service conditions. One output would be K_{th} versus diffusible hydrogen or

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[1] T. Fleece, BP, "Mitigating BOP Failures," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

crack velocity, da/dt versus hydrogen content.[2] Best case and worst case heats could be examined much as done in a previous study of HY-130 steel where hydrogen embrittlement of welds were examined in this manner.[3] Using this as a data base, the susceptibility under selected field conditions could be assessed by comparing operational conditions (stress state, stress intensity, crack or flaw length, hydrogen levels in service), etc. The real challenge here is to define the field conditions and construct scenarios that could lead to failures.

Value Proposition

The metallurgical analysis of decommissioned bolts would lead to a database that includes service conditions along with any discovered fastener property degradation. Such a comparison would be valuable in predicting cases where connector failures were probable. The database would also shed light on what factors might or might not be important as current evaluations are lacking and vague correlations are the basis for decisions (i.e., blanket prohibition of banding in continuous cast fasteners). If hydrogen uptake susceptibility is analyzed versus carefully controlled hydrogen content (including analysis of crack path and morphology), then a more complete picture of impactful factors in materials as well as “windows of susceptibility”[4] might emerge. Finally, with such population data some defensible probabilistic risk assessments could be performed, which is impossible now considering industry’s lack of data.

Feasibility

As discussed above the techniques suggested are available and many are well established. Other industries employ such approaches. Such testing must be coupled

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[2] Note that slow diffusional egress of H from reversible traps is required and may underestimate diffusible hydrogen in low strength steels. The period of life assessment of a bolt has been addressed in Figure K.1 in Appendix K and in R.P. Gangloff and R.P. Wei, Gaseous hydrogen embrittlement of high strength steels, *Metallurgical and Materials Transactions A* 8(7):1043-1053, 1977, where a bolt geometry was considered and crack growth rate versus applied potential can be used to obtain lifetime to failure.

[3] P.A. Klein, R.A. Hays, P.J. Moran, and J.R. Scully, “Hydrogen Cracking Initiation of a High-Strength Steel Weldment,” pp. 202-222 in *Slow Strain Rate Testing for the Evaluation of Environmentally Induced Cracking: Research and Engineering Applications* (R.D. Kane, ed.), ASTM STP 1210, American Society for Testing and Materials, Philadelphia, Pa., 1993.

[4] Window of Susceptibility—a common logic in the stress corrosion cracking and hydrogen embrittlement community is that some dependency space exists, usually define by metallurgy, chemistry, and fracture mechanics conditions where cracking occurs and other regions where cracking does not occur. This has been made popular by a Venn diagram of overlapping circles but it is clear that conditions are more complex.

with the previously discussed record keeping of manufacturing history and past service for connectors.

Damage Tolerant Analysis Using Computational Methods

There is commercially available software that accepts crack growth rate and threshold stress intensity as a function of hydrogen concentration.[5] This software can assume a given flaw in a fastener material, perhaps ascertained from analysis of harvested bolts (see above), along with environment, load and geometry to compute a stress intensity factor. The model considers a probabilistic spread in crack length over some time interval, stress level, environments (such as diffusible hydrogen), and crack growth rates as a function of these variables. The code then runs a fast Monte Carlo analysis to predict HAC lifetimes as life in each run will be distributed based on variable conditions such as stress and hydrogen level. The code then assesses future crack length as well as whether K_{IC} is exceeded. This allows various conditional scenarios to be considered to ascertain the impact of variables on lifetimes. For example, Figure 5.1 (from experimental data) demonstrates the relation between crack growth rate and applied cathodic potential controlled in a laboratory test. Crack growth rate (da/dt) increases with cathodic potential and the threshold stress intensity for environmental cracking K_{Iscc}, decreases.[6] It can be seen that at potentials more negative than −800 mV SCE that crack growth rates are significantly enhanced above a Kth of about 15 $MPa(m)^{1/2}$. Figure 5.2 shows the life time or time to failure (ttf) of a bolt subjected to various stress intensities indicated on the vertical axis (a combination of applied and residual stress with initial flaw length yields a SIF) given a distribution of cathodic potentials ranging from −714 to −946 mV_{SCE}. Recall that the most negative potentials results in a greater diffusible hydrogen concentration. This range of potentials might be typical of service under cathodic protection. For each simulated initial K (vertical axis in Figure 5.1) the shortest ttf (left red symbols) corresponds to the most negative potential with the highest da/dt (Figure 5.1) while the longest life corresponds to a lower da/dt at a more modest potential (Figure 5.1). Note the four orders of magnitude change in lifetime. The lifetime approaches an extremely long time as the

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[5] R.P. Gangloff, Probabilistic fracture mechanics simulation of stress corrosion cracking using accelerated laboratory testing and multi-scale modeling, *Corrosion* 72(7):862-880, 2016. P.M. Scott, M.C. Meunier, D. Deydier, S. Silvestre, and A. Trenty, "An Analysis of Baffle/Former Bolt Cracking in French PWRs," pp. 210-223 in *Environmentally Assisted Cracking: Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures* (R.D. Kane, ed..), STP 1401, American Society for Testing and Materials, West Conshohocken, Pa., doi:10.1520/STP10220S, 2000.

[6] The fracture toughness (K_{ISCC}) is the stress intensity factor (SIF) at a crack tip under simple uniaxial loading. The subscript I stands for Mode I loading (unixial), while the subscript SCC stands for Stress Corrosion Cracking.

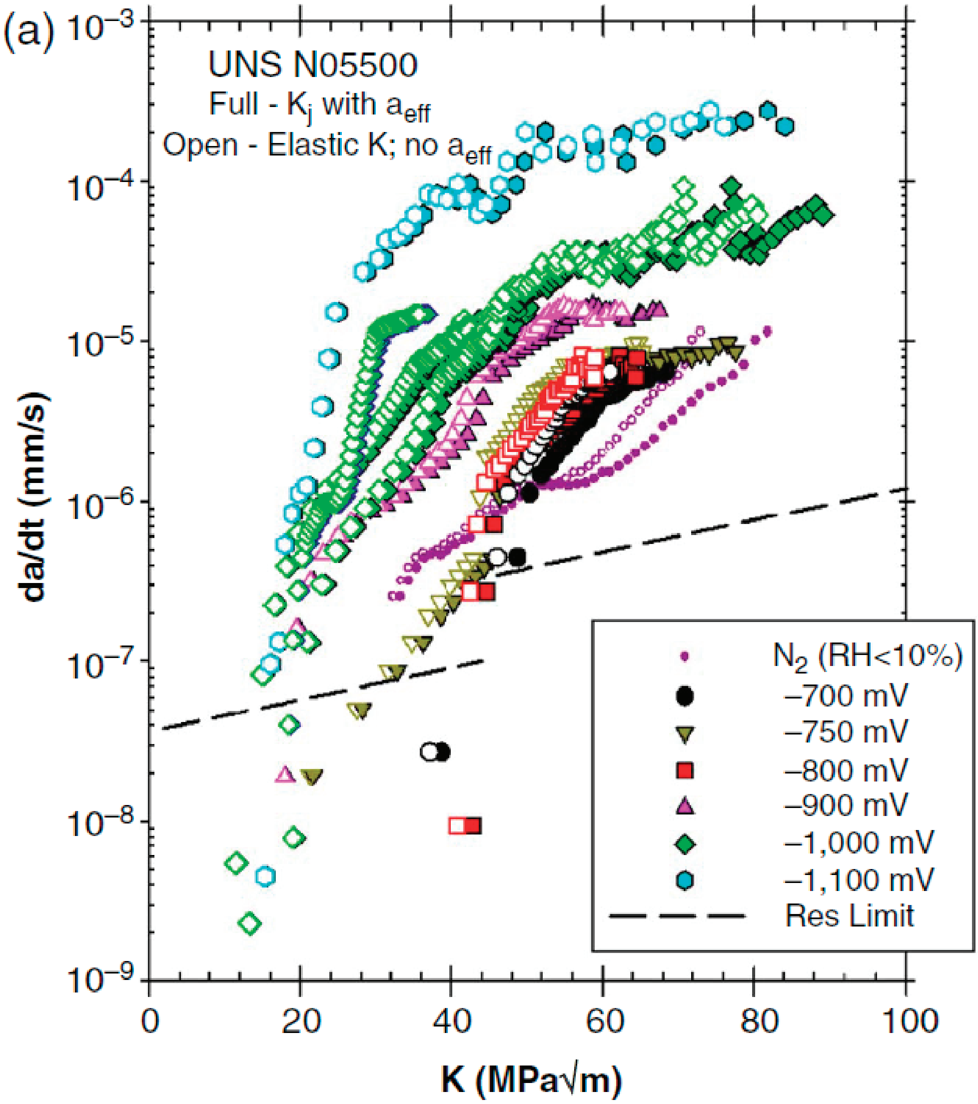

FIGURE 5.1 SENT sample laboratory crack growth rates for Monel K500 in 0.6 M NaCl subjected to various applied cathodic potentials that emulate cathodic polarization of fasteners in service. SOURCE: R.P. Gangloff, H.M. Ha, J.T. Burns, et al., Measurement and modeling of hydrogen environment-assisted cracking in Monel K-500, *Metallurgical and Materials Transactions A* 45:3814, 2014.

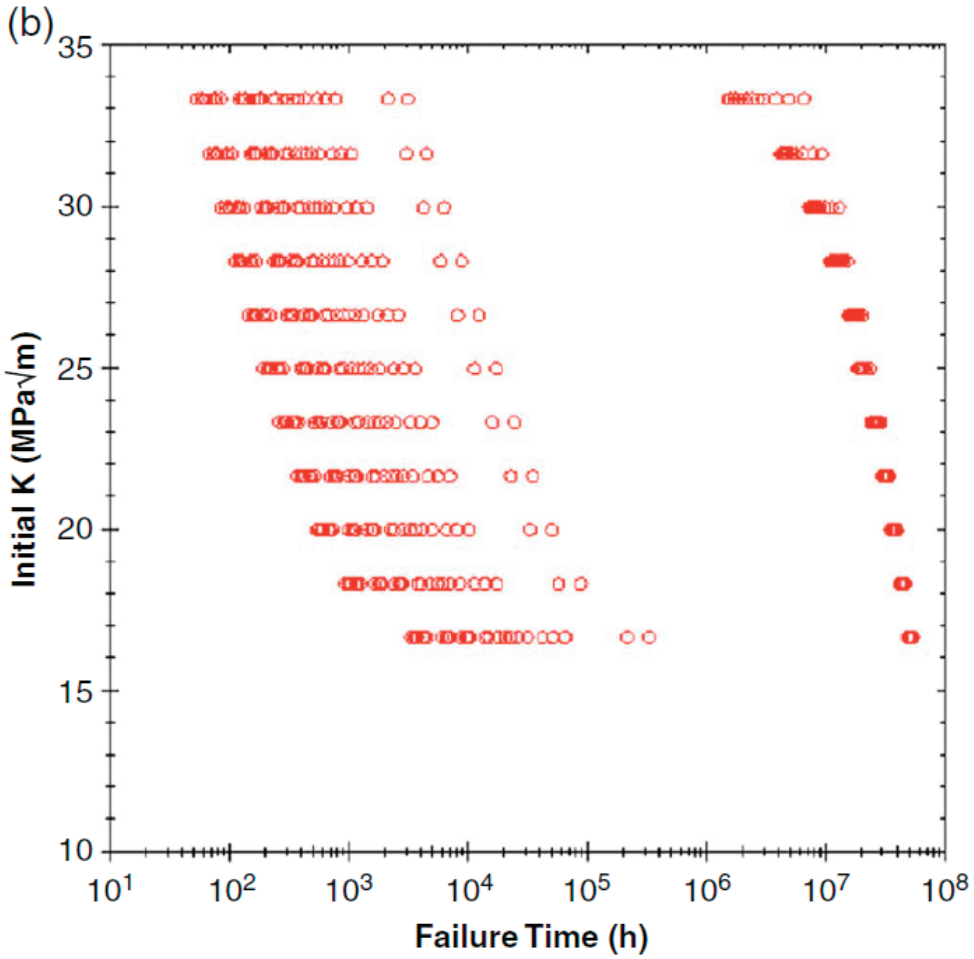

FIGURE 5.2 Failure time from hydrogen embrittlement as an initial applied stress intensity as a function of the assumed applied potential range from −714 to −946 mV_{SCE}, which produces a corresponding change in hydrogen level detailed elsewhere (see J.H. Ai, H.M. Ha, R.P. Gangloff, and J.R. Scully, Hydrogen diffusion and trapping in a precipitation-hardened nickel-copper-aluminum alloy Monel K-500 (UNS N05500), Acta Materialia 61(9):3186-3199, 2013). Data with longer failure times contained a lower hydrogen level.

hydrogen level produced by the cathodic protection is reduced. At the threshold stress intensity as indicated in Figure 5.1, the lifetime approaches infinity, especially for materials with fast crack growth rates once HAC is initiated. The focus of this type of software might therefore have to be on the threshold conditions for onset of HAC. The best utility might be to answer questions like; what are the range of field conditions (that are captured in the model) that can avoid crack initiation. In this regard, there may be gaps in the capabilities of existing software to meet the needs of oil and gas application. At the threshold stress intensity indicated in Figure 5.1, the lifetime approaches infinity.

Value Proposition

Such tools can be a valuable adjunct to other methods in predicting lifetimes of undersea bolts in environments where hydrogen uptake is likely. The value of the tool is to run various possible scenarios; not in its precise ability to predict life as the model cannot capture everything in the field conditions that might be important. However, the sensitivity to a field variable can be assessed if that variable can be captured in the model.

Feasibility

These computational codes are commercially available now.[7] There are companies and federal agencies that utilize these tools now especially in the aerospace fatigue community where AFGRO^{TM} and NASGRO TM[8] are routinely employed in the case of fatigue.[9] The nuclear industry is another example.[10] The challenge here is to replace dry fatigue data with stress corrosion and HAC data from da/dt vs. K (SIF) and incorporate environmental factors such as cathodic potential and hydrogen content which AFGRO^{TM} does not easily accommodate, and to replace the data base approach with mechanistic data. Programs should be undertaken to develop the fidelity of such a model including physical, environmental metallurgical and electrochemical factors. Models could be greatly improved via a multi-year study with an entity that can develop the software coupled with an entity that un-

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[7] VEXTEC Corporation, VEXTEC, 2015, http://www.Vextec.com.

[8] Southwest Research Institute, "NASGRO Fracture Mechanics and Fatigue Crack Growth Analysis Software," NASGRO, Ver. 8.0, 2015, http://www.swri.org/4org/ d18/mateng/matint/nasgro.

[9] AFGROW.net, "AFGROW Fracture Mechanics and Fatigue Growth Analysis Software Tool," AFGROW, Ver. 5.01, 2010, http://www.afgrow.net.

[10] B.A. Young, S.M. Lee, and P.M. Scott, "Sensitivity Analyses for a PWR SCC Case Using the Probabilistic Loss-of-Coolant-Accident (Pro-LOCA) Software," Paper No. PVP2016-63085 in *Proceedings of the ASME Pressure Vessels and Piping Conference 2016*, Volume 6a, 2017, http://proceedings.asmedigitalcollection.asme.org.

derstands the mechanisms and the theory as well as acquires the data. However, the simple models are deployable now without this added sophistication.

Robust Understanding of Rare Failure Events

One of the challenges of bolt failures in the oil and gas drilling industry is the reported extremely low failure rate a product of the rare reported failures. Until an industry wide fastener inspection program finds more failures what is needed is a robust understanding of the causes of rare failure events in a large population of fasteners, which pending more thorough analysis might not have much HAC damage seen in the form of subcritcal cracks. It is imperative to understand what detailed factors are the drivers for HE and which are not. The first step is to obtain a better definition of failure and then analyze the failure rate. Voluntary reporting of failures has been a major challenge in the past, and lack of such reporting is a severe shortcoming; since mandatory reporting of identified failures is now required, over time this challenge will be met.

Moreover, if a failure is defined by separation of a single fastener, the presence of cracks beyond an equivalent initial flaw size in many fasteners that did not separate, or the loss of a pressure boundary may not be adequately captured in the failure database. The definition of failure for legal and warranty purposes differs from the definition of failure that is the most useful to the understanding of such rare events. The first step in developing this understanding is the availability of a more complete data set to enable such a data driven analysis. Assuming the suggestion of rare events, there is a shortage of data on the condition of a large population of fasteners under substantial similar conditions as those of the failed fasteners. Industry is encouraged to harvest a large number of fasteners before the next time separations are detected as is done in the nuclear community.[11] The conditions for the actual separation event are likely due to a complex multi-variable process where the combination of low probability conditions sum in some unknown way to trigger cracking. However, it should be recognized from Figures 5.1 and 5.2 that EAC is an extremely non-linear process. Figure 5.2 vividly illustrates that a seemingly routine change in cp level can change ttf by 10^4 hours or more while stress reduction can have high impact as well Currently, the interactive effects of several adverse variables are unknown. Similar conditions may lack one key variable and thereby evade cracking or crack at an extremely low rate and remain undetected. This status is unclear and needs to be understood.

The complexity associated with evaluating and identifying low probability failures is similar to the challenge faced in the issue of steam generator tube cracking in nuclear pressurized water reactors (PWRs). Cracking by stress corrosion cracking (SCC) is one of the most significant corrosion problems along with denting of

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[11] Scott et al., "An Analysis of Baffle/Former Bolt Cracking in French PWRs," 2000.

tubes in commercial nuclear reactors. Reliability issues in steam generators have been studied by Scott, Steahle and Gorman[12,13,14] among others using holistic, deterministic and probabilistic approaches.[15] Scott examined identical heats of alloy 600 (of a type used in a few nuclear generating plants) and found no major differences in the metallurgical conditions of heats which underwent SCC and those that did not. The fact that SCC was observed in multiple heats leads to a challenge that requires scrutiny of approaches used to analyze other rare events. A root cause analysis combined with a fault tree type of analysis might be in order. The approach utilized in the Aerospace and Nuclear communities can serve as an example. Presentations by DNV suggested Bayesian approaches.[16,17,18,19]

Value Proposition

Bolt failures are rare events and any insight into the causes will allow the design of better bolts and more robust connections

Feasibility

Examples have been provided showing how such methods are used. For the needed broad data set, cooperation in reporting bolt failure events will be needed.

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[12] R.W. Staehle and J.A. Gorman, Quantitative assessment of submodes of stress corrosion cracking on the secondary side of steam generator tubing in pressurized water reactors: Part 1, *Corrosion* 59(11):931-994, 2003.

[13] R.W. Staehle and J.A. Gorman, Quantitative assessment of submodes of stress corrosion cracking on the secondary side of steam generator tubing in pressurized water reactors: Part 2, *Corrosion* 60(1):5-63, 2004.

[14] R.W. Staehle and J.A. Gorman, Quantitative assessment of submodes of stress corrosion cracking on the secondary side of steam generator tubing in pressurized water reactors: Part 3, *Corrosion* 60(2):115-180, 2004.

[15] P.M. Scott, 2000 F.N. Speller Award Lecture: Stress corrosion cracking in pressurized water reactors—Interpretation, modeling, and remedies, *Corrosion* 56(8):771-782, 2000.

[16] J.A. Gorman, 2015 Frank Newman Speller Award: Stress corrosion cracking and nuclear power, *Corrosion* 71(12):1414-1433, 2015.

[17] S. Jain, F. Ayello, J.A. Beavers, and N. Sridhar, "Development of a Probabilistic Model for Stress Corrosion Cracking of Underground Pipelines Using Bayesian Networks: A Concept," pp. 615-625 in *2012 9th International Pipeline Conference, Volume 4: Pipelining in Northern and Offshore Environments; Strain-Based Design; Risk and Reliability; Standards and Regulations*, American Society of Mechanical Engineers, New York, N.Y., 2012.

[18] F. Ayello, S. Jain, N. Sridhar, and G.H. Koch, Quantitive assessment of corrosion probability—A Bayesian network approach, *Corrosion* 70:1128-1147, 2014.

[19] G. Koch, F. Ayello, V. Khare, N. Sridhar, and A. Moosavi, Corrosion threat assessment of crude oil flow lines using Bayesian network models, *Corrosion Engineering, Science and Technology* 50:236-247, 2015.

IN SITU MEASUREMENTS

In Situ Bolt Load Measurement

Currently industry does not measure actual bolt tension in situ—either real time or recorded. At least two companies who have exhibited at past Oil & Gas Innovation Showcases potentially have the ability to do this.[20,21] Both systems were originally developed for accurate pre-tensioning of studs and bolts. In the aerospace community instrumented fasteners have been developed and utilized as well.

Value Proposition

If such a system could be modified for deep water environments and deployed on a ROV, pressure boundary bolt inspections could be done on deep water riser system without having to pull the riser and BOP to the surface. Such a system could detect incipient failure and greatly enhance system reliability.

Consider the flange bolts beneath the BOPs themselves. These bolts are ultra-critical because their failure could lead not only to loss of well fluids, it could lead to loss of well control. Consider also that the Failure Analysis portion of a riser design as described in Appendix I is intended to ensure that any riser system failure would occur above the BOPs, and that the riser design effort itself assumes "as new" condition of all riser system components.[22] The ability to inspect such bolts while in service could greatly reduce the likelihood of catastrophic events.

Feasibility

These base technologies are well-developed and fully commercialized. Modification to in situ bolt tensioning monitoring and reporting would likely require some development. Adaptation of this technology to subsea environments is probably not developed and therefore significant development would be required.

In Situ bolt Defect Identification

The Nuclear Regulatory Commission has experience with, and has qualified, existing technology that enables ultrasonic crack detection on underwater bolts

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[20] See the Load Control Technologies website at http://www.loadct.com, accessed October 11, 2017.

[21] See the Sensosurf website at http://sensosurf.de/en/home, accessed October 11, 2017.

[22] Kenneth Bhalla discussions with Willard C. Capdevielle on July 13, 2017; presented to the committee on September 28, 2017.

in situ.[23] The technology consists of an ultrasonic transducer (UT) probe that is remotely placed on a (small. 5/8") bolt head. The probe sends an ultrasonic pulse and analyzes the return signal to detect small cracks.

Value Proposition

If such a system could be modified for deep water environments and deployed on a ROV, periodic bolt inspections could be done on critical fasteners in a deep water riser system without having to pull the riser and BOP to the surface. Such a system could detect incipient failure and greatly enhance system reliability. Also, this ability to inspect bolts while in service may allow greater in-service time for a drilling riser system.

Feasibility

The basic technology is already deployed for underwater use but not for deep ocean environments. Therefore, considerable development would be needed to design new systems or adapt existing systems for larger bolts in high pressure saline environments.

In Situ Assessment of Hydrogen Contents in Steels

During service, hydrogen can enter steel from the environment as modified by cathodic protection systems, interactions with corrosive environments (e.g., sea water), and other potential sources. Assessment of accurate hydrogen contents present in steel connectors during service, based on measurements on bolts removed from service is very challenging as hydrogen will diffuse[24] out of the steel. Hydrogen contents in steels are usually considered as two types, diffusible and trapped hydrogen. As discussed in the sections above, diffusible hydrogen is the primary source of HAC including embrittlement. Several laboratory techniques are

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[23] Jack McHale, Bureau of Safety and Environmental Enforcement Bolt Forum, September 29, 2016.

[24] Diffuse is used here with respect to hydrogen that desorbs at temperatures up to 200°C, which includes weakly trapped and lattice hydrogen.

available to determine both diffusible and total hydrogen contents in steels.[25,26,27,28,29] However, to date, no technique has been developed to evaluate steel connector hydrogen contents in situ. Recently advanced nondestructive techniques have been developed to assess hydrogen contents during service in pipeline steels.[30] It is recommended that a critical assessment of potential methods to evaluate hydrogen contents in off-shore connectors during service be undertaken to identify potential innovative techniques for further study.

Value Proposition

The availability of an innovative hydrogen measuring technique that could accurately assess the hydrogen contents of connectors in service would be an extremely valuable tool to help ensure safety of off-shore connectors that are susceptible to HAC. With such a development, essential data on the actual hydrogen contents in bolts as a function of time could be determined. The hydrogen concentration results compared to similar data obtained on laboratory samples failed under controlled conditions with known hydrogen contents, could potentially be used to assess the probability of failure in installed connectors and guide planned maintenance.

Feasibility

Development of a technique for in situ hydrogen measurements will require significant effort as it has low probability of yielding near-term results.

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[25] M. Smialowski, *Hydrogen in Steel—Effect of Hydrogen on Iron and Steel During Production, Fabrication, and Use*, Pergamon Press, Oxford, U.K., 1962.

[26] T.D.A.A. Senadherra, "Accurate Measurement of Hydrogen in Steel," Ph.D. Thesis, University of Calgary, Calgary, Alberta, Canada, April 2013.

[27] LECO, "DH603: Residual and Diffusible Hydrogen Determination by Hot Extraction," https://www.leco.com/products/analytical-sciences/total-hydrogen/dh603, accessed May 2017.

[28] TWI, "How Do I Measure the Diffusible Hydrogen Level in My Ferritic Steel Weld?," http://www.twi-global.com/technical-knowledge/faqs/material-faqs/faq-how-do-i-measure-the-diffusible-hydrogen-level-in-my-ferritic-steel-weld/ (accessed May 2010).

[29] Z. Feng, L.M. Anovitz, P. Kironko, A. Duncan, T. Adams, and P. Sofronis, "Permeation, Diffusion, Solubility Measurements: Results and Issues," presentation to the 2007 Hydrogen Pipeline Working Group Workshop, September 25, 2007, https://energy.gov/sites/prod/files/2014/03/f10/pipeline_group_feng_ms.pdf.

[30] G2MT, "Oil and Gas," http://www.g2mt.com/technologies/oil-and-gas/, accessed May 2017.

In Situ Analysis of Hydrogen and Hydrogen-Assisted Cracking Susceptibility Using Surrogate and "Canary" Materials

Another approach to testing for local area of susceptibility is to deploy surrogate materials instrumented for in situ hydrogen sampling or even direct evidence of HAC. In one instrumented test rig produced under DOD sponsorship,[31] a compact EAC sensing device was designed to provide insightful early warning capability, alerting engineers to environmental conditions which produced cracking susceptibility in a surrogate material. The primary sensing element employs a circumferentially notched tensile sample of similar material as the structure of interest. An alternative is to use a "canary" material[32] with slightly greater susceptibility than the material deployed. The idea is that the canary material with undergo environmental cracking before the deployed material in service and serve to give early warning and indication of potentially problematic conditions. The sample is preloaded to the nominal stresses in the structure. Electrically coupling the sample to the structure places it under similar electrochemical conditions as seen in the field such as cathodic polarization level. An onboard Ag/AgCl reference electrode provides a secondary indicator of the cracking potential. Crack propagation is monitored by observing preload shedding with an embedded load cell. Analysis of hydrogen concentrations in high carbon strain wire for use in prestressed concrete has demonstrated that correlations to hydrogen concentrations can be made. For this example, a commercially available low carbon steel permeation sensor was used.[33,34] A related approach could measure hydrogen content through exploiting the resistance change in a wire electrode as a function of hydrogen content or using another novel in situ hydrogen measurement method. The approach discussed above has been developed and an example is shown in Figures 5.3 and 5.4. Figure 5.3 shows such an instrumented bolt that is open on the sides to the marine environment of service environment of interest.[35] The bolt is instrumented with a

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[31] N.K. Brown and F.J. Friedersdorf, Luna Innovations, Inc., "LUNA, Compact Fracture Mechanics-Based Sensor for Monitoring Environment Assisted Cracking," paper presented at the DOD Allied Nations Corrosion Conference, 2011, http://lunainc.com/wp-content/uploads/2013/04/Luna-EAC-sensor-DoD-Corrosion-2011.pdf.

[32] The term "canary" comes from an analogy with the use of canaries to sense and provide early warning of dangerous gases in underground mines.

[33] D.G. Enos, A.J. Williams, Jr., G.G. Clemena, and J.R. Scully, Impressed-current cathodic protection of steel-reinforced concrete pilings: Protection criteria and the threshold for hydrogen embrittlement, *Corrosion* 54(5):389-402, 1998.

[34] D.G. Enos, A.J. Williams, Jr., and J.R. Scully, Long-term effects of cathodic protection on prestressed concrete structures: Hydrogen embrittlement of prestressing steel, *Corrosion* 53(11):891-908, 1997.

[35] Brown and Friedersdorf, "LUNA, Compact Fracture Mechanics-Based Sensor for Monitoring Environment Assisted Cracking," 2011.

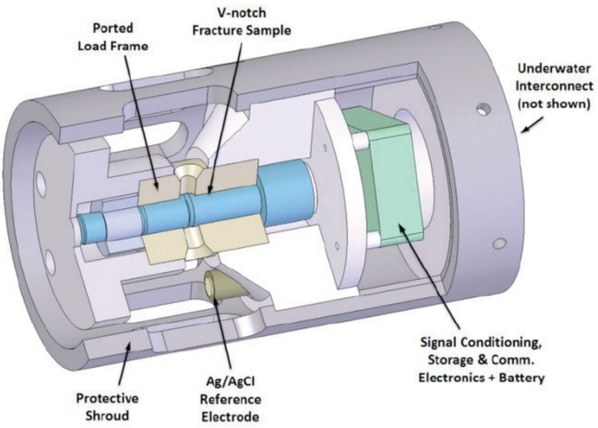

FIGURE 5.3 LUNA hydrogen-cracking sensor consisting of a bolt machined from the canary alloy, a reference electrode, and a load cell to calculate crack length based on load drop in a spring-loaded arrangement with a load cell sensor.

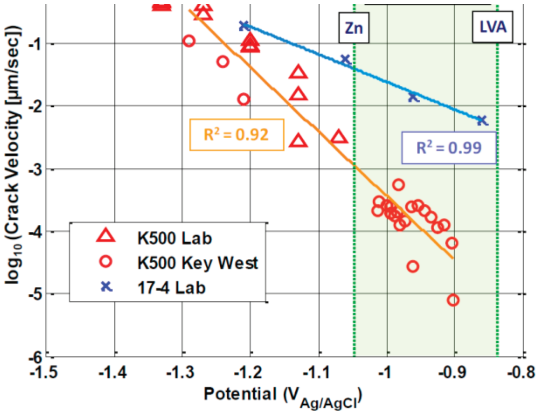

FIGURE 5.4 Crack velocity versus potential obtained from the LUNA instrumented bolt. The polarization levels provided by a low voltage anode (LVA) and zinc anode (Zn) are indicated.

reference electrode to monitor cathodic potential. Figure 5.4 shows the measured crack growth rate as a function of applied cathodic potential for two materials; Monel K-500 and 17-4 PH precipitation aged hardened stainless steel. The galvanic couple potential to Zn and low-voltage anodes (LVAs) is shown. The target potential of –0.8 V SCE is seen to lower the crack growth rate of the MK 500 to at or below 10^{-5} μm/sec.

Value Proposition

This is another method which could provide early warning of incipient failures, such as those that would only be otherwise discovered at the worst possible time—that is, during a catastrophic well control event. Such a system has the potential to prevent serious environmental accidents caused by bolting failures by providing an early warning. The use of canary alloys can be exploited to provide an alarm that warns of conditions that warrant extra scrutiny. The sensitivity to changes in operations or the impacts of one-time events may be detectable with current technology.

Feasibility

This technology has been developed for undersea applications. The LUNA bolt was developed under an Office of Naval Research (ONR) initiative for subsea applications. The most immediate challenge is to develop the methodology for oil rig applications with robust durability in the field and measurement longevity. It also would be useful to gain an understanding of where on a BOP to deploy such a "high value" sensor. Another challenge is to develop a calibration curve to relate the canary alloy hydrogen concentration to the concentration in the fastener material itself. Finally, methods would be needed to supply this information to the surface vessel or platform.

Fatigue Monitoring System

A fatigue monitoring system is an instrumented system capable of monitoring vibrations of risers to better estimate fatigue, and communicate results to the surface.[36,37]

Value Proposition

Even though fatigue failures have not been noted in riser/BOP systems to date, fatigue is a critical design parameter for subsea equipment such as drilling risers that are exposed to cyclic loads from wind, waves, currents, and flow; vortex-

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[36] A prototype of such a system has reportedly been developed by Stress Engineering. This system reports the existence of vibrations. See Stress Engineering Services, Inc., "Riser & Wellhead Fatigue Monitoring," http://www.stress.com/capabilities/upstream/instrumentation-and-data/riser-wellhead-fatigue-monitoring.

[37] Additional references and further reading for this section include the following papers submitted for Offshore Technology Conferences, all available at http://www.onepetro.org/conference paper: D.J. Kluk, S.I. McNeill, K. K. Bhalla, T. Saruhashi, I. Sawada, M. Kyo, E. Miyazaki, and Y. Yamazaki, "Development of a Real-Time Riser Fatigue Monitoring System," OTC 24216, 2013; P. Agarwal, S. McNeil, K. Bhalla, and K. Walker, "Validation of Global Riser/Wellhead Analysis Using Data from a Full-Scale Measurement Campaign," OTC-27808-MS, 2017; S. McNeill, P. Agarwal, D. Kluk, K. Bhalla, R. Young, S. Burman, S. Liapis, S. Jain, V. Jhingran, and S. Hodges, "Subsea Wellhead and Riser Fatigue Monitoring in a Strong Surface and Submerged Current Environment," OTC-25403-MS, 2014; S. McNeill, P. Agarwal, D. Kluk, K. Bhalla, "Exploring the Benefits of Wellhead Fatigue Monitoring," OTC-25677-MS, 2015.

induced vibration (VIV). The ability to measure actual fatigue loads on a riser system can provide data to better:

- Ensure the integrity of the riser system and its components,
- Calibrate fatigue models used in the design process, and
- Understand post mortems on failed and un-failed equipment.

Feasibility

At least one prototype system has been developed and was subjected to field trials. Other systems may exist in development. Questions such as long-term reliability, accuracy, and wireless communication capability would also have to be proven, as well as the value proposition of cost versus benefit.

Monitoring of Connector Integrity

While the holy grail of connector integrity, real time monitoring, is achievable in the laboratory, the harsh undersea conditions make this ideal approach difficult as discussed in the examples above. A less ambitious monitoring approach that might still produce a tangible warning that connector integrity is at risk should be considered. Such a warning would then warrant further targeted connector inspection, perhaps by a remotely operated vehicle (ROV) using a crack detection technology such as ultrasound (discussed above), that could be applied in situ before employing more difficult and expensive means. Since many of the pressure boundary critical connectors are also the load bearing elements between the riser and the well head, it is a reasonable hypothesis that the compliance of the BOP and LMRP in response to the continuing tension from the riser system would measurably change at some point as its structural integrity was reduced by cracking or failures of these critical connectors. The same circuitry used to monitor the yellow and blue pods, running from the lower marine riser to the surface, could be utilized to transmit this additional monitoring information to the surface. This particular application would appear to be well suited to the current advances in artificial intelligence, which are highly useful in distilling vast amounts of incoming data to information of interest. If this processing were collocated undersea with the sensors (strain gages, accelerometers, microphones, etc.), the data bandwidth demand to the surface would be small. Properly executed machine learning could improve the accuracy of the system with time.

Value Proposition

This proposal would likely be faster to implement and less costly to develop than the more specific in situ testing of individual bolts.

Feasibility

Much of this proposed technology is well established and the remaining task is that of deploying it undersea with the associated communications needed.

IMPROVING THE HYDROGEN-ASSISTED CRACKING RESISTANCE OF BOLT ALLOYS

Uncovering Sources of Embrittling Hydrogen in Fastener Materials

One of the shortcomings that plagues a root cause analysis is unequivocal sourcing of damaging hydrogen that enters fasteners. Past fastener failures have been blamed on hydrogen not baked out in manufacturing. In situ it is common to assume that the dominant and most long-lasting source of hydrogen in deep seawater exposure is cathodic reactions supplied by sacrificial anode based cathodic protection, impressed current cathodic protection or a sacrificial coating. Cathodic protection (CP) systems are favored as the likely source because the seawater and CP systems are open systems with an infinite supply of hydrogen. In contrast, plating results in a finite amount of hydrogen entry during processing and then the process is terminated unless exposed in a corrosive environment. Then the coating functions like the cathodic protection system to cathodically polarize the bolt until it reaches its coating lifetime at which point cathodic protection from the coating ceases. The presence of finite hydrogen contents due to plating may be true broadly speaking, however, recent bolt failures reported to BSEE have occurred in bolts that were zinc plated, not baked to remove hydrogen and then exposed to marine service.[38] and those that were baked well beyond the requirements.[39] Thus, whether the observation of cracking in plated bolts is indicative of combined sources of hydrogen from coating deposition or service remains to be seen. Few studies have combined prior plating and partial or incomplete baking with subsequent exposure to cathodic protection to sort out and assess the importance of damaging sources.[40] That thousands of reportedly unbaked bolts were returned from undersea service with no reported cracking certainly throws doubt on the RCA that blamed the lack

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[38] TransOcean Failure report is the reference here.

[39] Seadrill WC Failure report.

[40] H.E. Townsend, A study of the entry and removal of hydrogen during coating and thermal-treatment of steel, *Corrosion* 37:115-120, 1981.

of baking. The fate of hydrogen during surface preparation, processing, coating, interim storage and then service with cathodic protection is complex.[41] This is especially the case in high strength materials where hydrogen sourced from plating is only partially outgassed (and may be enhanced by improper baking) except at very high temperatures precluded by tempering effects which are to be avoided.[42]

As background, internal hydrogen repartitions to traps and tensile stress fields at second phases and at crack tips. The amount of hydrogen remaining after baking may seem to be small in comparison to the field supply. However, if intermediate strength traps retain hydrogen even after baking this hydrogen can then redistribute to sharp crack tips with high triaxial tensile stress, then a critical hydrogen level might be attained. This is due to the combination of residual hydrogen from the coating that is repartitioned and service exposure to cathodic protection. Other sources of hydrogen should be mentioned such as greases and lubricants that might contain hydrogen recombination poisons that acerbate hydrogen uptake. The complexity regarding the viable sources of hydrogen continue to rise as harsh service conditions expand and as deep seawater service become more prevalent. It should be noted that iron corrosion is thermodynamically possible during coupled water reduction in the absence of any cathodic protection. Therefore, a thorough study of hydrogen sources and quantification may be warranted.

Value Proposition

A comprehensive understanding of the sources of embrittling hydrogen would be the first step in permitting control of the sources and potentially prevent hydrogen induced cracking in bolts. This would also allow a process of elimination in root cause analyses that might otherwise offer misguided advice on the source of hydrogen and culprit in failures; these incidents do not help move safety and reliability forward.

Feasibility

As outlined above there are many possible sources of hydrogen for undersea bolting. A research program is needed to separate and quantify the importance of these sources. In the studies of Townsend and Scully herein, different sources and the benefits of outgassing steps were identified. The laboratory instrumentation exists now to conduct a step by step analysis only requiring harvested bolts and a

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[41] H.E. Townsend, Effects of zinc coatings on stress-corrosion cracking and hydrogen embrittlement of low-alloy steel, *Metallurgical Transactions A* 6:877-883, 1975.

[42] H. Dogan, D. Li, and J.R. Scully, Controlling hydrogen embrittlement in precharged ultrahigh-strength steels, *Corrosion* 63(7):689-703, 2007.

program to make such investigations. Well controlled studies in a laboratory setting would remove uncertainty over outgassing during retrieval.

21st Century Metallurgical Design of Hydrogen Resistant Alloys

The knowledge exists today to optimize the design of connector alloys with improved intrinsic resistance to HAC cracking. An issue is always whether all fastener materials property requirements can be met. Alloys may be designed to (1) resist hydrogen production and uptake, (2) trap and sequester hydrogen away from fracture sites like grain boundaries, (3) provide improved fracture resistance (or a higher critical hydrogen concentration) through interface engineering or/or grain boundary and texture engineering to render the material less susceptible to a given hydrogen level. The chart below illustrates some of the strategies. A recent survey of possible alternative fastener alloys using off-the-shelf materials was compiled by Raymond.[43] In this case, empirical screening was used. Precipitation aged hardened variants of Cu-Ni and Ni-Cr-Mo alloys were explored and found to exceed the hydrogen resistance of steels when subjected to cathodic polarization. Gangloff recently explored some martensitic stainless steels that would not require zinc plating, organic coatings, or cathodic protection.[44] These alloys were invented using the CALPHAD approach of ICME[45] with empirical intuition. The alloy was optimized via the Rice-Wang approach to interface engineering.[46]

Amongst the measures available for intrinsic improvements in alloy resistance are segregation control such as by adding rare earth elements for gettering of deleterious elements like sulfur,[47] trap control, alloy cleanliness and other measures

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[43] L. Raymond, *Fracture and Stress Corrosion Cracking Resistance of C465, BioDur 108, SpT 13-8, K-Monel 500, and Zeron 100*, Report #CTC'071024, L. Raymond and Associates, Newport Beach, Calif., 2008.

[44] G.L. Pioszak and R.P. Gangloff, Hydrogen environment assisted cracking of modern ultra-high strength martensitic steels, *Metallurgical and Materials Transactions A* 48:4025-4045, 2017.

[45] G.B. Olson, Genomic materials design: The ferrous frontier, *Acta Mater* 61:771-781, 2013.

[46] J.R. Rice and J.S. Wang, Embrittlement of interfaces by solute segregation, *Materials Science and Engineering: A* 107:23-40, 1989.

[47] C.L. Briant, Grain boundary structure, chemistry, and failure, *Materials Science and Technology* 17:1317-1323, 2001; C.L. Briant, Solid solubility and grain boundary segregation, *Philosophical Magazine Letters* 73:345-349, 1996; C.L. Briant, Sources of variability in grain-boundary segregation, *Acta Metallurgica* 31:257-266, 1983; N. Bandyopadhyay and C.L. Briant, Caustic stress-corrosion cracking of NiCrMoV rotor steels—The effects of impurity segregation and variation in alloy composition, *Metallurgical Transactions A* 14:2005-2019, 1983; H.K. Birnbaum, B. Ladna, and E. Sirois, Hydrogen segregation to grain-boundaries and external surfaces, *Zeitschrift für Physikalische Chemie* 164:1157-1164, 1989; D.H. Lassila and H.K. Birnbaum, Intergranular fracture of nickel—The effect of hydrogen-sulfur co-segregation, *Acta Metallurgica* 35:1815-1822, 1987; D.H. Lassila and H.K. Birnbaum, Hydrogen embrittlement of nickel—The effect of hydrogen segregation at grain-boundaries, *JOM: Journal of The Minerals, Metals and Materials Society* 36:61, 1984.

to increase resistance to cracking for a given hydrogen level.[48] In some materials, boron has been added as a bond promoter. Computational material design enables rapid through-put screening of alloying elements that are bond promoters. Similarly, screening of elements that change the kinetics of the hydrogen evolution may be undertaken. Figure 5.5 shows a number of strategies. Many models of HE proposed that stage II crack growth rate is a direct function of hydrogen diffusion rates.[49] A series of benign traps such as vanadium or molybdenum carbides can be engineered to slow diffusion. The trap binding energy needs to be strong enough so that hydrogen is not supplied to the stress field of the crack tip.[50] Pd added to PH 13-8 Mo operated in a similar manner.[51] A PdAl precipitate was formed that sequestered hydrogen and minimized partitioning of hydrogen to the crack tip. Other trap engineering concepts could sequester hydrogen permanently through strong irreversible trapping at sites which do not trigger boundary cracking such as TiC.[52]

Caution is warranted in oil and gas systems where the open system (continual hydrogen production) can lead to saturation of such traps and subsequent EAC. Different measures may be utilized to decrease hydrogen production, uptake and trapping with the goal of bringing about a lower diffusible hydrogen content. The goal is not to change intrinsic susceptibility but to lower the hydrogen content or getter the hydrogen at innocuous trap sites. It should be noted that trap site control is complex and may not be feasible in open systems (see Box 5.1) allowing continual hydrogen production and uptake where trap filling and saturation may occur. There are also new emerging compositionally complex alloys which might experience reduced hydrogen transport rates such as high entropy alloys or HEAs. These materials might enable more resistant fastener materials.

Value Proposition

A high strength fastener material with high HAC resistance exhibited by high fracture toughness and high threshold stress intensity in the presence of hydrogen

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[48] R.P. Gangloff, "Hydrogen Assisted Cracking of High Strength Alloys," pp. 31-101 in *Comprehensive Structural Integrity* (I. Milne, R.O. Ritchie, B. Karihaloo, eds.), Vol. 6, Elsevier Science, New York, N.Y., 2003.

[49] R.P. Gangloff, "Diffusion Control of Hydrogen Environment Embrittlement in High Strength Alloys," in *Hydrogen Effects on Material Behavior and Corrosion Deformation Interactions* (N.R. Moody, A.W. Thompson, R.E.. Ricker, G.S. Was, and R.H. Jones, eds.), The Minerals, Metals and Materials Society, Warrendale, Pa., 2002.

[50] H.K.D.H. Bhadeshia, Prevention of hydrogen embrittlement in steels, *ISIJ International* 56:24-36, 2016.

[51] J.R. Scully, J.A. Vandenavyle, M.J. Cieslak, A.D. Romig, and C.R. Hills, The influence of palladium on the hydrogen-assisted cracking resistance of PH 13-8 Mo stainless-steel, *Metallurgical Transactions A* 22:2429-2444, 1991.

[52] Internal trapping in TiC does require high temperature and high thermal energy but the interface may trap hydrogen or be engineered to trap hydrogen in seawater near room temperature.

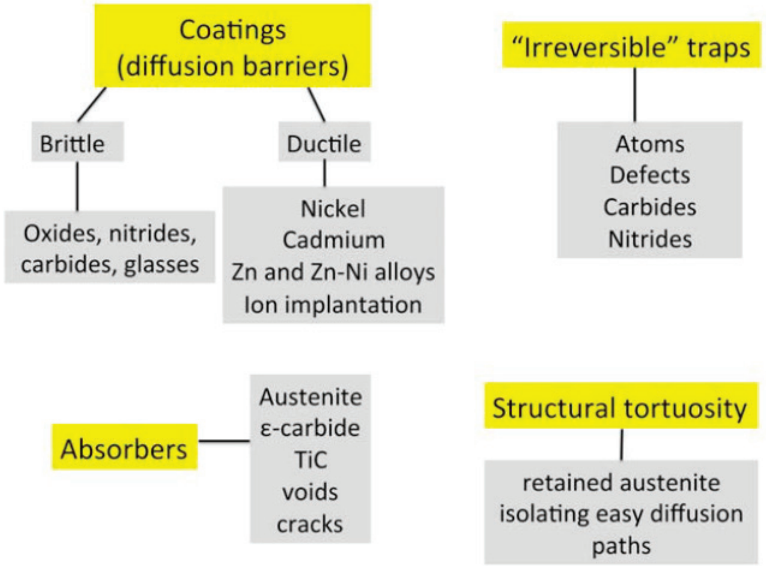

FIGURE 5.5 Strategies for improving the resistance to hydrogen-assisted cracking in steels using a variety of strategies indicated in yellow and specific details in grey. SOURCE: Cambridge, permission granted.

would be very beneficial to design and deployment of HAC "immune" or "highly resistant" materials that would have a low probability of HAC in service. This would lessen pressures to optimize cathodic protection such as with low voltage anodes or other measures aimed at controlling the environment and allow a larger margin of error concerning accidental non-baking and cathodic protection hot spots. The margin of error due to over torque or bending loads would also be increased.

Feasibility

A major challenge in many commercial industry sectors is the need for high strength materials with excellent resistance to hydrogen. The goal of a >1 GPa (145 ksi) yield strength materials with excellent resistance to intermediate level of diffusible hydrogen is now likely realizable if all the principles of ICME are harnessed. These include grain boundary and interface engineering, use of bond promoters, use of gettering agents such as rare earth treatments perhaps integrated with a choice of an alloying element which forms an oxide film that functions as a permeation barrier. Computational approaches now exist for high-throughput searching for the best combination of alloying elements to achieve the above goals while maintaining desirable strength and toughness. The state of the art is ripe for achieving this goal.

BOX 5.1
Closed versus Open Systems for Hydrogen Charging

In a closed system there are a fixed number of moles of hydrogen already absorbed in the fastener such as from zinc plating and no more enters or leaves—this situation applies to circumstances such as some hydrogen entry during processing and presence of a coating or natural oxide that is a permeation barrier. In the limit there is no further entry in service (see open systems below). The significance to mitigation strategies is that fasteners could be metallurgically engineered to trap or sequester hydrogen at "benign" sites especially when there is a finite quantity of hydrogen. Benign in this case means that the hydrogen is captured in metallurgical sites that are not or do not also serve as fracture paths such as prior austenite grain boundaries in steels. In these cases it could be argued that only a fraction of the hydrogen absorbed needs to be captured such that an insufficient quantity of hydrogen can repartition to the tensile triaxial stress field of a notch or crack.

In an open system the number of moles is not fixed and instead there can be hydrogen mass transport across interfaces both in and out of a fastener. The flux of hydrogen and the fugacity or coverage of adsorbed hydrogen (surface conc) may change in response to the service conditions (In this case corrosion or cathodic protection level) and additional hydrogen entry is thereby possible. The significance to trap and interface engineering against hydrogen-assisted cracking is that the additional flux and accumulation of hydrogen may eventually saturate so called "saturable" trap sites or exceed the critical hydrogen coverage required for grain boundary fracture even if the interface engineered boundary requires an increased hydrogen coverage to trigger fracture. Each trap can fill in an open system independent of other traps if an equilibrium lattice hydrogen concentration is raised in response to severe cathodic protection. However, it should be noted that presence of traps of sufficient binding energy and density provides a permanent impedance to transport such that stage II crack propagation rate proportional to the effective hydrogen diffusion rate never approaches the perfect lattice hydrogen diffusion rate. Consequently, traps can function to slow hydrogen diffusion and thus cracking even in an open system.

COATING TECHNOLOGIES

Nitrided 4130, 4340 Bolts for Improved Corrosion Resistance

Bolts made from medium carbon martensitic steels, such as 4130, 4140 and 4340, can be interstitially hardened with nitrogen to a shallow case depth (e.g., 0.15 mm, 0.006 in.) for the purpose of providing a surface layer resistant to corrosion.[53,54]

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[53] D. Pye, "Practical Nitriding and Ferritic Nitrocarburizing," Chapter 2 in *Why Nitride*, ASM International, Metals Park, Ohio, 2003.

[54] P. Weymer, "Principles of Gas Nitriding, Heat Treating Progress," *Heat Treating Progress*, ASM International, Metals Park, Ohio, July/August 2009.

Value Proposition

Nitriding has reportedly been useful in reducing the corrosion rate of steels. It is a well-developed, relatively low-cost process.[55] Since nitriding is a gaseous process, it is capable of diffusing into the threaded area without requiring special tooling, so the coverage can be uniform. Nitriding does not affect surface finish or part dimensions.

Feasibility

The nitriding process itself is mature. For example, GE Aviation, after an extensive qualification program, started nitriding M50 steel used in mainshaft engine bearing races and rolling elements. The motivation was to increase surface hardness and reduce susceptibility to spallation of the race. Surface residual stress is about −700 to −1050 MPa (−100 ksi to −150 ksi) to a depth of 0.15 mm (0.006 in.) have been reported. Since instituting nitriding 5 years ago, there have been no bearing failures.[56]

There are no reports of nitrided bolts being employed in subsea critical applications, so it is an immature technology, but with significant promise. The qualification process could be used to mature the technology.

Key development risks that would need to be investigated include the following:

- The susceptibility of the nitrided bolt to standard aqueous corrosion (when the bolt is out of the seawater) needs to be determined. There are literature reports that nitrided surfaces are less susceptible to aqueous corrosion but quantitative data is not presented.[57]
- Process control of the kinetics of nitrogen diffusion is critical. A uniform diffusion zone is most desirable, minimizing the formation of a brittle "white layer" which is composed of iron nitrides.[58,59] For the selected nitriding

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[55] J. Darbellay, "Gas Nitriding: An Industrial Perspective," MSE 701 Seminar, Department of Materials Science and Engineering, McMaster University, March 22, 2006 coursenotes.mcmaster.ca/701-702.../2005.../701_JeromeDarbellay_March_2006.pdf, accessed June 16, 2017.

[56] M. Rhoads, M. Johnson, K. Miedema, J. Scheetz, and J. Williams, *Introduction of Nitrided M50 and M50NiL Bearings into Jet Engine Mainshaft Applications*, STP1580, ASTM International, Washington, D.C., June 2015.

[57] Ibid 168 and 169.

[58] E.J. Mittemeijer, "Fundamentals of Nitriding and Nitrocarburizing," in *ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes* (J. Dossett and G.E. Totten, eds.), ASM International, Metals Park, Ohio, 2013.

[59] K.-M. Winter and J. Kalucki, "Gas Nitriding and Gas Nitrocarburizing of Steels," in *ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes* (J. Dossett and G.E. Totten, eds.), ASM International, Metals Park, Ohio, 2013.

method, process parameters will have to be established for each bolt size and material. Slow nitriding is a low temperature process, performed around 450°C (840°F).[60,61] Nitriding is the last processing step, unless a coating is applied on top of the nitrided surface. The bolt must be austenitized, hardened, tempered, and fully formed before nitriding.[62]

- Demonstrate no loss of fracture toughness or loss of ductility in the nitrided bolt.
- Demonstrate that a nitrided steel bolt will not fail by HAC within the time period of interest. The surface residual stress may have to be tempered, but there is some evidence that nitriding can be beneficial in forestalling hydrogen embrittlement·[63,64,65]
- The resulting surface will be hardened to 55 HRC or greater. This will require change to the specifications that currently require final hardness value much lower than this. Hardness checks should be made pre-nitriding and post-nitriding.
- Qualify nitrided bolts for subsea critical applications.

Multi-Functional and Smart Coatings

Oil and gas fasteners are produced from high strength quenched and tempered steels. Coatings used to date for fasteners are mostly focused on general corrosion, friction, and galling concerns. Organic coatings such as Xylan[66] resist corrosion through functioning as a barrier and serve to reduce make-up and breakout torque. Sacrificial anode based coatings such as zinc are often electroplated to protect against general corrosion especially prior to deployment. Many of these coatings may not last beyond interim surface storage before offshore service. However, hydrogen baking is still necessary since zinc is electroplated and requires baking to remove hydrogen co-deposited with metal. A study with Cd indicated that baking

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[60] D. Pye, "The Power of Pulsed Plasma Ion Nitriding," *Heat Treating Progress*, ASM International, Metals Park, Ohio, July/August 2009.

[61] D. Pye, "Practical Nitriding and Ferritic Nitrocarburizing," Chapter 1 in *Introduction to Nitriding*, ASM International, Metals Park, Ohio, 2003.

[62] Ibid 169

[63] X.F. Li, J. Zhang, M.M. Ma, and X.L. Song, Effect of shot peening on hydrogen embrittlement of high strength steel, *International Journal of Minerals, Metallurgy, and Materials* 23:667-675, 2016.

[64] A. Turnbull and S. Zhou, Residual stress relaxation in shot peened high strength low alloy steel and its implications for hydrogen assisted cracking, *Journal of Materials Science and Technology* 26:824-832, 2010.

[65] U.S. Patent 20120298262 A1, "High Strength Steel and High Strength Bolt Excellent in Delayed Fracture Resistance and Methods of Production of Same," issued November 29, 2012.

[66] Whitford, "Industrial Coating Guide," http://whitfordww.com/industrial/oil-and-gas.html, accessed October 11, 2017.

can result in both some hydrogen ingress and some greater hydrogen uptake into the material from the co-deposited hydrogen and cadmium. This needs to be a controlled aspect of baking practice and not subject to vendor variability. Moreover, older baking standards have rarely considered baking followed by cathodic protection (the real service conditions).

Several objectives are required for the ideal fastener coating that functions to reduce HAC susceptibility; these include corrosion protection, minimization of hydrogen uptake and production, and some ability to protect scratches, defects or flaws. From a probability standpoint (each layer may fail or cease to perform its function over its service life), deployment of several of these strategies at the same time would be attractive. Some newer commercial metallic coatings seek to tune the metallic galvanic couple behavior to be less aggressive than zinc based coatings. Inhibitor type coatings are also possible that release chemical inhibitors that inhibit cracking. These are prevalent in aerospace but might lack the lifetime necessary for offshore service. Moreover, there are hydrogen permeation barrier coatings such as metal oxides that have low hydrogen diffusion rates; but these are often brittle.[67] Oxide permeation barrier coatings are common today but provide no active protection mechanism for scratches which expose bare metal.[68,69,70]

There are a few multi-functional coatings for HAC resistance that are designed to serve several hydrogen resisting functions at the same time, perhaps in a multilayer format. Moreover, an outer hydrophobic layer could be designed with an inner permeation barrier and/or another buried inhibitor layer. Coatings could control potential and promote hydrogen recombination even in the case of high cathodic currents. Moreover, chemical inhibitors may be deployed which inhibit cracking. Chemical inhibitors released from a coating and transported to the crack tip could be designed to interfere with the steps leading to hydrogen uptake and ultimately limit hydrogen accumulation in the thread root of a fastener. For instance, inhibition of the hydrogen evolution reaction kinetics has been investigated with selected inhibitors that chemically precipitate under the alkaline conditions at the crack tip such as when subjected to cathodic polarization. The inhibitors' effect on lowering hydrogen absorption was also determined. Steels were hydrogen charged under conditions representative of crack tips. Absorbed hydrogen was quantified with and without the inhibitor as a function of hydrogen overpotential and found

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[67] Possible coatings would most likely be a multi-functional coating with several delaying strategies, all that would contribute to a longer lifetime.

[68] T. Fukai and K. Matsumoto, Surface modification effects on hydrogen permeation in high-temperature, high-pressure, hydrogen hydrogen-sulfide environments, *Corrosion* 50:522-530, 1994.

[69] A. Aiello, G. Benamati, and C. Fazio, "Hydrogen Permeation Barrier Development and Characterisation," pp. 145-155 in *Nuclear Production of Hydrogen*, Paris, France: Organisation for Economic Co-Operation and Development, Nuclear Energy Agency, 2001.

[70] T. Tanabe, Surface-barrier for tritium permeation, *Fusion Technology* 28:1278-1283, 1995.

to be reduced. Experimentally determined threshold stress intensity (KTH) and da/dtII were improved with the inhibiter at intermediate cathodic potentials. The coating might have barrier, potential control, and chemical inhibition capability all built into one coating. Each of these functions may be challenged in open systems exposed for long time periods, but the concept would be to severely delay hydrogen accumulation in fasteners, not necessarily to eliminate it. Even self-healing of bare spots is a common technology today in the case of organic coatings used[71,72,73,74] in aerospace applications. It seems that a multi-functional coating could be perfected that serves several functions with proven technologies used in other applications.

Value Proposition

Current understanding of the possible use of coatings in undersea bolting applications is not well developed. This has sometimes led to the avoidance of coatings because it was not clear whether they would be helpful or harmful. An understanding of the utility and benefit of these multifunctional and smart coatings could lead to more robust bolting for undersea applications.

Feasibility

While there are examples of the use of sophisticated coatings in other industries, research and development is needed to determine the value of multifunctional and smart coatings in the undersea drilling industry.

Coating Design for BOP Bolts

A new approach could be to design a new type of coating for bolts. Components for high temperature applications have been used with coatings with Al_2O_3 to resist oxidation for extended periods of time. However, at temperatures above

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[71] S.B. Ulaeto, R. Rajan, J.K. Pancrecious, T.P.D. Rajan, and B.C. Pai, Developments in smart anticorrosive coatings with multifunctional characteristics, *Progress in Organic Coatings* 111:294-314, 2017.

[72] F. Presuel-Moreno, M.A. Jakab, N. Tailleart, M. Goldman, J.R. Scully, Corrosion-resistant metallic coatings, *Materials Today* 11(10):14-23, 2008.

[73] P.C. Dodds, G. Williams, and J. Radcliffe, Chromate-free smart release corrosion inhibitive pigments containing cations, *Progress in Organic Coatings* 102:107-114, 2017.

[74] H.C. Qian, D.K. Xu, C.W. Du, D.W. Zhang, X.G. Li, L.Y. Huang, L.P. Deng, Y.C. Tu, J.M.C. Mol, and H.A. Terryn, Dual-action smart coatings with a self-healing superhydrophobic surface and anticorrosion properties, *Journal of Materials Chemistry A* 5:2355-2364, 2017.

800°C they tend to spall off unless the surface contains addition of rare earth elements such as Y and Hf.[75,76,77,78,79] In subsea applications, corrosion is the biggest challenge along with erosion from continuous flow of seawater. Cr_2O_3 is known for its corrosion resistance. Use of oxides with high corrosion resistance as well as high adherence to the base material should be explored. Stainless steel is often used for some subsea applications, which has Cr_2O_3 oxide protection but they also fail under subsea condition. The challenge will be to identify elements such as Y and Hf, which help the protective oxide adhere to the surface and also to not be porous.

Cathodic protection practice adds further complication. The challenge will be to identify elements, which will improve the adherence of the oxide for corrosion resistance under mechanical loading and an electric field.

Value Proposition

This is another example of coatings which may protect bolts used in undersea applications. If successful, these could prolong the life and increase the reliability of bolted connections.

Feasibility

As discussed, these coatings have been successful in some applications. Development work is needed to determine effective coatings for the alloys used and for the subsea conditions.

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[75] J. Singh and J. Mazumder, Microstructural evolution in high energy helium implanted nickel—I. Room temperature (*t* – 100°C) implantation, Acta Metallurgica 35: 1929-1941, 1987.

[76] I.M. Allam, D.P. Whittle, and J. Stringer, pp. 103-117 in *Corrosion and Erosion of Metals* (K. Natesen (ed.), Metallurgical Society of AIME, Warrendale, Pa., 1980.

[77] J.G. Smeggil, A.W. Funkenbush, and N.S. Bornstein, A relationship between indigenous impurity elements and protective oxide scale adherence characteristics, *Metallurgical Transactions A* 7:923-932, 1986.

[78] D.P. Whittle and J. Stringer, Improvements in high temperature oxidation resistance by additions of reactive elements or oxide dispersions, *Philosophical Transactions of the Royal Society A* 295:309, 1980.

[79] C. Ribaudo and J. Mazumder, Oxidation behavior of a laser-clad nickel-based alloy containing hafnium, *Journal of Materials Science and Engineering A* 121:531-538, 1989.

Hydrophobic Coatings for Bolts[80]

Low energy (hydrophobic) and high energy (hydrophilic) coatings with high wear resistance are well-developed technologies being used in many industries. The oil and gas industry is just beginning to use these alternate coatings in the field. One potential application would be to coat flange bolts in hydrophilic "paint" to prevent exposure to water, even at depth.

Value Proposition

The potential value would be to reduce or eliminate exposure of the base material to water. This could mitigate the exposure of equipment to elemental hydrogen and salt water. Additionally, it could mitigate conventional corrosion of the material when exposed to salt air.

Feasibility

While this is a proven technology, key development risks exist for this application that would need to be investigated. These include the following:

- The application method could be conventional painting or electrodeposition. Confirmation of coating thickness and coating durability with each method is required. Additionally, the ability to bake out hydrogen using existing standards needs to be confirmed.
- The ability of the coating to remain effective after multiple thread make-ups and break-outs needs to be assessed.
- The ability of the coating to exclude water—to the point of mitigating corrosion—under extreme (5,000 psi) pressure and other harsh environmental conditions for extended periods of time needs to be proven.

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[80] For more information, see J.F. Heathman, R. Taylor, G.A. Fuller, G. Arumugam, P. Sullivan, S. Thapa, and V. Veedu, "Development of Nanotechnology Pipe Treatment to Improve Acoustic Cement Evaluation," Paper OTC-27893-MS, Offshore Technology Conference OTC 2017, 2017, http://www.onepetro.org/conference paper; E.P. Brown, S. Hu, S. Wang, J. Wells, M.A. Nakatsuka, V. Veedu, and C.A. Koh, "Low-Adhesion Coatings as a Novel Gas Hydrate Mitigation Strategy," Paper OTC- 27874-MS, Offshore Technology Conference OTC 2017, 2017, http://www.onepetro.org/conference paper.

Nano-Laminated Metallic Coatings[81]

Nano-laminated metallic coatings are electro-deposited nickel, zinc, or other alloy coatings that are designed to have specific properties that have been shown to be very effective in preventing surface-type corrosion. There is a patented electrochemical controlled deposition process that produces precisely-defined configurations of nanometer-scale layered metal alloys that can be applied to various substrates.[82] These nano-scaled layers are designed to enhance a number of material properties, including:

- Corrosion resistance
- Elastic modulus
- Strength
- Hardness
- Fracture toughness
- Wear resistance
- Damping
- Stiffness

Value Proposition

The potential value would be to have the nano-laminated coating exposed to the water rather than the base metal. Because the nano-lamination process is "self-leveling" there may also be an anti-galling potential due to the option to have an exceptionally smooth finish. Additionally, it could mitigate conventional corrosion of the material when exposed to salt air.

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[81] For more information, see M.W. Joosten, J. Vander Laan, S. Lomasney, C. Lomasney, L. Collinson, and J. St. Clair, "Nano-Laminated, Metallic Coatings for Corrosion and Abrasion Resistance," NACE Paper 5735, NACE Corrosion 2015, 2015, https://www.onepetro.org/conference-paper/; O. Paz, B. Chaloner-Gill, N. Yamali, S.M. Taha-Hussain, C. Lomasney, S. Lomasney, and D. Casioppo, "Nano-Laminated Alloys for Improved Return on Oilfield Assets," SPE Paper 179923-MS, SPE International Oilfield Corrosion Conference and Exhibition, May 2016; Nano-Layers in metallic coating enhance its corrosion resistance, Material Performance, Vol 54, No. 5, May 2015, pp 14-19; C. Lomasney, "Nanomaterials Aid Corrosion Resistance," *Hart Energy E&P*, December 1, 2014, http://www.epmag.com/nanomaterials-aid-corrosion-resistance-761816.

[82] Modumetal, Inc., "Products: Corrosion-Resistant Alloys," https://www.modumetal.com/pages/products-corrosion-resistent-alloys, accessed October 24, 2017.

Feasibility

The technology is field-proven with the nano-laminated coating currently commercialized for studs and nuts. However further work is warranted, including the following:

- Clarifying whether the new API Spec 20E for Alloy and Carbon Steel Bolting, which prohibits zinc plating with 100 percent zinc, would allow a lesser percentage of zinc
- Assessing if any of the other non-zinc containing nano-laminated products (for example, nickel-based) could be used and be effective as a corrosion barrier for studs and nuts.
- The ability of the coating to withstand deepwater environments for extended periods of time needs to be tested
- The ability of the coating to exclude water under extreme (5,000 psi) pressure and other environmental conditions—to the point of mitigating corrosion—needs to be proven.
- A further innovation would be to evaluate the feasibility of electroplating a superhydrophobic coating[83] over a nano-laminate coating.

NEW FASTENER DESIGNS

Alternative Thread Designs[84]

The 8-round thread design has been used successfully in oil and gas applications for years. This old technology may not extrapolate well to the extreme service requirements for deepwater drilling riser bolts. With 8-round thread, as with many thread designs, the root of the first thread takes 65 percent of the tensile load. Better thread designs could be developed or sourced from other industries.[85] Future research could also consider methods for spreading the load out to all the threads in a connection, such as stress relieving grooves in nuts and threaded flanges.[86]

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[83] Oceanit, “Anhydra,” https://www.oceanit.com/products/anhydra, accessed October 24, 2017.

[84] For more information, see H. Stafansson, “Controllable Pitch Propeller Blade Bolt Design,” presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

[85] For example, Cameron uses a stub Acme thread for parts of their BOP. This is a coarse square-profile thread that is harder to cross-thread and a square shoulder. One example of a potentially applicable thread design is the Rolls Royce’s Moregrip technology used by the U.S. Navy for propeller attachment.

[86] S. Venkatesan and G.L. Kinzel, Reduction of stress concentration in bolt-nut connectors, *ASME Journal of Mechanical Design* 128:1337, 2006.

Value Proposition

A thread design that more evenly distributes the tensile load across the treads will reduce point loading and should make the treads less susceptible to stress-induced cracking.

Feasibility

Incorporation of alternate thread designs is a well-established technology, available as needed.

Other Connector Geometries[87]

API Flange connectors are used exclusively in BOP stacks. This is a time-tested technology; it is well understood, and specifications exist for them. In addition they are relatively lightweight and small. However, they do put the flange bolts in the direct (tensile) load path albeit the additional tensile loads on the bolts are minimal until the flange preload is exceeded.

Industry has considered the idea of using a different connector, such as clamps. Clamps (such as Greylock clamps) have been used in the oil and gas industry. There is some interest in further evaluating their use. However, clamp systems are very large, heavy, and expensive. They do take the bolts out of the direct load path, but tensile load is still imparted but on fewer bolts. Additionally, there is concern about the ability of clamped connections to handle significant bending moments.

Value Proposition

The value of a different type of connector would be making the connector less susceptible to (pressure and structural) failure.

Feasibility

Development issues are not insignificant. Any new connector configuration, even for proven technologies like clamps, would require extensive evaluation and testing before being accepted by the oil and gas industry for such critical and demanding service. Finding or developing a better connector system for deepwater drilling risers would require a significant industry-wide impetus to start and maintain such an effort. This having been said, there is probably a better connector

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[87] For more information, see J.M. Bednar, W.P. Dixon, and W.H. DuMay, "Effect of Blowout Preventer End Connections on the Pressure Integrity of a Subsea BOP Stack Under Riser Loads," Paper OTC-2649-MS, Offshore Technology Conference, May 3-6, 1976.

technology already developed that could benefit the deepwater drilling riser application if the requirement is made known and there is promise of a development program to qualify the successful solution.

Human Systems Integration[88]

Considering that humans contact bolts through every step of the bolt life cycle, they are important in innovating solutions to overcome bolt failure. Attending to each of the dimensions of human systems and to the larger system in which they work will result in a system in which the human system is well-integrated with other system components and one that is resilient to perturbations coming from within or outside of the system.

Solutions can be identified that involve training humans (e.g., tensioning training), design of tools (e.g., heat treating basket of US Bolt) or processes to redesign work to reduce or eliminate human system failures. Other solutions involve organizational changes such as reporting procedures or communication protocol. Though such interventions may seem inconsequential, they have the potential to eliminate much of the variance associated with human activity and reduce bolt system failures.

- *Design Innovations.* There are examples of re-designing the work process to make it resilient to human error. For instance, in one example the bolt manufacturer did not pay proper attention to the forging temperature; this eventually caused microcracks that then failed after over-tightening. As a result, 60 of the 600 bolts were defective. Because of this incident, the manufacturer instituted an automatic fail-safe system to prevent overheating.[89]

  In another example, furnace loading can cause uneven heating. There is a tendency to put as many bolts in the basket as possible to lower the cost of

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[88] For further reading, see D.A. Boehm-Davis, F.T. Durso, and J.D. Lee, *APA Handbook of Human Systems Integration*, Washington, D.C.: American Psychological Association, 2015; S.C. Peres, R. Bias, N. Quddus, W.S. Hoyle, L. Ahmed, J.C. Batarse, and M.S. Mannan, *Human Factors and Ergonomics in Offshore Drilling and Production: The Implications for Drilling Safety*, Technical Report by the Ocean Energy Safety Institute, 2016; National Research Council, *Human-System Integration in the System Development Process: A New Look* (R.W. Pew and A.S. Mavor, eds.), Washington, DC: National Academies Press, 2007; R. Flin and G. Slaven, "Introduction," pp. 1-6 in *Managing the Offshore Installation Workforce* (R. Flin and G. Slaven, eds.), Tulsa, Okla.: PennWell books, 1996.

[89] L. Burgess, "Bolt Manufacturing—A Look at Critical Operations," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 10-11, 2017.

heat treating. To fix this baskets have been designed with individual vertical slots for bolts and adequate separation and furnace load diagrams. This new design prevents poor loading practices.

- *Training Innovations.* Current training for personnel who assemble BOP and riser components focuses on safety issues, but often not on specific procedures such as bolt tightening. Further, even if operators are trained in procedures, the rationale behind the procedure is often lacking. This type of training may work well under nominal conditions, but once an exceptional event occurs, the operator will have little basis for deciding on alternative procedures.
- *Organizational Innovations.* Reporting systems of failures and near misses have worked very well in other industries such as nuclear and aviation. Such systems allow patterns of failures to be detected early and mitigated before a disaster occurs. Established protocol for sharing this information within and across organizations is also essential for system-wide effectiveness, and other industries, such as aviation, have already developed protocols for anonymously sharing information of a sensitive nature. Most important, however, is rewarding those who constructively participate in a failure reporting system.
- *Action Plan.* Establishing an industry function to review all nonproprietary aspects of the design, manufacturing, installation, operation, and maintenance of drilling riser systems and their components would allow non-technical, human-systems experts to have a “cold-eyes” look at these systems and suggest improvements.

Value Proposition

Humans are essential components of the bolt system. Preventing bolt failures requires considering the integration of the human system with other system components and considering multiple dimensions of the human system. Work processes can be re-designed at relatively low costs to make them more resilient to system failures while increasing productivity and product quality. Training and failure reporting systems can similarly increase the effectiveness of human systems.

Feasibility

Human systems integration has been incorporated successfully in other industries such as aviation, nuclear power plants, and space.

SUMMARY AND RECOMMENDATION

These innovation opportunities have the potential to significantly advance the reliability of subsea fasteners in critical service. Some of these innovations can be investigated and qualified within a few years since they leverage work that has been commercialized in other industrial sectors. Other opportunities will require a long-term research and development effort.

Finding: Numerous innovative concepts for potentially reducing failures of connector bolts in undersea exploration for gas and oil have now been identified. These range from procedures and technologies that could be quickly implemented to concepts that require a long-term development effort; some may result in significant incremental improvement, some a large step-change improvement and others may never be practical to implement in the deep ocean environment.

Option 5.1: BSEE could take a leadership role in forming a consortium with components from industry, academia and government to evaluate the innovative concepts presented, potentially add to these, and implement those that are deemed beneficial and require little development. The oil and gas industry should have a strong role in determining the priorities of which ideas to pursue. BSEE, using the recommendations of the consortium, could also initiate research and development efforts for those innovations that may offer considerable safety advantages but are not currently available as products or systems.

6

Summary of Recommendations

Overall Finding: Both the Bureau of Safety and Environmental Enforcement (BSEE) and the oil and gas industry has made important advances in improving bolting reliability for deep sea drilling operations. However, there are multiple opportunities for the industry and BSEE to work together to further enhance the safety culture and to increase fastener reliability.

The options and recommendations presented below are a reiteration of the options and recommendations that are discussed in detail in Chapters 2 through 5. In accordance with the statement of task (Appendix A), the committee developed options for the regulatory agency, BSEE, to consider for action but no recommendations. The committee has offered recommendations for the oil and gas industry.

Summary Option 6.1 is a synthesis of recommendations in the report that deal with actions that BSEE could take to guide the oil and gas industry in constructing a multi-faceted roadmap for actions that could lead to improvements in subsea bolting reliability. New regulatory action would be guided not only by the statutory requirement to determine which *best available and safest technology* options meet an economic feasibility hurdle. But also by working within the standards development process, by promulgating new regulations to supplement standards, or by requesting statutory changes.[1]

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[1] Bureau of Safety and Environmental Enforcement, "Statutory Requirements of OCSLA Regarding the Use of BAST," https://www.bsee.gov/what-we-do/regulatory-safety-programs/statutory-requirements, accessed November 13, 2017.

Summary Option 6.1: BSEE could undertake the proactive role of working with the oil and gas industry to construct a comprehensive roadmap that could advance the safety of threaded subsea fasteners. The multi-faceted roadmap would contain key objectives and priorities that could be executed and implemented by the industry, much as was done in the Federal Aviation Administration's (FAA's) Jet Engine Titanium Quality Consortium and the U.S. Navy's SUBSAFE efforts. Industry should have a large role in determining the priority for addressing potential improvements. The roadmap could be divided into several sections:

- Investigate bolting cluster failures using a large-scale fully instrumented flange test rig that simulates subsea conditions on fasteners in bolted joints including structural loads, environmental conditions and cathodic protection. [Option 2.9]
- Research and development of specific innovation opportunities that have the potential to significantly advance the reliability of offshore fasteners in critical service. [Options 2.2, 2.4,5.1]
- Identification of gaps in current standards and obtaining the necessary data to guide updating the standards. [Options 2.5, 2.10, 3.1, 3.2, 3.3]
- Promotion of a strategic vision for the safety culture throughout the oil and gas industry. This would include collecting and disseminating information about fastener performance, failures, and near misses across different disciplines and organizations, and using this information to guide roadmap priorities. [Options 2.1, 2.3,2.6, 3.4, 3.5]

Summary Recommendation 6.2 is a synthesis of the six recommendations in the report that address actions which the oil and gas industry should take in concert to improve subsea bolting reliability. The activities to implement these recommendations could be incorporated into the comprehensive roadmap activity mentioned in Summary Option 6.1.

Summary Recommendation 6.2: Actions that the oil and gas industry should take to improve subsea bolting reliability include the following:

- Establish a comprehensive methodology/program to optimize the cathodic protection (CP) practice for critical assets containing fastener metallic materials. [Recommendation 2.7]
- Review the usage of materials in contact with fasteners that are known to poison the chemical reaction of atomic hydrogen converting to hydrogen gas. [Recommendation 2.8]
- Establish a standard accepted laboratory standard test method to assess the susceptibility to environmentally assisted cracking/hydrogen embrittlement

of bolting materials and their coatings used in offshore applications [Recommendation 2.10]
- Conduct systematic studies to assess effect of bolt designs on hydrogen embrittlement susceptibility. [Recommendation 2.11]
- Review the standards relating to bolt tensioning, both in terms of loading as a percent of yield strength and in terms of preloading technique, to minimize the probability for excessive stress on bolts operating in subsea environments. [Recommendation 2.12]
- The oil and gas industry should promote an enhanced safety culture across organizations and disciplines that is reflected in work rules and that involves encouragement at all levels of the organization to improve the reliability of subsea bolts. [Recommendation 4.1]
- Support activities related to Summary Options 6.1

Option 2.1: BSEE could convene an industry study group to investigate flange bolt design and installation standards. Options which could be considered include:

- Put a hold on requirements for industry to use more accurate torqueing equipment.
- API Spec 17D could be revised to "require" rather than "recommend" that bolts be accurately preloaded. Eliminate the term "torque" as torque has been determined to be inherently inaccurate.
- Suggest the use of a more accurate bolt pre-tensioning method for critical flange bolt preloading on all new equipment fabrication and at 5-yearly inspections. (Appendix J lists some alternative bolt pre-tensioning methods.)
- Consider commissioning engineering design studies to determine realistic tension loading safety margins for flange bolts. Such a study could initially concentrate on the preload variability that results from torqueing, however assessments of operational loading uncertainty and in-service material degradation could also be considered.
- Consider commissioning a study to evaluate the impact of a single bolt failure on overall connector reliability. This study could cover a range of flange sizes (i.e. number of flange bolts).
- Consider new and revised specifications, standards and recommended practices to be incorporated into Code of Federal Regulations (CFR) 30 section 250 based on proactive assessment of risk areas.

Option 2.2: BSEE could request an industry-led consortium with academic participants to initiate systematic studies to investigate and evaluate the environmentally assisted cracking/hydrogen embrittlement susceptibility of continuous cast and ingot cast steels. The results on continuous cast steels could also include "modern" product produced in newer facilities and characterized with non-destructive testing techniques to assess soundness. The consortium could also evaluate alternate steel alloys and processing histories leading to improved in-service performance. The prohibition of banding to maintain product quality for subsea bolting could also be reviewed.

Option 2.3: Under the oversight of BSEE, the industry could collect data on the service conditions and performance of bolting in all critical riser/BOP applications for every deepwater drilling operation. This would include subjecting all fasteners, failed and un-failed, in these critical applications to a thorough post-operational inspection—requiring a full dimensional check and metallurgic post-mortem, with root-cause analysis being performed when the equipment did not perform according to design.

Option 2.4: The oil and gas industry should pursue technologies that offer more effective NDT inspection of bolts in situ, on the deck, and in the shop. Employment of these technologies should be made mandatory by BSEE as they have been qualified in other industries.

Option 2.5: BSEE could establish inspection requirements for un-failed bolts during the 5-year shop inspection, or could require that all critical bolts be replaced during this inspection. BSEE should also establish/require serial numbers on all critical bolts so that inspections of any specific bolt could be documented and catalogued. The results from inspections could be reported as determined by mutual agreement between BSEE and the organization performing the 5-year shop inspection.

Option 2.6: BSEE could take steps to incorporate the following API specifications and recommended practices, (in total or in part) into CFR 30 section 250 by reference to ensure that the best known maintenance practices are instituted:

- API Spec 16F, “Specification for Marine Drilling Riser Equipment”
- API RP 17G, “Recommended Practice for Completion/Worker Risers”
- API RP 16Q, “Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems”

Recommendation 2.7: The oil and gas industry should establish a comprehensive methodology and or program to optimize the cathodic protection (CP) practice for critical assets containing fastener metallic materials. For current structures, CP monitoring and assessment practice should be instituted. As new

structures are designed, the industry should establish CP design requirements optimized for materials in use, based on electrochemical fundamentals. This project should evaluate the use of "low voltage" aluminum anodes currently being used by the U.S. Navy and the French Navy to reduce the risk of hydrogen embrittlement of their high-strength alloys.

Recommendation 2.8: The industry should review the usage of materials (e.g. lubricants containing sulfides) in contact with fasteners that are known to poison the chemical reaction of atomic hydrogen converting to molecular hydrogen (hydrogen gas), and identify substitute materials so that the concentration of atomic hydrogen at the metal surface is reduced.

BSEE could consider immediately prohibiting the use of sulfide-containing lubricants until such a study indicated that they can be used without enabling hydrogen uptake.

Option 2.9: The committee suggests that cluster failures be investigated by BSEE in large-scale fully instrumented flange test rig that simulates subsea conditions on fasteners in bolted joints including structural loads, environmental conditions, and cathodic polarization. These investigations are necessary to definitively establish the origins of these cluster failures and to prove the effectiveness of mitigation strategies.

Recommendation 2.10: The oil and gas industry should establish through adequate research an accepted laboratory standard test method to assess the susceptibility to hydrogen-assisted cracking of bolting materials and their coatings used in offshore applications.

Recommendation 2.11: The oil and gas industry should:

- **Assess various thread designs and manufacturing methods for maximum resistance to environmentally assisted fracture.**
- **Conduct systematic studies to assess effect of bolt designs (including the tread geometry) on hydrogen-assisted cracking susceptibility.**
- **Pursue research into thread designs which could reduce the stress concentration in bolt threads.**

Recommendation 2.12: The oil and gas industry should review the standards relating to bolt tensioning, both in terms of loading as a percent of yield strength and in terms of preloading technique, to minimize the probability for under or over-tensioning bolts operating in subsea environments.

Option 3.1: BSEE could leverage the results of the study at Argonne National Laboratory that is evaluating fastener standards to bring industry together in addressing detailed standards and best practices in design, materials, manufacture and operation of offshore structures**.**

Option 3.2: The committee endorses the Summary Recommendation 6.1 contained in the National Academy of Engineering/National Research Council 2012 report on the Macondo Well Deepwater Horizon blowout:[2] "The United States should fully implement a hybrid regulatory system that incorporates a limited number of prescriptive elements into a proactive, goal-oriented risk management system for health, safety, and the environment." BSEE could implement this Summary Recommendation.

Option 3.3: Safety critical standards and specifications could be enforced by BSEE throughout the supply chain by incorporation of such standards into the Code of Federal Regulations.

Option 3.4: The committee agrees with the BSEE 2016 QC-FIT report, Evaluation of Fastener Failures Addendum that recommended that all bolts used in critical service in US OCS waters shall be manufactured by organizations that maintain sufficient quality certifications.[3] BSEE could consider fully implementing this recommendation.

Option 3.5: The FAA and U.S. Navy regulatory approach and governing authorities have elements that BSEE could tailor for their domain of interest. In some cases, additional statutory authority may be necessary.

Recommendation 4.1: The oil and gas industry should promote an enhanced safety culture across organizations and disciplines that is reflected in work rules and that involves encouragement at all levels of the organization to improve the reliability of subsea bolts. This would include:

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[2] National Academy of Engineering/National Research Council, *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*, Washington, D.C.: The National Academies Press, 2012.

[3] Bureau of Safety and Environmental Enforcement, *QC-FIT Evaluation of Fastener Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, Washington, D.C., February 2016, https://www.bsee.gov/sites/bsee_prod.opengov.ibmcloud.com/files/memos/public-engagement/qc-fit-bp-bolts-report-final.pdf.

- **The creation of a dedicated organizational Human Systems stakeholder**
- **Attention to the individual worker and skill development through training, selection and work process design**
- **Company and industry-wide sharing of best practices for collecting and disseminating information about fastener performance, failures, and near misses**
- **Assessing gaps that could be mitigated by technology developments**

Option 5.1: BSEE could take a leadership role in forming a consortium with components from industry, academia and government to evaluate the innovative concepts presented, potentially add to these, and implement those that are deemed beneficial and require little development. The oil and gas industry should have a strong role in determining the priorities of which ideas to pursue. BSEE, using the recommendations of the consortium, could also initiate research and development efforts for those innovations that may offer considerable safety advantages but are not currently available as products or systems.

Two recent BSEE Quality Control-Failure Incident Team (QC-FIT) reports[4] contain recommendations that are related to the above recommendations. Table 6.1 is a summary relating QC-FIT recommendations to those contained in this appendix.

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[4] Bureau of Safety and Environmental Enforcement, *Evaluation of Fasteners Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, February 2016, *https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf;* Bureau of Safety and Environmental Enforcement, *Evaluation of Connector and Bolt Failures—Summary of Findings*, QC-FIT Report #2014-01, Office of Offshore Regulatory Programs, August 2014, *https://www.bsee.gov/sites/bsee.gov/files/bolt_report_final_8-4-14.pdf.*

TABLE 6.1 BSEE QC-FIT Report Recommendations

QC-FIT Report	QC-FIT Recommendation	Report Options and Recommendations
2016[a]	Industry should: (1) ensure that API Specification (Spec) Q1 contains sufficient controls over second- and third-tier vendors, (2) ensure that the API monogram program provides sufficient audit mechanisms to ensure that OEMs are in full compliance with API Spec Q1, and (3) review current regulations and standards to ensure that the sections on mechanical integrity and contractor qualification are sufficiently robust.	3.1, 3.2, 3.3, 3.4
2016	Industry should perform a comprehensive review of industry standards related to fasteners and develop consistent guidance for ideal material property requirements for subsea fastener manufacturing. The review should also include a comprehensive analysis of manufacturing best practices and environmental service conditions for subsea fasteners.	2.7, 2.8, 2.11, 3.1
2016	BSEE should consider incorporating API Spec 20E First Edition, August 2012 "Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry" into regulations to provide consistency in material property requirements for use of subsea fasteners on the OCS.	3.1
2016	The failure mechanism of the subsea fasteners is not fully understood. Industry and/or BSEE should perform technical studies to evaluate the combined effect of fastener material properties, coatings, and load and environmental conditions to better understand fastener performance and prevent such failures from happening in the future. It should be noted that due to the natural dissipation of hydrogen, direct evidence of a hydrogen embrittlement (HE) failure is not possible. Other possible causes of a brittle fracture of the fasteners were not evaluated, and environmentally-assisted cracking (EAC) was the likely failure mode of the fractured studs. There are well established laboratory analysis protocols to study the brittle fracture of steel. Micro-cracks were also observed at the root of the threads in some of the samples analyzed, which would be due to inadequate heat treatment procedures that contributed to premature failure of the fasteners under normal loading condition.	2.9
2014[b]	Improve industry standards	2.10
2014	Initiate joint industry research initiatives	2.2, 2.4, 5.1
2014	Promote failure reporting	2.3, 2.5, 4.1

[a] Bureau of Safety and Environmental Enforcement, *Evaluation of Fasteners Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, February 2016, https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf.

[b] Bureau of Safety and Environmental Enforcement, *Evaluation of Connector and Bolt Failures—Summary of Findings*, QC-FIT Report #2014-01, Office of Offshore Regulatory Programs, August 2014, https://www.bsee.gov/sites/bsee.gov/files/bolt_report_final_8-4-14.pdf.

Appendixes

A

Statement of Task

Upon completion of the initial RCA Bolt Workshop, a follow-up study that builds upon the workshop's presentations and discussions will be conducted. The study will develop useful options for consideration by industry and BSEE on all aspects of connector manufacture and use in an offshore environment after further assessment and information collection, the study should address the following issue under Tasks 1-8.

Task 1: Assess the critical drill-through equipment fastener systems and the appropriateness of materials and coatings selected for incorporation into fasteners, for optimal performance for subsea environment operating conditions. The assessment should address the following questions and issues:

Are existing industry best practices and BSEE regulations adequate enough to ensure that fasteners will perform satisfactorily in the subsea conditions under which they are expected to be used?

What additional steps should be taken to improve the development and implementation of best practices and regulations governing fastener performance for critical drill-through equipment for subsea applications?

What are the best techniques and practices to address the design, load, fatigue loading, material properties (YS, UTS, elongation, hardness) requirements, coating selection, cathodic protection, QA/QC, quality management systems (QMS) oversight of subcontracted vendor manufacturing process issues (procurement-forging, manufacturing, heat treatment, coating processes, etc.), fastener failure type and failure reporting, and failure analysis techniques for use in managing fastener use and quality?

Options for optimal material specifications for inclusion in relevant industry standards for future use and implementation of fasteners used for subsea oil and gas applications.

Identification of best practices from other industries like refinery, both onshore and offshore, aerospace, aviation, nuclear industry, military, naval (submarine and ship), pipeline, and automotive.

Risk Assessment timelines and protocols for replacing existing in-service sub-sea fasteners (e.g. replace all offshore bolts of concern based on risk, age, etc.).

Data collection needs: who collects the failure data; when is the failure data collected; when, to whom and how is the failure data reported?

Task 2: Design issues and human-systems interaction factors.

This analysis will not be limited to the technical components but will also encompass the entire system and bolt lifecycle (design, procurement, manufacturing, installation,

maintenance, commissioning, and operation), including the human components. Specific emphasis will be placed on the management of the manufacturing process from the first tier OEM down through the second, third, fourth, etc., sub tier sub-contractors.

Task 3: Options on improving safety of offshore drilling and pipeline operations as related to the use of fasteners for critical drill through equipment components like the LMRP (connector) and pipeline fasteners.

Identify options for reducing or eliminating the identified gaps for fastener manufacture, and provide valuable insight on how/if alternative fastener designs are capable of improving safety of offshore drilling and pipeline operations. Options to include:

Options on the methodology for the selection for material properties (such as hardness, yield, UTS, etc.), and other critical parameters identified by the industry standards or codes, in accordance with the subsea bolt application and operating environment; and

Options encompassing the use of both domestic and international standards and regulations that are in place today on fasteners to BSEE on how to proceed or how the existing industry standards should be modified to address project findings, or how BSEE should structure a 30 CFR 250 regulation to require these conditions should be met.

Task 4: Evaluation of the performance of fastener systems currently in use including the process of manufacturing (e.g. smelting, casting, drawing, heat treatment, coatings, mechanical/material properties, performance properties-shear stress, fatigue life, etc.), corrosion protection (cathodic protection) installation (e.g., torqueing), maintenance and inspection processes associated with fastener systems.

Task 5: The subsea environmental effects (seawater salinity along with high pressure/high temperature in presence of CO_2, Cl- or H_2S,) on the mechanical properties of bolts and corrosion resistance.

Task 6: The impact of cathodic protection systems on fastener performance in a subsea environment.

Task 7: Identification of the similarities and differences in industry standards related to the design, material specification for strength, hardness, coatings, corrosion resistance performance in atmospheric as well as subsea application conditions, cathodic protection, performance and maintenance requirements as related to fastener systems worldwide.

Task 8: Evaluation of alternative fastener designs used globally by the oil and gas and pipeline industry (OCS, other offshore areas, onshore), refineries, aerospace, aviation, nuclear, Naval (submarine, ship), automotive, and/or other industries, etc. Identification of ideas and concepts taken from industries outside of oil and gas which can be integrated into the offshore oil and gas community to effect improvements on safety and environmental protection.

B

Mapping of Statement of Task to Report Chapters

The report chapters and sections noted in Table B.1 address the specified tasks, but often there are other sections of the report also address aspects of the task.

TABLE B.1

Task	Report Statement of Task	Report Chapter(s) and Section(s)
Task 1	Assessment of the critical drill-through equipment fastener systems and the appropriateness of materials and coatings selected for incorporation into fasteners, for optimal performance for subsea environment operating conditions. The assessment should address the following questions and issues:	
Task 1.1	Are existing industry best practices and BSEE regulations adequate enough to ensure that fasteners will perform satisfactorily in the subsea conditions under which they are expected to be used?	Chapter 2, Fastener Design Appendix J, Safety Factors for Flange Bolts Chapter 3, Regulatory Considerations and Other Industry Practices Chapter 4, Gaps in US Human System Integration in the Oil and Gas Industry
Task 1.2	What additional steps should be taken to improve the development and implementation of best practices and regulations governing fastener performance for critical drill-through equipment for subsea applications?	Chapter 2, Fastener Design Chapter 2, Fastener Life Cycle Chapter 3, Fastener Standards and Specifications Chapter 3, Quality Assurance Options Chapter 4, Human Systems Integration and Fasteners Appendix J
Task 1.3	What are the best techniques and practices to address the design, load, fatigue loading, material properties (YS, UTS, elongation, hardness) requirements, coating selection, cathodic protection, QA/QC, quality management systems (QMS) oversight of subcontracted vendor manufacturing process issues (procurement-forging, manufacturing, heat treatment, coating processes, etc.), fastener failure type and failure reporting, and failure analysis techniques for use in managing fastener use and quality?	Chapter 2, entire chapter Chapter 3, entire chapter Appendix J
Task 1.4	Options for optimal material specifications for inclusion in relevant industry standards for future use and implementation of fasteners used for subsea oil and gas applications.	Chapter 2, Options for Improving the Selection of Bolting Material Properties Chapter 3, Fastener Standards and Specifications
Task 1.5	Identification of best practices from other industries like refinery, both onshore and offshore, aerospace, aviation, nuclear industry, military, naval (submarine and ship), pipeline, and automotive.	Chapter 3, Regulatory Considerations and Other Industry Practices Chapter 4, Human Systems Integration in other Industries and Countries
Task 1.6	Risk Assessment timelines and protocols for replacing existing in-service sub-sea fasteners (e.g. replace all offshore bolts of concern based on risk, age, etc.).	Chapter 2, Fastener Life Cycle Appendix J, Safety Factors for Flange Bolts

TABLE B.1 Continued

Task	Report Statement of Task	Report Chapter(s) and Section(s)
Task 1.7	Data collection needs: who collects the failure data; when is the failure data collected; when, to whom and how is the failure data reported?	Chapter 2, Fastener Life Cycle Chapter 5, Testing Protocol
Task 2	Design issues and human-systems interaction factors. This analysis will not be limited to the technical components but will also encompass the entire system and bolt lifecycle (design, procurement, manufacturing, installation, maintenance, commissioning, and operation), including the human components. Specific emphasis will be placed on the management of the manufacturing process from the first tier OEM down through the second, third, fourth, etc., sub tier sub-contractors.	Chapter 2, Fastener Life Cycle Chapter 4, entire chapter
Task 3.1	Options on improving safety of offshore drilling and pipeline operations as related to the use of fasteners for critical drill through equipment components like the lower marine riser package (LMRP) (connector) and pipeline fasteners.	Chapter 2, Fastener Life Cycle Chapter 3, Fastener Standards and Specifications
Task 3.2	Identify options for reducing or eliminating the identified gaps for fastener manufacture, and provide valuable insight on how/if alternative fastener designs are capable of improving safety of offshore drilling and pipeline operations.	Chapter 2, Fastener Life Cycle Chapter 5, New Fastener Designs Chapter 5, Coating Technologies
Task 3.3	Options on the methodology for the selection for material properties (such as hardness, yield, UTS, etc.), and other critical parameters identified by the industry standards or codes, in accordance with the subsea bolt application and operating environment	Chapter 2, Options for Improving the Selection of Bolting Material Properties
Task 3.4	Options encompassing the use of both domestic and international standards and regulations that are in place today on fasteners to BSEE on how to proceed or how the existing industry standards should be modified to address project findings, or how BSEE should structure a 30 CFR 250 regulation to require these conditions should be met.	Chapter 2, Fastener Design Chapter 3, Fastener Standards and Specifications Chapter 3, Quality Assurance Options Appendix J
Task 4	Evaluation of the performance of fastener systems currently in use including the process of manufacturing (e.g. smelting, casting, drawing, heat treatment, coatings, mechanical/material properties, performance properties-shear stress, fatigue life, etc.), corrosion protection (cathodic protection) installation (e.g., torqueing), maintenance and inspection processes associated with fastener systems.	Chapter 2, entire chapter Chapter 4, Human Systems Integration and Fasteners Chapter 4, Human Interactions with Subsea Fasteners Appendix J

TABLE B.1 Continued

Task	Report Statement of Task	Report Chapter(s) and Section(s)
Task 5	The subsea environmental effects (seawater salinity along with high pressure/high temperature in presence of CO2, Cl- or H2S,) on the mechanical properties of bolts and corrosion resistance.	Chapter 2, Ductile and Brittle Failure Modes Appendix G, Subsea Environmental Factors for Fastener Design
Task 6	The impact of cathodic protection systems on fastener performance in a subsea environment.	Chapter 2, Cathodic Protection and Hydrogen Cracking Chapter 2, Cluster Failures
Task 7	Identification of the similarities and differences in industry standards related to the design, material specification for strength, hardness, coatings, corrosion resistance performance in atmospheric as well as subsea application conditions, cathodic protection, performance and maintenance requirements as related to fastener systems worldwide.	Appendix H, Bolting Regulations & Standards Comparison not done—see explanation in Preface
Task 8	Evaluation of alternative fastener designs used globally by the oil and gas and pipeline industry (Outer Continental Shelf (OCS), other offshore areas, onshore), refineries, aerospace, aviation, nuclear, Naval (submarine, ship), automotive, and/or other industries, etc. Identification of ideas and concepts taken from industries outside of oil and gas which can be integrated into the offshore oil and gas community to effect improvements on safety and environmental protection.	Chapter 3, Regulatory Considerations and Other Industry Practices. Chapter 5, Coating Technologies and New Fastener Designs

C

Acronyms

σ	yield strength
ALARP	as low as reasonably practicable
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Section of the International Association for Testing Materials
BOP	blow-out preventer, safety equipment that seals the well in case of an emergency
BSEE	Bureau of Safety and Environmental Enforcement (Department of the Interior)
BSL	bolting specification levels
CALPHAD	Calculation of Phase Diagrams
C_{Hdiff}	diffusible hydrogen
C_{Htot}	total hydrogen
CP	corrosion potential
CRA	corrosion resistant alloys

DBTT	ductile-to-brittle transition temperature
DER	designated engineering representative
DOD	Department of Defense
DOE	Department of Energy
EAC	environmentally assisted cracking
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FDM	Finite Difference Method
FoS	factor of safety
HAC	hydrogen-assisted cracking
HE	hydrogen embrittlement
HEC	hydrogen-enhanced cracking
HEDE	hydrogen-enhanced decohesion
HELP	hydrogen-enhanced local plasticity
HSI	Human Systems Integration
IADC	International Association of Drilling Contractors
ICME	Integrated Computational Materials Engineering
IOGP	International Association of Oil and Gas Producers
JETQC	Jet Engine Titanium Quality Consortium
K_{Iscc}	Fracture toughness (K_I) is the stress intensity factor at a crack tip under simple uniaxial loading. The subscript I stands for Mode I loading (unixial), while the subscript SCC stands for stress corrosion cracking
KPI	key performance indicators
LMRP	Lower Marine Riser Package—the upper section of a two-section subsea blowout preventer (BOP) stack consisting of a hydraulic connector, annular BOP, ball/flex joint, riser adapter, jumper hoses for the choke, kill, and auxiliary lines, and subsea control pods. This interfaces with the lower subsea BOP stack. (from API RP 16Q, Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems)
LRFD	load and resistance factor design

MODU	Mobile Offshore Drilling Unit
MoS	margin of safety
NACE	National Association of Corrosion Engineers
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NDT	non-destructive testing
NRC	Nuclear Regulatory Commission
OCS	Outer Continental Shelf—all submerged lands lying seaward of state coastal waters (3 miles offshore) that are under U.S. jurisdiction (from Bureau of Ocean Energy Management, "OCS Lands Act History," https://www.boem.gov/ocs-lands-act-history/, accessed July 10, 2017)
OEM	original equipment manufacturer
OESI	Ocean Energy Safety Institute
PRA	Probabilistic Risk Assessment
QA/QC	quality assurance/quality control
Q&T	quenched and tempered
RC	Rockwell "C" (hardness measurement scale)
RCA	root cause analysis
RKB	Rotary Kelly Bushing
ROI	return on investment
ROV	remotely operated underwater vehicle
SCC	stress corrosion cracking
SEMS	Safety and Environmental Management Systems
SF	safety factor (see factor of safety)
TDS	total dissolved solids
TiC	titanium carbide
UERR	Undiscovered Economically Recoverable Resources (from Bureau of Ocean Energy Management, *Assessment of Undiscovered Oil and Gas Resources of the Nation's Outer Continental Shelf*, 2016, https://www.boem.gov/2016-National-Assessment-Fact-Sheet)
UHSS	ultra-high-strength steel
UT	ultrasonic transducer

UTM	ultrasonic method
UTRR	Undiscovered Technically Recoverable Resources (from Bureau of Ocean Energy Management, *Assessment of Undiscovered Oil and Gas Resources of the Nation's Outer Continental Shelf*, 2016, https://www.boem.gov/2016-National-Assessment-Fact-Sheet)
VIV	vortex induced vibration

D

Brief History of Subsea Oil Exploration[1]

The exploration history of the U.S. offshore oil and natural gas industry began in the Pacific Ocean more than 70 years ago (Figure D.1). As recently as 1947, no company had ever risked drilling beyond the sight of land (Figure D.2).

In 1896, as enterprising businessmen pursued California's prolific Summerland oilfield all the way to the beach, the lure of offshore production enticed Henry L. Williams and his associates to build a pier 300 ft. out into the Pacific—and mount a standard cable-tool rig on it.

By 1897 this first offshore well was producing oil and 22 companies soon joined in the boom, constructing 14 more piers and over 400 wells within the next 5 years. The Summerland offshore field produced for 25 years—fueling the growth of California's economy.

PIERS, PLATFORMS AND A PATENT

> In 1894, Henry Williams drilled two wells on a California beach. He drilled another in 1895 with encouraging results. This led Williams and others to exploring for oil offshore the next year.
>
> They constructed piers and drilled wells, leading to the realization that the Summerland oilfield extended offshore. This would be the first offshore field developed in the nation by drilling offshore wells from piers
>
> —From Santa Barbara County records

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[1] NOTE: This appendix is excerpted from American Oil and Gas Historical Society, "Offshore Petroleum History," http://aoghs.org/offshore-history/offshore-oil-history/, accessed November 13, 2017.

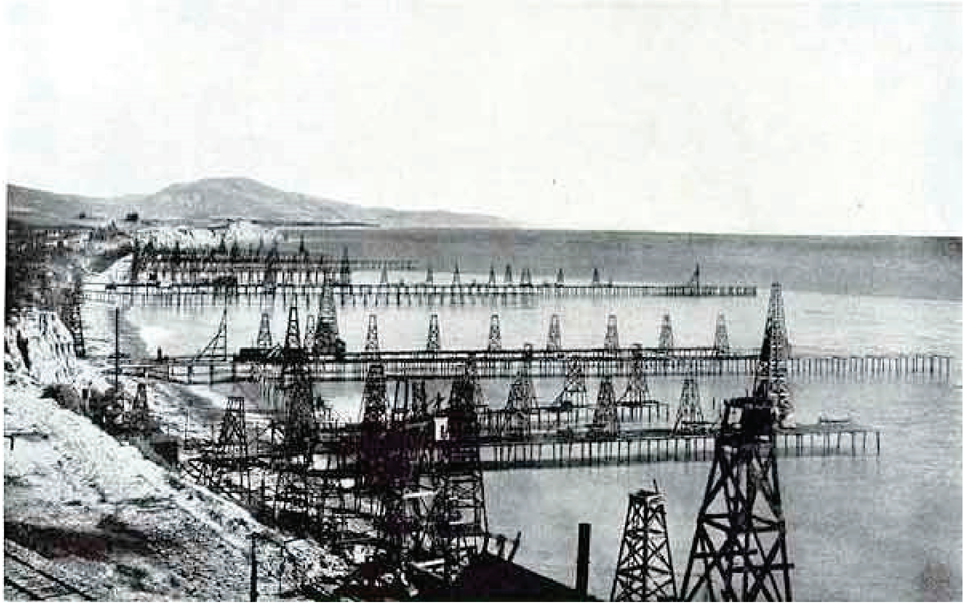

FIGURE D.1 America's offshore petroleum industry began in the late 19th century in the Pacific Ocean with drilling and production piers at Summerland, California. Drilling platforms also appeared on lakes in Ohio and Louisiana. By the 1940s, technology was taking wells far into the Gulf of Mexico.

In 1911, Gulf Refining Company abandoned the use of piers. It drilled Ferry Lake No. 1 on Caddo Lake, Louisiana, using a fleet of tugboats, barges, and floating pile drivers. When the well came in at 450 barrels per day, Gulf constructed platforms every 600 ft. on each 10-acre lakebed site.

The Caddo Lake wells—completed over water without a pier connection to shore—have frequently been called America's first true offshore drilling. A major petroleum company based in Pittsburgh, Pennsylvania drilled the first "over water" oil well in 1911, according to historian Bob Bowman of the East Texas Historical Association. "In the early l900s, 27-year-old Walter B. Pyron, of Blossom, Texas, a production foreman for Guffy Oil Company, noticed gas bubbles rising from Caddo Lake," Bowman explains. "He and other Guffy employees rowed across the lake, lighting strings of the bubbles."

"In early May, 1911, after months of hard work and battles with mosquitoes, alligators and moccasins, the Ferry Lake No. 1 was drilled to a depth of 2,185 and began producing 450 barrels of oil a day," reports Bowman. Pyron convinced his superiors at Gulf Oil Corporation—the successor of Guffy Petroleum Company—to drill on the lake (Figure D.3).

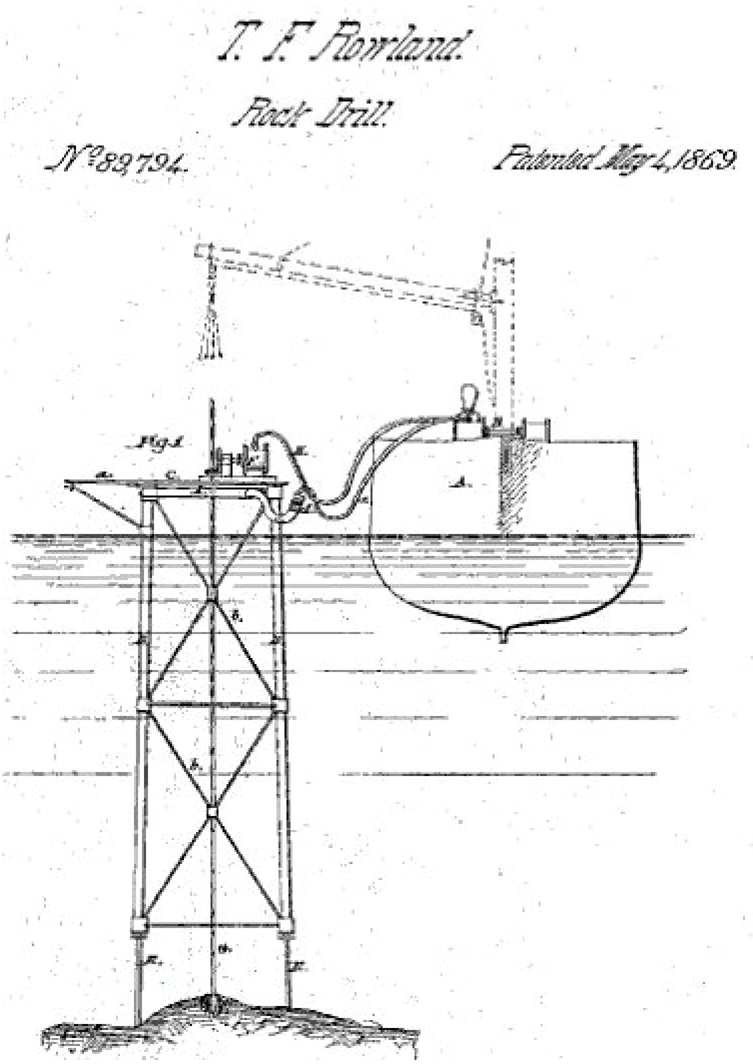

FIGURE D.2 Although never built, Thomas Rowland's 1869 design for an offshore platform was far ahead of its time.

FIGURE D.3 Derricks on Cygnet, Ohio, circa 1885.

However, Ohio oil documents record hundreds of oil wells pumping far out into a lake—20 years before drillers ventured into the waters of Caddo Lake.

As early as 1891, the first submerged oil wells were drilled from platforms built on piles in Grand Lake St. Marys in Ohio, notes historian Judith L. Sneed in "The First Over Water Drilling: The Lost History of Ohio's Grand Reservoir Oil Boom." Even earlier, some historians say the true beginning of the modern offshore industry can be traced to an 1869 U.S. patent. Thomas Fitch Rowland of Greenpoint, New York, patented a "submarine drilling apparatus" on May 4, 1869. Rowland's design included a fixed, working platform for drilling offshore to a depth of almost 50 ft. The anchored, four-legged tower—with telescoping legs "suitable hydraulic attachments or devices"—resembles modern offshore platforms (Figure D.4).

GULF OF MEXICO TECHNOLOGIES

In 1938, Pure Oil and Superior Oil Company built a freestanding drilling platform in the Gulf of Mexico—despite many logistics, engineering and communications challenges.

They hired a Houston engineering and construction company, Brown & Root Marine Operators to build a 320-ft. by 180-ft. freestanding wooden deck in 14 ft. of water about a mile offshore. The chosen drilling site was near Creole, Louisiana. Using onshore building criteria and intuition, the Creole platform was designed to withstand winds of 150 mph and constructed 15 ft. above the water. Three hundred treated yellow pine pilings were driven 14 ft. into the sandy bottom. The Superior-Pure State No. 1 well was successful—but was wiped off its pilings by a hurricane

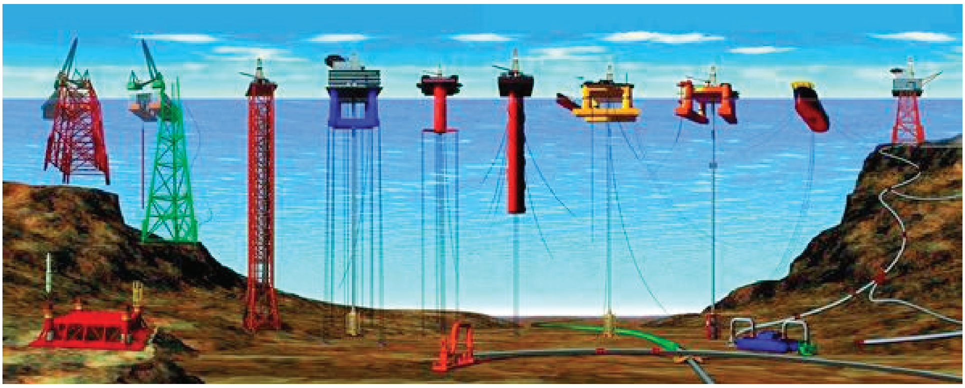

FIGURE D.4 Modern offshore structures include (*left to right*): (1 and 2) conventional fixed platforms; 3 is a compliant tower; 4 and 5 are vertically moored tension leg and mini-tension leg platforms; 6 is a spar platform; 7 and 8 are semi-submersibles; 9 is a floating production and offloading facility; 10) sub-sea completion and tie-back to host facility.

in 1940. The platform was quickly rebuilt and put back into production in the four million barrel field.

"It may be tentatively assumed that the Gulf of Mexico is a potential source of salt-dome oil," reported geologist Orval Lester Brace in 1941. (See Figure D.5.) "Whether or not it will ever be economically feasible to explore these waters for the domes that must exist is a question for the future to answer." Kerr-McGee dramatically answered the salt dome question in 1947 with an experimental offshore rig.

Not much equipment specifically designed for offshore drilling existed and exploration remained an extraordinarily speculative and risky business venture. An offshore dry hole could easily swallow the huge capital costs sunk into construction of a large, permanent rig platforms.

Nevertheless, Dean McGee of Kerr-McGee Oil Industries Inc. partnered with Phillips Petroleum and Stanolind Oil & Gas Co. to secure leases for exploratory wells in the Gulf of Mexico. They hired Brown & Root to build a freestanding platform 10 mi. out to sea.

KERR-MCGEE'S MIGHTY KERMAC NO. 16

"We decided to explore the areas where the really potential prolific production might be—salt domes—the good ones on land were gone, but we could move out in the shallow water and, in effect, get into a virgin area where we could find the real class-one type salt dome prospect," McGee said.

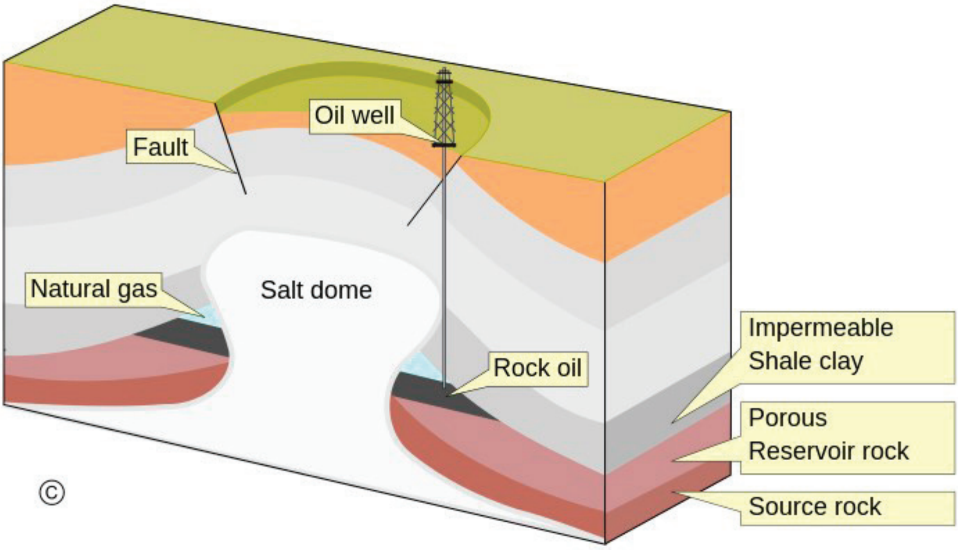

FIGURE D.5 Onshore salt domes were recorded as early as 1890 by the Geological Survey of Texas.

Vessels were needed to provide supplies, equipment, and crew quarters for the drilling site, 43 mi. southwest of Morgan City, Louisiana. The gradually sloping Gulf of Mexico reached only about 18-ft. deep at the drilling site.

A second platform would be built about 8 mi. from the first at Ship Shoal Block 28. Sixteen 24-inch pilings were sunk 104 ft. into the ocean floor to secure a 2,700 square foot wooden deck.

The Kermac No. 16 well stood in almost 20 ft. of water, 10 mi. at sea. The well was spudded on September 10, 1947. The biggest hurricane of the season arrived a week later—with winds of 140 mph. Kerr-McGee had $450,000 invested in the project. Both platforms were evacuated during the hurricane, but damage was minimal. Drilling promptly resumed. On November14, the Kermac No. 16 well came in at 40 barrels per hour. "Spectacular Gulf of Mexico Discovery. Possible 100-Million Barrel Field—10 Miles at Sea," proclaimed the *Oil & Gas Journal.* Kermac No.16 would produce 1.4 million barrels of oil and 307 million cu. ft. of natural gas by 1984.

NEW OFFSHORE RECORDS

By the end of 1949, 11 oil and natural gas fields were found in the Gulf of Mexico with 44 exploratory wells, according to the National Ocean Industries Association, which notes that the industry continued to through the 1950s (Figure D.6). Modern offshore energy industry benefits come from the hard lessons

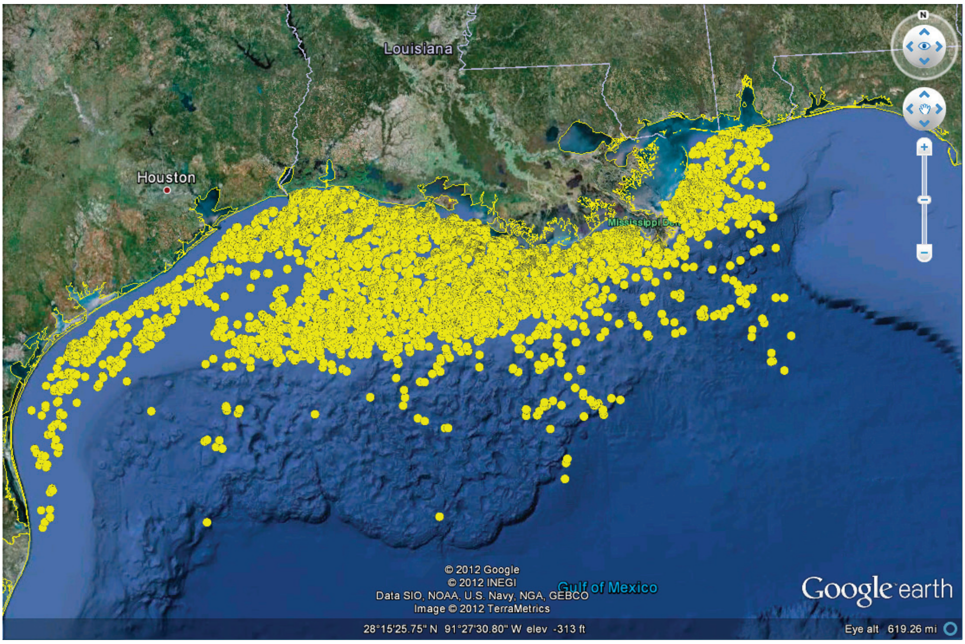

FIGURE D.6 Studies show that offshore platforms attract—and significantly increase—the numbers and species of fish. Today, 75 percent of recreational fishing trips off Louisiana visit one or more rig sites.

learned from 60 years of open water experience. Compared to the limits of just a few years ago, today's achievements will no doubt pale in comparison to what the future of offshore exploration will bring. Revenue generated from the production of oil became the second-largest revenue generator for the country, after income taxes. But deeper wells mean higher costs—and far greater technical challenges.

The National Ocean Industries Association notes: "As the industry entered the last decade of the 20th century, advancing technology ensued. New depth records for drilling reached 7,625 ft. in the Gulf of Mexico." In the North Sea, the Troll, a natural gas platform, stands in the North Sea in 1,000 ft. of water and is 1,500 ft. high (Figure D.7). According to a March 2013 article posted at Amusing Planet in 1996, the platform set the Guinness World Record for largest offshore gas platform. "The title now belongs to the Petronius Platform in the Gulf of Mexico, which stands 2,000 ft. above the ocean floor."

Figure D.8 is a Bell Helicopter advertisement from 1954, courtesy of the Ocean Star Offshore Drilling Rig and Museum.

A flat area on an LST (from WW Two's landing ship, tanks) anchored next to Humble Rig 28 served as landing pad for one of the first helicopters to be flown offshore. Today, helicopters are a common way for getting crews to and from offshore

FIGURE D.7 The Troll: A natural gas platform was not only “among the largest and most complex engineering projects in history,” it was “the largest object ever to be moved by man across the surface of the Earth.” SOURCE: Photo courtesy Amusing Planet.

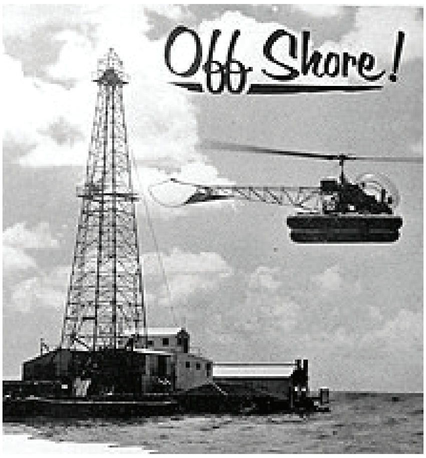

FIGURE D.8 The first use of helicopters offshore was at the request of Kerr-McGee and Humble Oil. Bell Helicopters recognized the opportunity and formed Petroleum Bell Helicopters Co.

platforms. Constructed on land, as components of an offshore rig are completed, they are shipped to the drilling location. Sometimes assembly takes place as the rig is being transported to its intended destination.

In addition, more scientists now recognize the role of petroleum platforms as artificial marine habitats. Whether placed as an artificial reef or a working (producing petroleum) structure, studies have been found rigs to increase the algae and invertebrates that attract—and significantly increase—numbers and species of fish.

On November 11, 2007, a mile and a half underwater, a petroleum company's remote control submersible camera captured a rarely seen Magnapinna squid (Figure D.9). The brief video, obtained by National Geographic News, shows the alien-like squid loiter above the seafloor in the Gulf of Mexico. The clip—from Shell Oil Company's Perdido production site—marks the first sighting of a Magnapinna or "big fin" squid near oil development. Marine biologists now partner with petroleum companies.

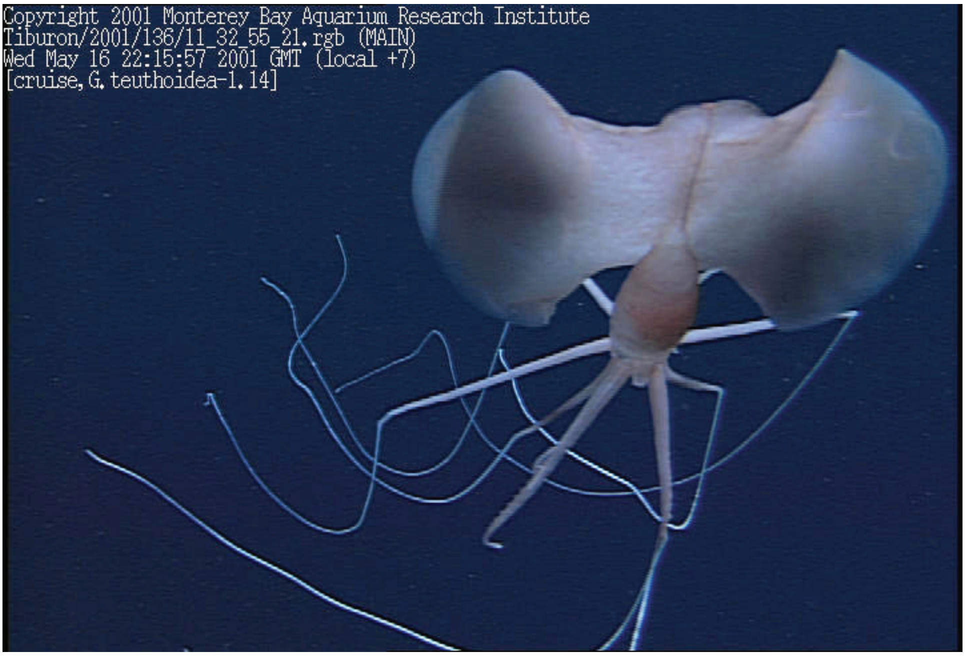

FIGURE D.9 A "big fin" squid underwater captured by MBARI marine biologists. SOURCE: Monterey Bay Aquarium Institute.

OFFSHORE OIL AND GAS RESOURCES

Gulf of Mexico federal offshore oil and natural gas production accounts for 23 percent of total U.S. crude oil production and federal offshore natural gas production in the Gulf accounts for 7 percent of total U.S. dry production, according to the Energy Information Administration. More than 40 percent of total U.S. petroleum refining capacity is located along the Gulf coast, as well as 30 percent of total U.S. natural gas processing plant capacity. To meet increasing U.S. demand while addressing environmental concerns, new technologies have resulted in drilling rigs capable of drilling 250 mi. offshore to ocean depths exceeding 10,000 ft. At stake are an additional 19 billion barrels of oil and another 86 trillion cu. ft. of gas. Fear of oil spills and heated environmental debates restrict access to many potential areas.

More than 5,000 offshore oil and natural gas platforms operate in the Gulf of Mexico around the clock, seven-days a week. It is the largest artificial reef system in the world.

According to the National Academy of Sciences, more than 60 percent of all oil found in seawater is not from wells, but from natural seepage (the largest emitting 1,000 barrels of oil a week); 32 percent comes from shipping and run-off from land. Four percent can be attributed to tanker spills. However, near Santa Barbara, Calif., offshore drilling's worst environmental disaster occurred in 1969 when an undersea well blew out. The calamity quickly brought industry changes that have protected the offshore environment ever since. Between 1980 and 1999, about 7.4 billion barrels of oil were produced in federal waters, says the U.S. Coast Guard. Less than a thousandth of one percent spilled—less than the natural seepage of oil from the sea floor.

E

Selected Subsea Bolt Failures

Table E.1 is a summary of selected subsea bolt failures but does not include data from proprietary failure databases.

TABLE E.1 Selected Subsea Bolt Failures

Date	Identification	Fastener Summary/Comments	Reference
≈2002	Specific application not identified	First Major riser bolt/insert environmentally assisted failure since drilling vessels began using impressed current systems (ICS) in 1998-2000. As a consequence, bolt hardness was reduced to HRC34; an ICS safety alert was issued related to removal of metallic coating from bolt holes. The number of incidents was not reported. Adamek noted that “riser bolt/insert cracking observed on several vessels with ICS; no failures observed on rigs with fixed anode systems.” The number of incidents was not reported.	Adamek, 2017

TABLE E.1 Continued

Date	Identification	Fastener Summary/Comments	Reference
May 21, 2003	Flanged riser bolt/bolt insert failure Transocean (TO) Discover Enterprise (DE)	"The bolts' inserts (nuts) that secure the drilling riser failed between joints 39 and 40. The inserts and the bolts' material was AISI 4340 with a material hardness of 34-38 HRC and yield strength of 145 ksi. The 2003 Combined RCA Report . . . identified that the bolt inserts and bolts fractured due to severe, accelerated, environmentally assisted corrosion. The high material hardness, yield strength, bolt design, impressed current and thermal spray aluminum coating were identified as contributing factors for the failure." (Product Advisory issued by Vetco Gray on April 8, 2005)	BSEE, 2014
2012-2013	Flanged riser bolt/bolt insert failure Transocean (TO)-Pathfinder TO-Horizon TO-Millennium TO-Deepseas	Per QC-FIT Report, Appendix G, "Riser bolt inserts (nuts) & bolt fractures due to environmentally assisted cracking, hydrogen embrittlement. Corrosion brittle fracture. High material hardness, coating/material compatibility issues, strength loading." The number of bolts and bolt inserts or details for each were not identified. Per QC-FIT Report, Appendix H, "In 2003, four other TO rigs: TO-Millennium, TO-Horizon, TO-Deepseas, and TO-Pathfinder bolt inserts failed in the same brittle corrosion fracture manner as the 2003 TO-DE and the 2012-2013 H4 connector bolt failures of TO-DI, TO-DAS, TO-Deepwater Champion and P-10K. The same third laboratory performed the RCA for both of the 2003 and recent 2012-2013 bolt failures."	BSEE, 2014
Before 2010; specific date not identified	Shaffer Division of National Oilwell Varco (NOV) for Diamond Offshore Drilling, Inc.	Studs used in the construction of a blow out preventer (BOP) stack; three fractured, 3-in.-diameter Inconel 718 studs were evaluated out of 20 (11 had fractured, and 9 exhibited stripped threads).	Jones and Buehler, 2010
November 1, 2012	Blind shear ram bolt failures Transocean (TO) Discoverer India (DID)	"Blind shear ram (BSR)/shear ram (SR) bolts fracture during a 15,000 psi pressure test (stump test). . . . A similar failure also occurred on an ENSCO 8506 drilling riser. The bolts failed due to tensile overload and bolt hardness due to incorrect heat treatment. The initial identified contributing factor for the failure was QC issues with GE's subcontracted vendor regarding communication and improper heat treatment procedures for the raw bolt material."	BSEE, 2014

TABLE E.1 Continued

Date	Identification	Fastener Summary/Comments	Reference
December 18, 2012	Transocean (TO) Discoverer India (DID)	Lower marine riser package (LMRP) separated from blow-out preventer (BOP); Thirty-six H4 connector bolts, AISI 4340, fractured; bolts identified as 2-in. diameter, approximately 9 in. long; Stress Engineering Services indicated “failures of the incident bolts initiated due to hydrogen stress cracking” and “it is likely that atomic hydrogen present in the bolts due to the plating process (and not removed via a subsequent bake-out) played a major role in the failures” (GE issued GE Safety Notice SN 13-001, REV. NC H4 Connector Bolt Inspection).	BSEE, 2014
January 5, 2013	Transocean (TO) Discoverer Americas (DAS)	Four fractured bolts were received for analysis by SES. The total number and bolt details for the application were not indicated. The SES report did note that the application appeared to “use the same series of connectors and part-numbered bolts” and “exhibit similar fracture features as those removed from the DID” (see December 18, 2012 above).	BSEE, 2014; SES, 2013
January 25, 2013	Petrobras 10,000 (PB10K)	Per QC-FIT report, PB10K was in service about 2.5 years when bolt failures discovered in response to GE safety notice. Five fractured bolts were received for analysis by SES. The total number and bolt details for the application were not indicated. The SES report did note that the application appeared to “use the same series of connectors and part-numbered bolts” and “exhibit similar fracture features as those removed from the DID” (see December 18, 2012, above).	BSEE, 2014; SES, 2013
January 5, 2013	Transocean (TO) Discoverer Clear Leader	Per QC-FIT Report, Appendix G, “H4 connector bolts failed inspection were rejected.” The bolts were inspected by magnetic particle techniques and the number of bolts and bolt details were not indicated.	BSEE, 2014
January 5, 2013	Transocean (TO) Deepwater Champion	Per QC-FIT Report, Appendix G, “H4 Connector bolts had significant corrosion products, fractures.” The number of bolts and bolt details were not indicated.	BSEE, 2014

TABLE E.1 Continued

Date	Identification	Fastener Summary/Comments	Reference
June 2014	Seadrill West Capricorn	Twenty HC Connector studs were received by SES for analysis. Of these, nine were completely fractured and four exhibited significant cracking based on magnaflux testing. The material was AISI 4340 steel with average bolt hardness values between 31 and 41 HRC. The 3-in. diameter double-ended studs were 18 3/4 in. long. The SES report indicated that the "studs exhibited multiple fracture origins at the root of the threads in what is likely the first engaged thread" and "that Environmentally Assisted Cracking (EAC) was the most probable cause of the observed fractures." Cameron issued a product advisory on July 15, 2014	SES, 2013; BSEE, 2014
Not specified	Brazil—Petrobras Vessel in Gulf of Mexico Region	Per QC-FIT Report, Appendix G, "Severe corrosion fractured failed H4 connector bolts." The number of bolts and bolt details were not indicated.	BSEE, 2014
Not specified	Brazil—Noble-Paul Wolf in Gulf of Mexico Region	Per QC-FIT Report, Appendix G, "Fractured bolts identified during leak during pressure test." The number of bolts and bolt details were not indicated.	BSEE, 2014
Not specified	Norway Vessel (BP Operator) in Gulf of Mexico Region	Per QC-FIT Report, Appendix G, "Chloride Stress Corrosion Cracking (Cl-SCC) fracture failure of bolts for valve. Likely same alloy material as H4 connector bolt." The number of bolts and bolt details were not indicated.	BSEE, 2014
Not specified	DNN-GL Failure Investigation Database Incidents varied and not specified	Presentation summarizes results from the DNV-GL failure investigation database and notes that 9% of the failure investigations were on fasteners. Of these, 65% were brittle fractures. Of these brittle fractures 57% were attributed to hydrogen embrittlement, 29% to temper embrittlement, and 14% to other/undetermined causes.	Heiberg, 2017

SOURCES: Adamek, F.C., Adamek Engineering and Technology Solutions LLC, "A Historical View of Subsea Bolting," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 10-11, 2017.

BSEE (Bureau of Safety and Environmental Enforcement), *QC-FIT Evaluation of Connector and Bolt Failures: Summary of Findings*, QC_FIT Rpt. #2014-01, Office of Offshore Regulatory Programs, August 2014.

Heiberg, G., 2017, "Bolted Connection: Is It a Need for Improved Requirements?," Paper No. OMAE2017-62730, 36th International Conference on Ocean, Offshore, and Arctic Engineering, June 28, 2017.

Jones, R.L., and W.M. Buehler, *Examination of Three Failed Inconel 718 Studs*, Report No. 0091-10-19492R, Stork Testing and Metallurgical Consulting, Inc., March 1, 2010.

SES (Stress Engineering Services, Inc.), *Site Inspection, Metallurgical Examination, and Mechanical Damage Analysis of Discover India LMRP*, Report No.: PN1252494, February 27, 2013, Houston, Tex.

SES, *Metallurgical Failure Analysis of HC Connector Studs from West Capricorn Facility*, Report No. 1253345-FA-RP-01, October 6, 2014, Houston, Tex.

F

Recent Industry and Regulator Response to Critical Subsea Bolt Failures

The purpose of this appendix is to identify gaps in industry and regulatory systems that could adversely affect the reliability of subsea bolts in critical service. This appendix highlights recent proactive actions that the oil and gas industry have already taken in response to critical bolt failures in subsea service,

These responses were in addition to the many industry and Federal Government responses that were already underway responding to the Macondo incident.

In addition to the BSEE initiatives the industrial representatives reported to the committee that the oil and gas companies, drilling contractors, and equipment manufacturers are actively working together to improve bolting reliability. They stated that the following efforts were being carried out: (1) documenting failures in an industry database, (2) developing the root cause of failures, and (3) responding to the root cause with corrective actions.

The industry representatives reported the following corrective actions to the committee: (1) through the API Multi-Segment Task Group they were developing enhanced standards; (2) Through the API Bolting Workgroup drilling contractors were executing voluntary industry actions, and tracking actions and bolting performance; (3) Manufacturers were applying updated standards to the manufacturing processes; (4) Quarterly meetings where API and industry brief BSEE on the status of industry's bolt replacement efforts.

BOLT FAILURES

Bolts, even the large bolts used in connecting BOP components, have tended to be considered inconsequential commodities. There were several bolt failure incidents that prompted BSEE and industry to start looking in earnest at critical bolts in subsea service. These are detailed in Appendix E, "Selected Subsea Bolt Failures."

The failure of a multitude of bolts on the Transocean Discoverer India H4 connector of a GE BOP stack on December 18, 2012, was a cluster failure of such a magnitude and critical nature that it made evident to BSEE and to industry that there was a potential systemic problem in the specification, manufacture, installation, or maintenance of bolts in operating in a subsea—many of which served a critical function.

BSEE RESPONSES

1. In response to the December 18, 2012, incident on the Discoverer India, BSEE formed a Quality Control-Failure Incident Team (QC-FIT) in January 2013, within weeks of the incident. The remit of this team was to conduct technical evaluations of failed bolts, to assess "fitness for service" of the manufactured bolts, and to identify gaps in industry standards, industry practices, or regulations.[1] More importantly, the team was given the task "to evaluate the possibility of additional bolt failures and make recommendations to mitigate potential risks of future failures, either domestically or internationally."[2]

   During its technical evaluation the team was made aware of "other offshore oil and gas failures related to bolts, studs, inserts and connectors, appearing to share similar contributing factors."[3] It was at this point that BSEE tasked the QC-FIT "to evaluate whether the causes of these other failures were related and whether evidence existed of an industry-wide issue."[4]

   The QC-FIT worked closely with Transocean, Chevron, and GE in evaluating the H4 failures on the Transocean Discoverer India. In order to assess the potential for an industry-wide, systemic problem, the QC-FIT team also worked with other operators, drilling contractors, equipment manufacturers, a classification society, and BSEE's international counterparts.

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[1] Douglas Morris, OORP Chief; "National Academy of Sciences Workshop on Subsea Bolts Performance and Critical Drill-Through Equipment Fasteners," presentation to the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations on April 10, 2017.

[2] Bureau of Safety and Environmental Enforcement (BSEE), *Evaluation of Connector and Bolt Failures—Summary of Findings*, QC-FIT Report #2014-01, Office of Offshore Regulatory Programs, August 2014, *https://www.bsee.gov/sites/bsee.gov/files/bolt_report_final_8-4-14.pdf.*

[3] Ibid.

[4] Ibid.

The QC-FIT reported its findings in August, 2014 in "QC-FIT Evaluation of Connector and Bolt Failures: Summary of Findings." The team found that the Discoverer India H4 bolt failures were likely due primarily to hydrogen embrittlement (HE). Potential causes of the hydrogen embrittlement were identified as follows:

- Use of outdated specifications for post electroplating bake-out of hydrogen
- Failure of quality management systems to effectively cross multiple "tiers" of manufacturers and suppliers.
- Cathodic protection systems not being considered in connector and bolt design.
- Inadequate standards for connectors and bolts in subsea service.

The recommendations of the QC-FIT were the following:

- Improve various industry standards
- Initiate joint industry research initiatives to improve connector design and reliability
- Promote a comprehensive failure reporting system
- Develop regulations to ensure specific design standards are met.

This QC-FIT effort was immediate response to indications that there may be some broad, industry-wide issues affecting the reliability of critical bolting in subsea service.

2. On July2, 2014, BSEE, reconvened the QC-FIT following two more subsea bolt failures:

   - In February 2014, a connector leak was observed during pre-deployment testing of a LRMP.
   - On June 30, 2014, 20 fasteners were found to have failed on a LMRP connector during inspection of the BOP stack on the rig between wells. Like the 2012 Discover India incident, this was a significant cluster failure.

   This second QC-FIT reported its findings in February 2016 in *QC-FIT Evaluation of Fastener Failures—Addendum*."[5] The findings were very similar to the August 2014 report:

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[5] "BSEE, *Evaluation of Fasteners Failures—Addendum*, QC-FIT Report #2016-04, Office of Offshore Regulatory Programs, February 2016, *https://www.bsee.gov/sites/bsee.gov/files/qc-fit-nov-bop-bsr-bolt-report-7282017.pdf.*

- Environmentally-assisted corrosion
- Incorrect or conflicting industry standards on material hardness limits
- Need to fully implement the new API Spec 20E into the OCS regulations
- Insufficient understanding of material failure mechanisms on highly stressed materials used to construct bolts.

3. In February 2016 BSEE issued Safety Alert 318 to GOM operators advising them of bolting failures.[6,7]
4. In August 2016 BSEE sponsored a Bolt Forum with the purpose on enabling communication among the oil and gas industry, other industries, other regulators, and various standards organizations.
5. BSEE initiated a project with Argonne National Laboratory to review various industry standards to identify gaps, overlaps, and conflicts.
6. BSEE secured the services of NASA to be an independent third party testing laboratory.
7. BSEE formed an interagency bolt action team to develop recommendations on materials for fasteners on subsea service.
8. Of course, BSEE initiated this NAE study into improving subsea connector reliability.

API RESPONSE

Recognizing the potential consequences of these critical bolt failures, and especially the significance of the cluster failures, industry undertook failure analysis and root cause analysis, with participation by drilling contractors, OEMs, and operating companies.

The oil and gas industry (mostly through the API) tackled the issue—evidently cutting through a significant amount of red tape, through as hoc committees and through standards committees.

Figure F.1[8] shows the timeline of API activities to address the failure of critical bolts. Significant API activities are described in more detail below.

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[6] T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations on April 11, 2017.

[7] BSEE, "Connector and Bolt Failures," Safety Alert 318, February 20, 2016, https://www.bsee.gov/sites/bsee.gov/files/safety-alerts/safety/safety-alert-connector-and-bolt-failures-02-02-2016a.pdf.

[8] H. Hopkins, American Petroleum Institute, "Update on Industry Activities on Subsea BOP Bolting," presentation at the Subsea Bolt Performance Houston Site Visit Kickoff Meeting, March 22, 2017.

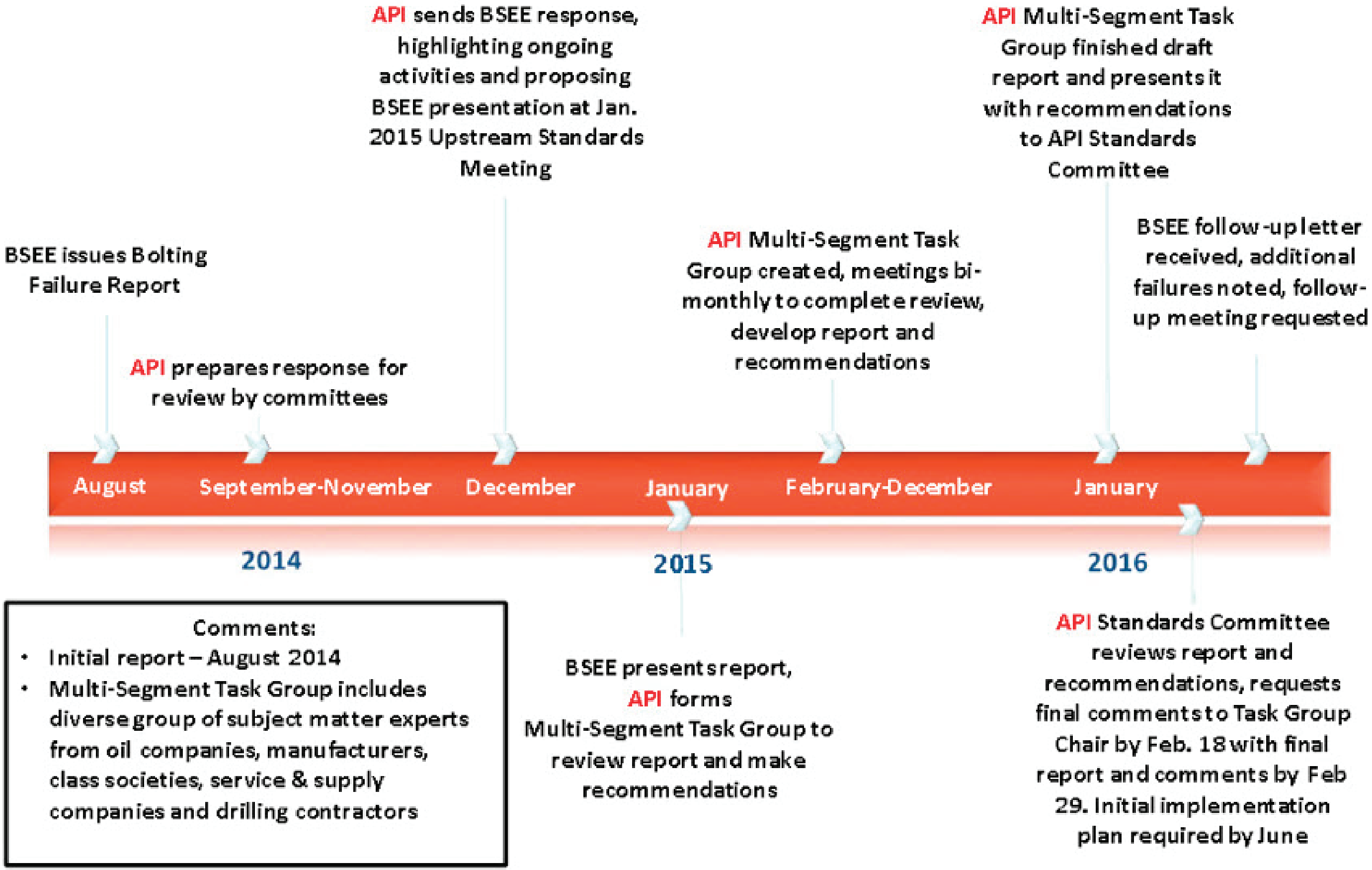

FIGURE F.1 Timeline of American Petroleum Institute (API) activities—(a) 2014 and 2015, (b) 2016, and (c) 2017.

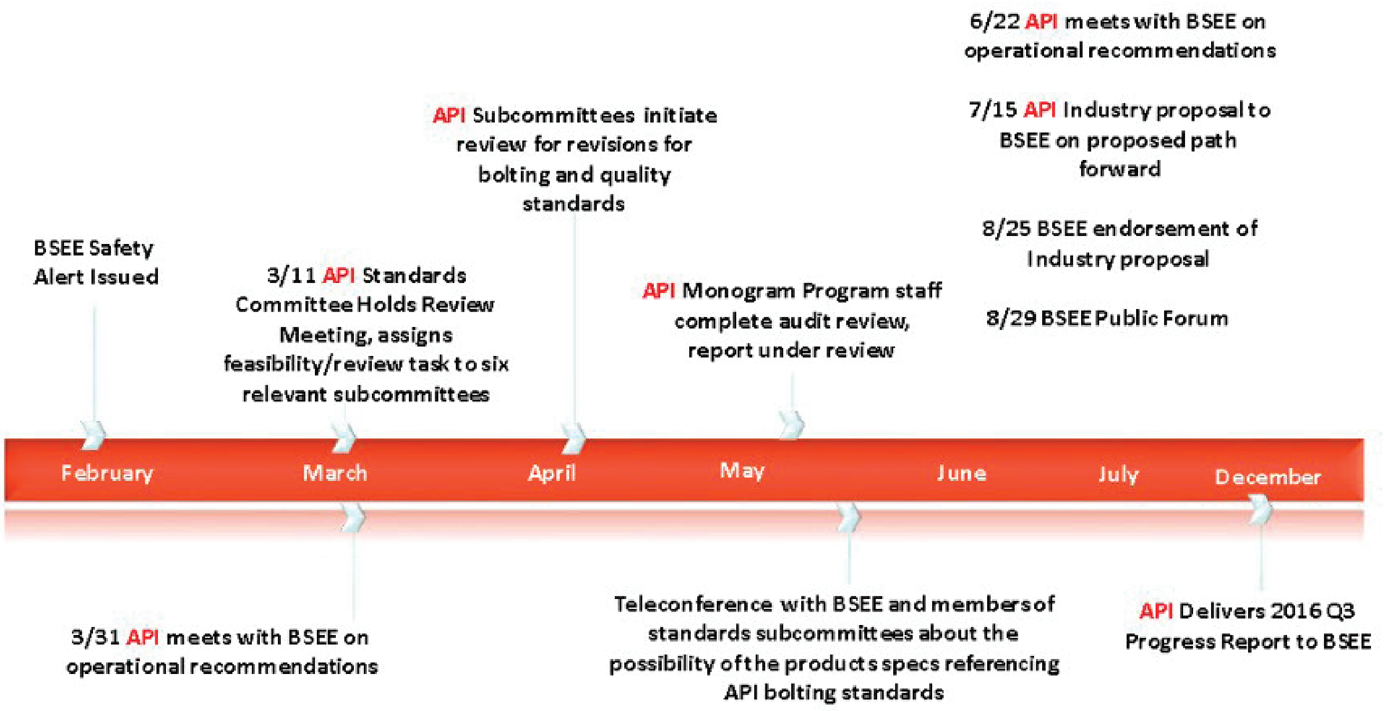

FIGURE F.1 Continued

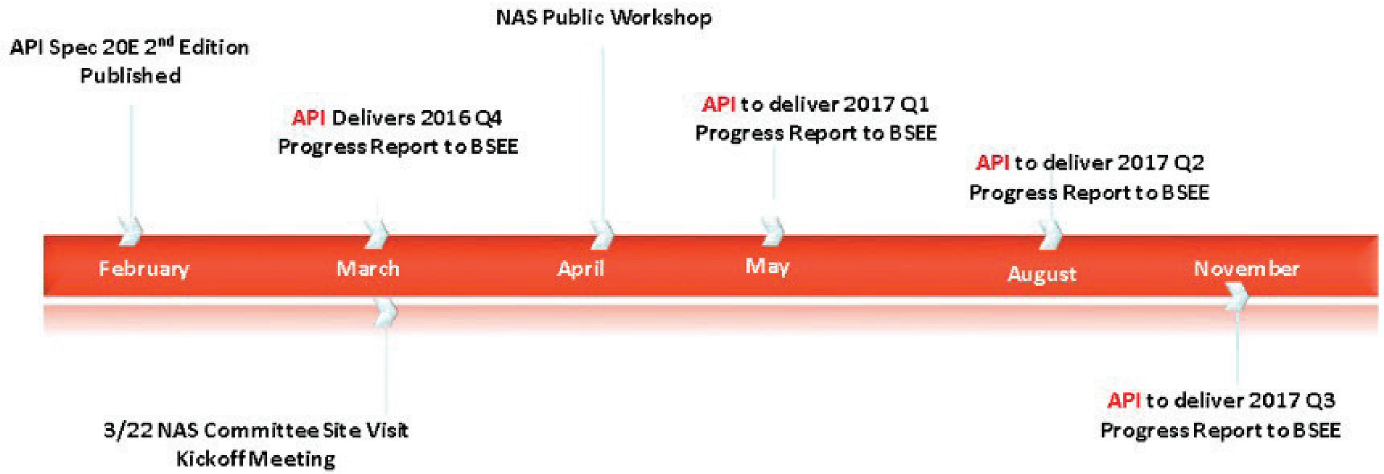

FIGURE F.1 Continued

1. In April 2016 the API held their first meeting with BSEE which resulted in the establishment of the API Multi-Segment Bolting Task Group.[9] The initial driver for forming this API task group was the 2014 BSEE QC-FIT report.[10] This task group was charged with the following:

    - Evaluating potential types of bolting failures that might occur in the upstream oil and gas industry,
    - Determine potential contributing factors to bolt failures,
    - Identify current bolt failure mitigations, and
    - Recommend Changes to industry standards.

    This task group promulgated 20 recommendations to API to improve the effectiveness of API standards and specifications in preventing bolt failures.[11]

    Actions taken by this task group also included the establishment of a bolt failure reporting system. This program is voluntary, and participation is growing.[12]
2. In April 2016, BSEE undertook a review of their monogram auditing program to assess the effectiveness of their monogram auditing program.
3. The API undertook a series of revisions to existing standards and development of new standards to improve their coverage of issues related to subsea bolt failures. Initially this centers on the development of two new specifications:

    - API Specification 20E, Alloy and Carbon Steel Bolting for Use in Petroleum and Natural Gas Industries—the second edition was published February 2017.
    - API Specification 20F, Corrosion Resistant Bolting for Use in Petroleum and Natural Gas Industries—the first edition was published in June 2015.

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[9] T. Fleece, BP, “Mitigating BOP Failures,” presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

[10] H. Hopkins, American Petroleum Institute, “Update on Industry Activities on Subsea BOP Bolting,” presentation at the Subsea Bolt Performance Houston Site Visit Kickoff Meeting, March 22, 2017.

[11] Ibid.

[12] T. Fleece, BP, “Mitigating BOP Failures,” presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

Additionally, other API specifications are being (or already have been) revised:[13]

- API 6A, 21st edition, will require bolts conform to API 20E.
- API 6DSS 3rd edition, will require conformance to API 20E and API 20F for pressure boundary bolts.
- API 16A, 4th edition, will require conformance to API 20E and API 20F for pressure controlling bolting and pressure retaining bolting.
- API 16AR, 1st edition, will require conformance to API 20E and API 20F for pressure controlling bolting, closure bolting and pressure retaining bolting.
- API 16F, 2nd edition, will require conformance to API 20E and API 20F.
- API 64, 3rd edition, will require conformance to API 20E and API 20F for primary and closure bolting.

The committee recommendations for further actions by the oil and gas industry and API should not diminish the great respect the committee has for the actions they have already undertaken.

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[13] H. Hopkins, American Petroleum Institute, "Update on Industry Activities on Subsea BOP Bolting," presentation at the Subsea Bolt Performance Houston Site Visit Kickoff Meeting, March 22, 2017.

G

Subsea Environmental Factors for Fastener Design

OCEAN ENVIRONMENT

Underwater Environments

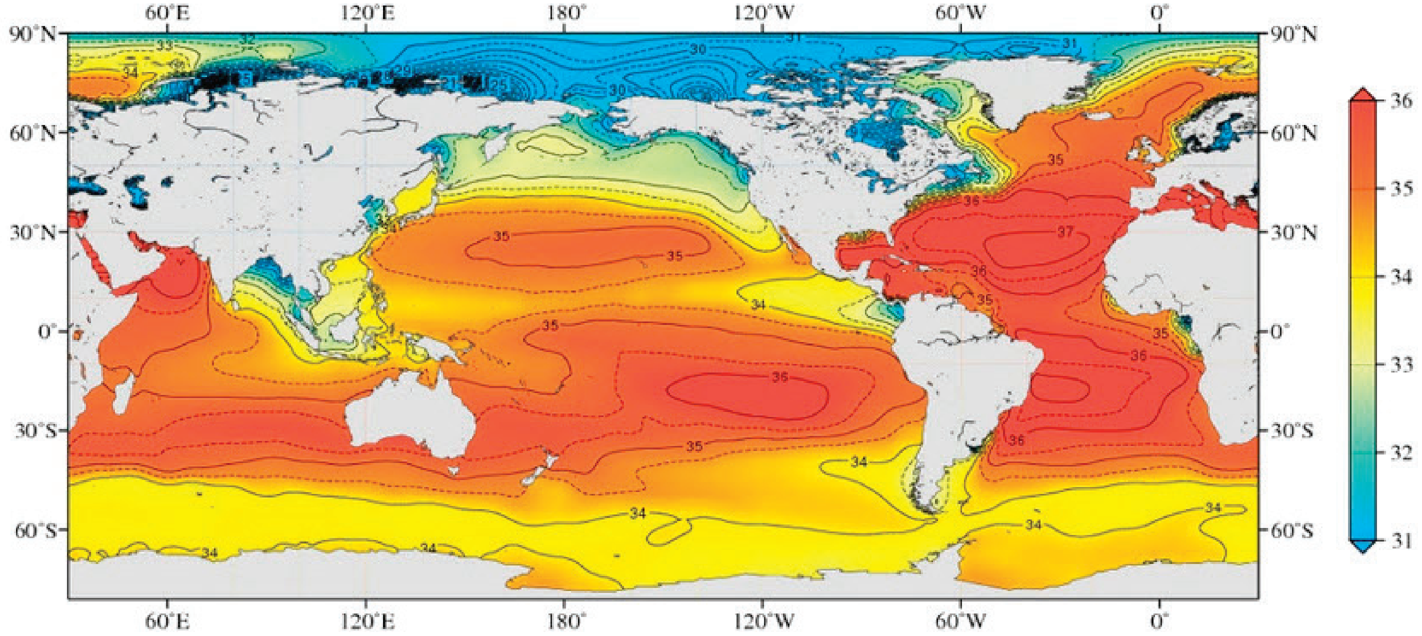
Salinity

Sea water contains various organic and inorganic matter and a few atmospheric gasses in suspension or in solution. The inorganic matter consists of salt ions, mainly sodium (Na^+) and chloride (Cl^-), though sulfate ($SO^2{}_4{}^-$), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+) may also be present. These ions make up approximately 99 percent of all salts dissolves in seawater.

The salinity of sea water is nominally 35 g/kg expressed as parts per thousand (ppt). However sea water salinity is not constant in terms of location, time, or depth. There are several factors that affect the salinity of sea water, including the following:

- Temperature,
- Pressure,
- Evaporation,
- Fresh water influx (rainfall, influx from fresh water streams, glacial melting),
- Wind, and
- Ocean currents.

Figure G.1 shows the 1955 to 2012 average annual mean sea water salinity around Earth. The North and South Atlantic have zones of relatively high salinity



Annual salinity at the surface (one-degree grid)

FIGURE G.1 Average annual mean sea surface salinity for the world oceans, 1955 to 2012 (in practical salinity units [psu]). NOTE: The practical salinity scale (PSS-78) created defines salinity in terms of the conductivity ratio of a sample to that of a solution of 32.4356 g of KCl at 15°C in a 1 kg solution. A sample of seawater at 15°C with a conductivity equal to this KCl solution has a salinity of exactly 35 psu. SOURCE: National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information, "Ocean Climate Laboratory Team, World Ocean Atlas 2013 Version 2, WOA13F V2 Interactive Image Access," https://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl, accessed October 18, 2017.

compared with the Pacific Ocean, which is diluted by rainfall during the monsoon season. The Mediterranean Sea has very high salinity levels. The Gulf of Mexico (GOM) has moderately high salinity in its southern half.

Table G.1 shows the effect of seawater salinity on density. This chart ignores the effect of water compressibility.

Water salinity in the Gulf of Mexico varies with time, depth, and location—varying between 35.6 ppt and 36.5 ppt. Salinity variations this small do not appreciably affect the density of water.

There are also hypersaline pools in the Gulf of Mexico. These hypersaline pools contain seawater with up to 8 times the chloride ion concentration of normal seawater.[1]

Temperature

The temperature of seawater at the ocean surface varies from approximately −2°C to +30°C, depending on surface temperature, cloud cover, latitude, ocean currents, and the time of year. Mid-ocean surface temperatures vary with latitude in response to the balance between incoming solar radiation and outgoing longwave radiation. There is an excess of incoming solar radiation at latitudes less than approximately 45° and an excess of radiation loss at latitudes higher than approximately 45°. Superimposed on this radiation balance are seasonal changes in the intensity of solar radiation and the duration of daylight hours due to the tilt of Earth's axis to the plane of the ecliptic and the rotation of the planet about this axis. The combined effect of these variables is that average ocean surface temperatures are higher at low latitudes than at high latitudes. Because the Sun, with respect to

TABLE G.1 Density of Seawater versus Salinity and Temperature (g/cm^3)

Temperature		Salinity (psu)				
°C	°F	5	10	20	30	35
0	32	1.00397	1.00801	1.01607	1.02410	1.02813
5	41	1.00401	1.00797	1.01586	1.02374	1.02770
10	50	1.00367	1.00757	1.01532	1.02308	1.02697
15	59	1.00301	1.00685	1.01450	1.02215	1.02599
20	68	1.00207	1.00586	1.01342	1.02098	1.02478
25	77	1.00087	1.00462	1.01210	1.01960	1.02336
30	86	0.99943	1.00315	1.01057	1.01801	1.02175

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[1] Carl Szczechowski, "Physical Oceanography Synopsis," presentation to the committee on June 6, 2017.

Earth, migrates annually between the Tropic of Cancer and the Tropic of Capricorn, the yearly change in heating of Earth's surface is small at low latitudes and large at mid- and higher latitudes."[2]

Figure G.2 shows the 1955 to 2012 average annual mean sea water temperature around Earth. As could be expected the Gulf of Mexico is in the warmer zone near Earth's equator.

Water temperature gets colder with increasing depth, due mainly to the lack of heating by solar radiation. In ultra-deepwater, temperatures can reach as low as −1°C (30.2°F).

Water temperature in the Gulf of Mexico varies with time, depth, and location—varying between 40°F and 79°F (4°C to 26°C). Although there is some expansion of water due to temperature, variations this small do not appreciably affect the density of water.

Dissolved Salts

The relative concentrations of various salt ions in sea water vary little, and should have very little impact on sea water density.

Water Compressibility

Water is relatively incompressible, ranging from 5.1E^{-10} Pa^{-1} ($3.5^{\text{E-6}}$ psi^{-1}) at 32°F (0°C) at zero pressure to a low of 4.4E^{-10} (3.0E^{-6}) at °F (45°C) and zero pressure.[3] Water compressibility, therefore, is not considered to be a significant factor in determining water density.

Water Density

Water density affects the pressure exerted on underwater equipment at depth. In fact water density and water depth are the only two factors in determining water pressure at depth. Figure G.3 shows the 1955 to 2012 average annual mean sea-surface density of water in the world's oceans.

Although water is relatively incompressible, it's density does increase slightly with water pressure.

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[2] National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information, "Ocean Climate Laboratory Team, World Ocean Atlas 2013 Version 2, WOA13F V2 Interactive Image Access," https://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl, accessed October 18, 2017.

[3] R.A. *Fine and F.J. Millero, Compressibility of water as a function of temperature and pressure, Journal of Chemical Physics 59(10):5529, 1973.*

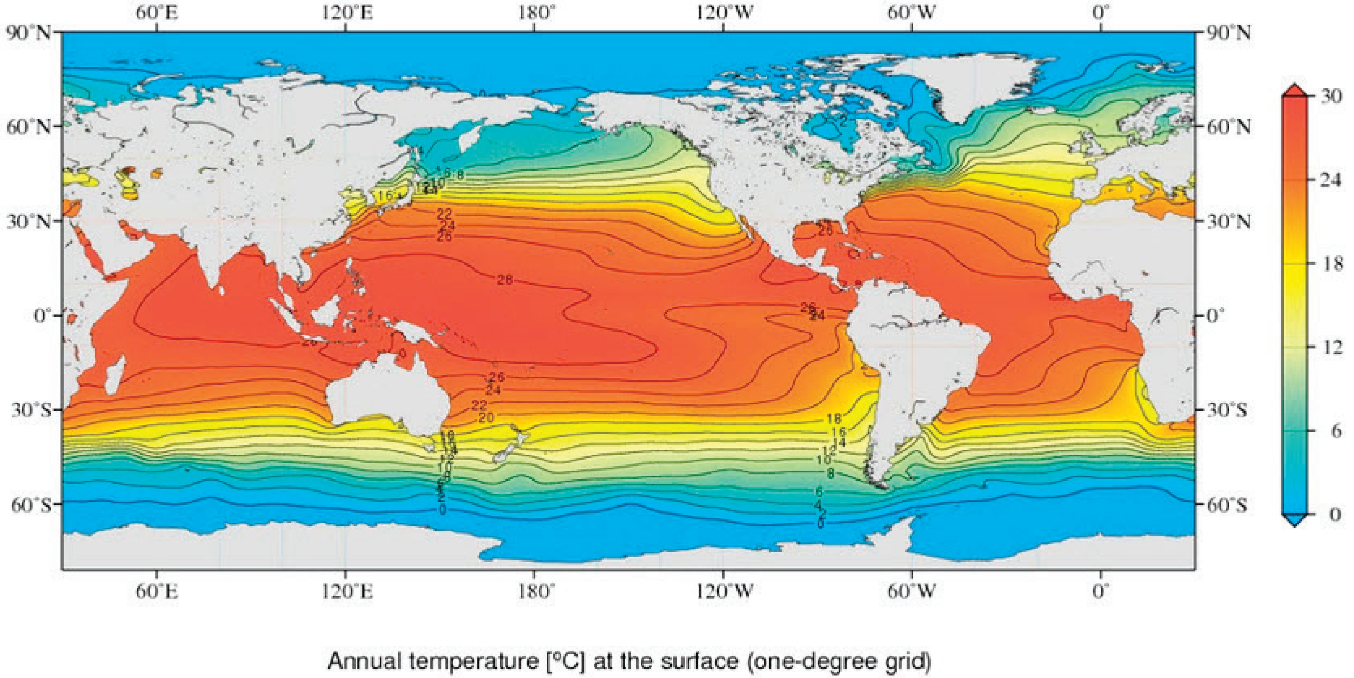


FIGURE G.2 Average annual mean ocean surface temperature, 1955 to 2015.

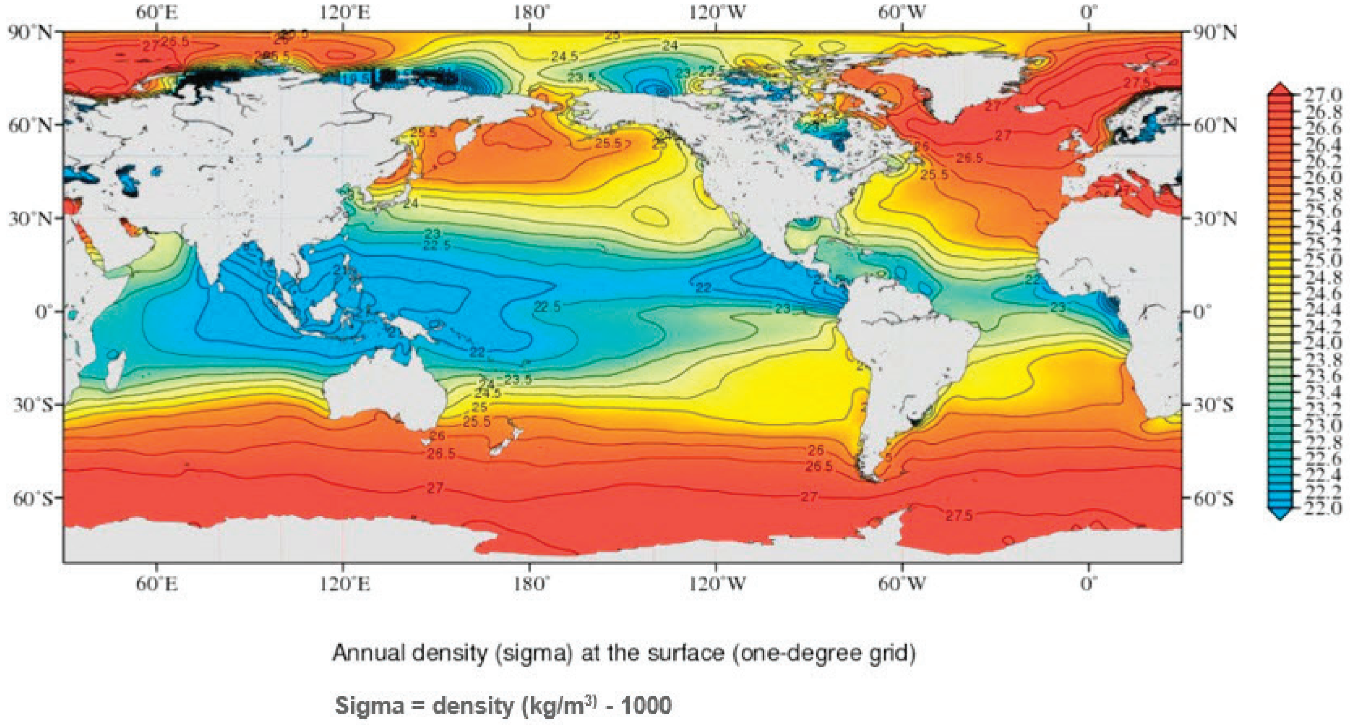


FIGURE G.3 Average annual mean surface water density, 1955 to 2012. SOURCE: National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information, "Ocean Climate Laboratory Team, World Ocean Atlas 2013 Version 2, WOA13F V2 Interactive Image Access," https://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl, accessed October 18, 2017.

Table G.2 shows the effect of pressure on density. It reflects the compressibility of 35 ppt sea water at 0°C.

It should be noted that the density values in Table G.2 have also been shown in customary U.S. (except California) of pounds per U.S. gallon.

As per current oilfield practice, density has also been converted to pressure gradient expressed in terms of psi per foot (of depth). Pressure gradient is calculated from density by the formula:

$$\text{Pressure gradient (psi/ft)} = \text{Density (ppg)} \times 0.052$$

For example, at 100 bar (145 psi) a 35ppt seawater at 0°C will have a density of 8.6196 ppg. At a depth of 100 ft., the pressure gradient will be:

$$8.6196 \text{ ppg} \times 0.052 = 0.448195 \text{ psi/ft.}$$

The pressure exerted by the water will be:

$$100 \text{ ft.} \times 0.448195 \text{ psi/ft.} = 44.8195 \text{ psi}$$

Neither Table G.1 nor Table G.2 give a full representation of the relationship of seawater density to the combination of salinity, temperature, and pressure. The actual density of seawater is a much more complex relationship. In addition, in-situ salinities and temperatures are very dynamic properties and are difficult to predict.

TABLE G.2 Density of Seawater versus Pressure

Density Changes with Pressure
(seawater 35 parts per thousand and 0°C)

Pressure (bar)	(psig)	Density (kg/m^3)	(ppg)	Pressure Gradient (psi/ft)
0	0.0	1028.13	8.57974	0.446147
100	145.0	1032.85	8.61913	0.448195
200	290.1	1037.47	8.65769	0.450200
400	580.2	1046.40	8.73221	0.454075
600	870.2	1054.95	8.80356	0.457785
800	1,160.3	1063.15	8.87199	0.461343
1,000	1,450.4	1071.04	8.93783	0.464767

SOURCE: F.T. Mackenzie, "Seawater," *Encyclopædia Britannica Online,* 2017, accessed April 28, 2017, https://www.britannica.com/science/seawater. In this reference, the "Density changes with depth" table on page 7 has been corrected to remove the depth parameter because the depth versus pressure relationship was erroneously based on the density of pure water, not 35 ppt sea water at 0°C.

Water Depth

Fresh water has a density of 1.00 g/cm^3, or 8.337 ppg (pounds per U.S. gallon). Generally, 35 ppt sea water has a density of 1.02813 g/cm^3 (1.02813 specific gravity). There are minor variations to this “nominal” sea water density depending on water salinity and temperature.

Table G.3 shows how water density, and the resulting pressure gradient, change with increasing pressure at depth. Note that the far-right column shows the calculated pressure using the oilfield norm of 8.6 ppg.

The assumed water density value of 8.6 ppg has served the industry for decades. As is shown Table G.3, if sea water density from Table G.2 is used to predict sea water density and pressure versus depth, the effective density at 2,000 m (6,562 ft.) feet is psi/ft. is 8.66 ppg, the pressure gradient is 0.44920 psi/ft., and the pressure is 2,941.0 psi. If the usual seawater density of 8.6 ppg is used, the calculated pressure

TABLE G.3 Density and Pressure of Seawater versus Depth (seawater 35 parts per thousand and 0°C)

Depth Section	Depth		Density		Gradient	Pressure	Pressure
			At depth	Average	At depth	Avg ppg	ppg=8.6
	(m)	(feet)	(ppg)	(ppg)	(psi/ft)	(psi)	(psi)
1	0	0	8.57974	8.57974	0.44615	0.0	0.0
2	1,000	3,281	8.61913	8.59944	0.44717	1,467.2	1,467.3
3	2,000	6,562	8.65769	8.63841	0.44920	2,941.0	2,934.5
4	4,000	13,124	8.73221	8.69495	0.45214	5,907.9	5,869.1
5	6,000	19,686	8.80356	8.76788	0.45593	8,899.7	8,803.6
6	8,000	26,248	8.87199	8.83777	0.45956	11,915.4	11,738.1
	10,000	32,810	8.93783	8.90491	0.46306	14,954.0	14,672.6

NOTE: Pressure at depth is calculated using the average sea water density on the depth section.

at depth is 2,934.5 psi. Similarly, at 13,124 ft., the difference in calculated pressure at depth is 5907.9 psi vs. 5969.1 psi.

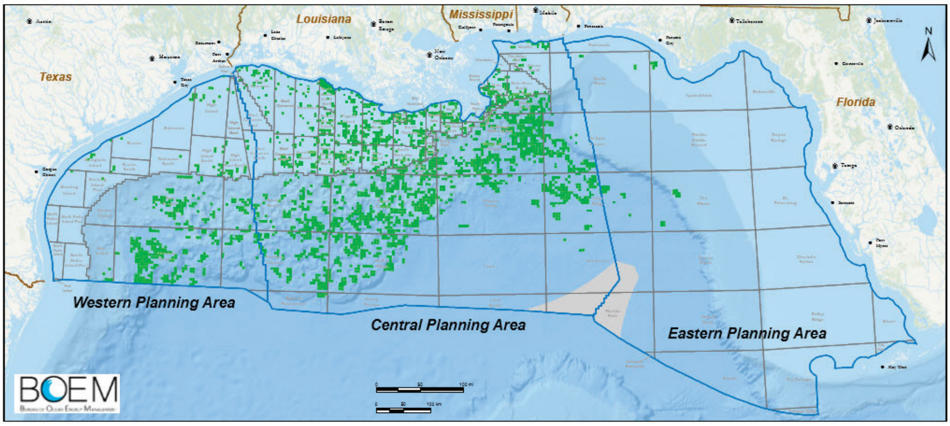
It can be concluded that the use of 8.6 ppg (1.031 SG; 0.4472 psi/ft.) is sufficiently accurate for use in the Gulf of Mexico where water depths rarely exceed 10,000 ft. (3,048 m)

Gulf of Mexico Application Environments

The previous section was intended to give an overview of the physical parameters of seawater that need to be considered when designing underwater equipment. This section will narrow in on the U.S. Gulf of Mexico which is the target area for this study.

Figure G.4 shows the oil and gas leases in the United Stated sector of the Gulf of Mexico. For the purposes of this study we will be further investigating the operating environment in this area.

BOEM Gulf of Mexico OCS Region
Blocks and Active Leases by Planning Area
October 2, 2017



Planning Areas	Total Blocks	Total Acres	Number of Leases	Acres Leased
Western	5,240	28,576,813	437	2,467,602
Central	12,409	66,446,351	2,359	12,329,712
Eastern	11,537	64,357,859	37	200,670
Sub-Totals	29,186	159,381,023	2,833	14,997,984
CPA / EPA Shared Blocks*	(86)		(3)	
Totals	**29,100**	**159,381,023**	**2,830**	**14,997,984**

🟩	Active Lease
▨	Exclusive Economic Zone Northern Portion of the Eastern Gap
☐	Planning Area Boundary

* CPA and EPA contain 86 shared blocks of which 3 are leased. These blocks are given both a CPA and EPA designation in the data which accounts for a higher block total.

FIGURE G.4 U.S. Gulf of Mexico lease planning, May 1, 2017. SOURCE: Office of Leasing and Plans, Mapping and Automation Section, "BOEM Gulf of Mexico OCS Region, Blocks and Active Leases by Planning Area," MAS201800271, May 1, 2018, https://www.boem.gov/Gulf-of-Mexico-Region-Lease-Map/.

Gulf of Mexico Bathymetry

Water depth is perhaps the most significant contributor to the design and operational challenges faced by the oil and gas industry in the Gulf of Mexico.

Figure G.5 shows the bathymetry of the entire Gulf of Mexico. In U.S. waters, the Gulf of Mexico is characterized by a wide, shallow shelf (the Outer Continental Shelf) that slopes gently down to 100 to 300 m (328 to 984 ft.). There is then a very steep slope down to approximately 1,000 m (3,281 ft.), followed by a moderately steep slope down to 3,000 m (9,843 ft.). The remainder of the Gulf appears to be a relatively flat plain with a depth of approximately 3,000 m (9,843 ft.). There are other features in the Gulf, such as the Mississippi Fan reflecting the sediments carried by the Mississippi River and dumped into the Gulf.

There is a similar sedimentary fan to the West of the Mississippi Fan likely formed by a prehistoric predecessor to the current-day Mississippi River. There is also a small fan at the outlet of the Rio Grande River.

High Currents in the Gulf of Mexico

Unique to the Gulf of Mexico, the loop current is an area of warm water flowing from the Caribbean Sea between Cuba and the Yucatan Peninsula. This ware water then loops east and exits the Gulf between Florida and Cuba (known as the Florida Current). The Florida Current, and its parent, the Loop Current, feed the Gulf Stream flowing warm water up the East Coast of the Atlantic Ocean. The Loop Current is one of the fastest currents in the Atlantic Ocean, reaching speeds of about 2.9 to 3.9 knots (1.5 to 2.0 m/s) at the surface. It is about 125 to 190 mi (200 to 300 km) wide and 2,600 ft. (800 m) deep.

The Loop Current pulsates "quasi-regularly" (every 3 to 17 months) north into the Gulf of Mexico as far as the U.S. coastline. The Loop Current occasionally "spins off" eddy currents as it moved back to the south. These eddy currents are large clockwise rotating rings of warm water swirling at 3.5 to 3.9 knots (1.8 to 2.0 m/s). They can have diameters of 125 to 250 mi (200 to 400 km) and can reach depths of 3,281 ft. (1,000 m). Eddy currents drift slowly west-southwest at about 1.2 to 3.1 mi/day (2 to 5 km/day) and have a lifespan of up to a year before hitting Texas or Mexico.[4,5,6,7]

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[4] J. Masters, "The Gulf of Mexico Loop Current: A Primer," Weather Underground, https://www.wunderground.com/hurricane/loopcurrent.asp, accessed October 18, 2017.

[5] Texas Pelagics, "Gulf of Mexico Loop Current," http://texaspelagics.com/gom-info/gom-loop/, accessed October 18, 2017.

[6] NOAA, Okeanos Explorer ,"Gulf of Mexico Loop Current," http://oceanexplorer.noaa.gov/okeanos/explorations/ex1202/background/loopcurrent/welcome.html, accessed October 18, 2017.

[7] J. Sheinbaum, J. Candela, A. Badan, and J. Ochoa, Flow structure and transport in the Yucatan Channel, *Geophysical Research Letters* 29(3):10-1-10-4, 2002, doi:10.1029/2001GL013990.

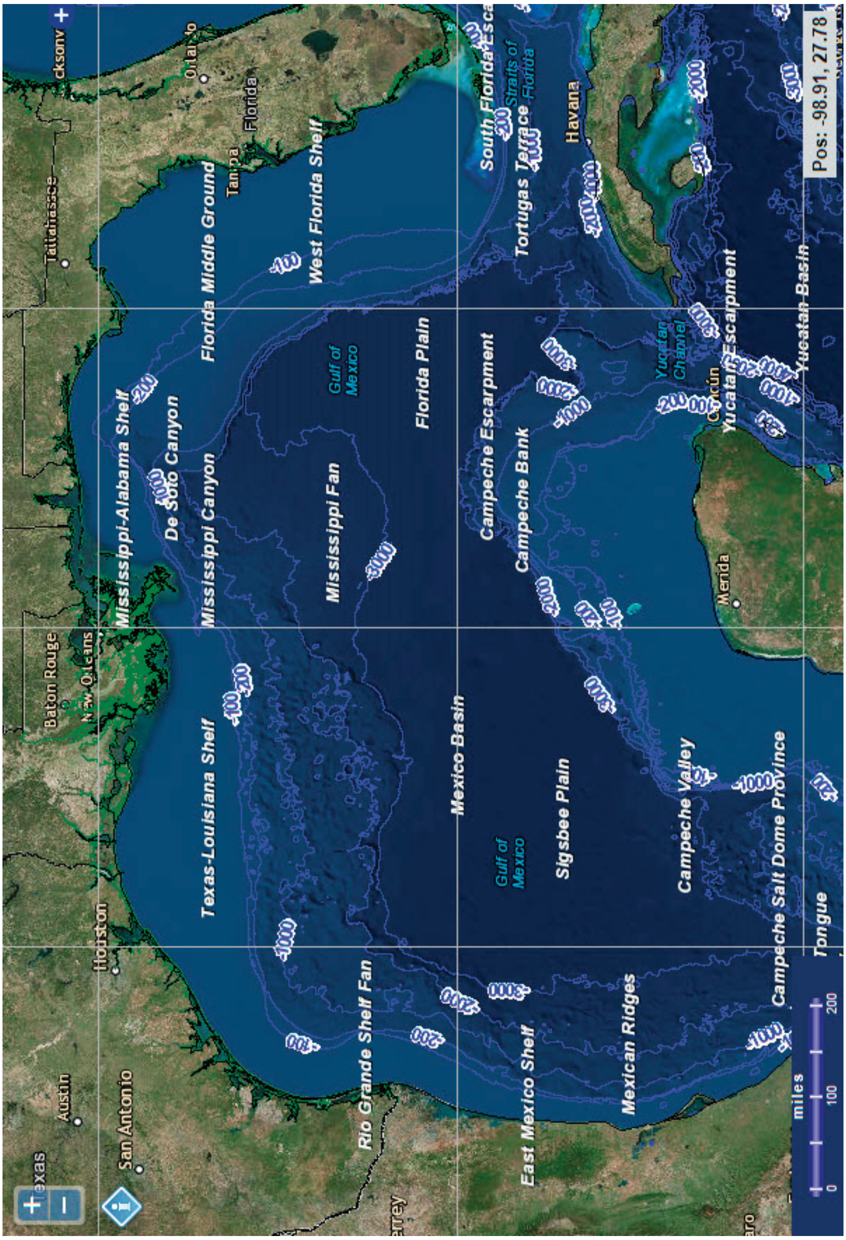

FIGURE G.5 Gulf of Mexico bathymetry (in meters). SOURCE: National Oceanic and Atmospheric Administration, "Gulf of Mexico Data Atlas," https://www.ncddc.noaa.gov/website/DataAtlas/atlas.htm, accessed October 18, 2017.

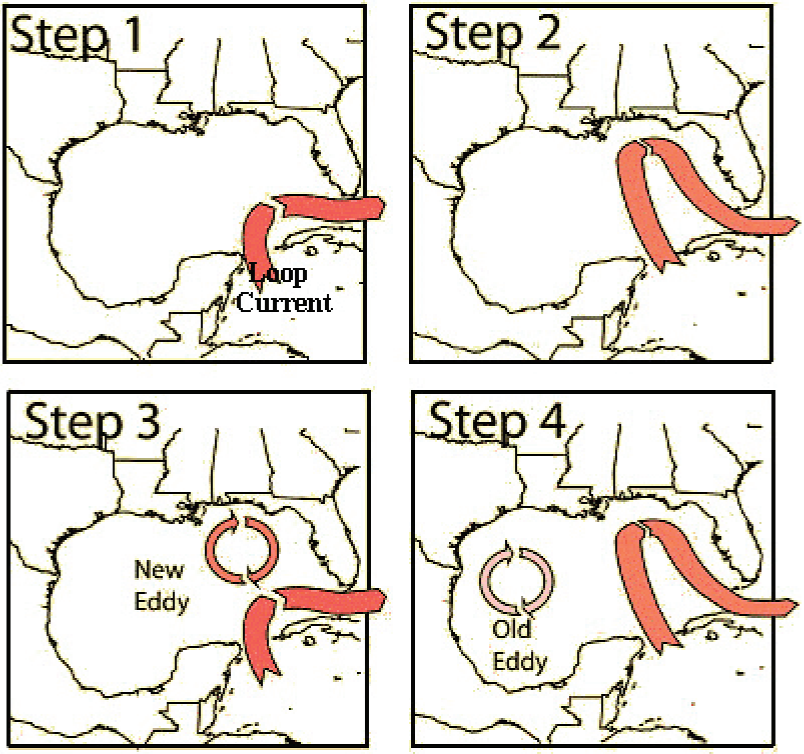

FIGURE G.6 Depiction of Gulf of Mexico Loop Current process. SOURCE: J. Masters, "The Gulf of Mexico Loop Current: A Primer," Weather Underground, https://www.wunderground.com/hurricane/loopcurrent.asp, accessed October 18, 2017.

Figure G.6 depicts this Loop Current/eddy current process. Figure G.7 is a diagrammatic Loop Current map that indicates the presence of counter-clockwise rotating "cold core eddies" spaced in between the cyclonic "warm core eddies" that are spun off the Loop Current.

Eddy currents are identified by satellite measurements of sea surface level. Warm core eddies cause a very slight increase in the local sea level because of the thermal expansion of water. Cold core eddies are associated with lower sea surface levels.

Current speeds are measured using several techniques:

1. Shallow water drifters are tethered just below the water surface to eliminate the effects of wind and waves. They transmit their location (offset) to a satellite, from which surface currents can be calculated.

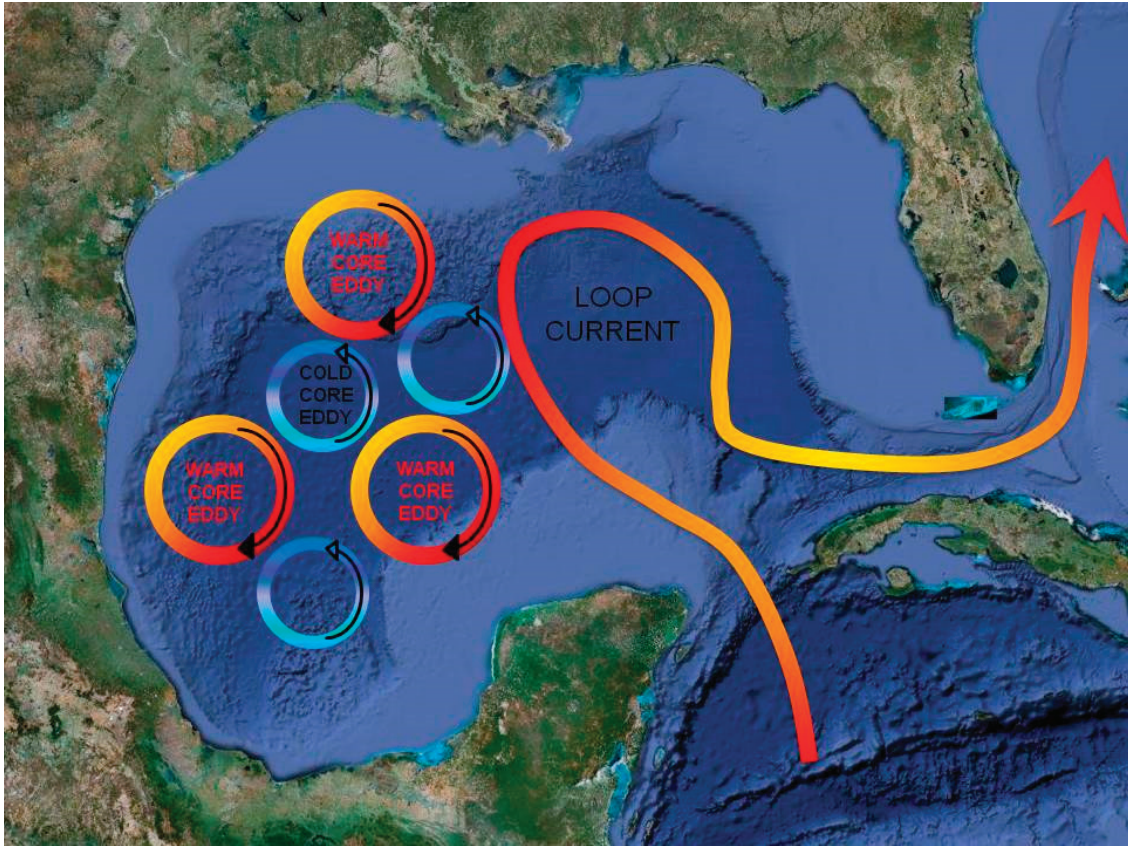

FIGURE G.7 Diagrammatic Loop Current map. SOURCE: Texas Pelagics, "Gulf of Mexico Loop Current," http://texaspelagics.com/gom-info/gom-loop/, accessed October 18, 2017.

2. Deep ocean drifters sit at the water surface, and are programmed to sink to a certain depth, remain there for a certain time, then refloat to the surface. They transmit their location (offset) to a satellite, from which deepwater currents can be calculated.
3. Acoustic Doppler devices, such as the Acoustic Doppler Current Profiler (ADCP), measure currents using the Doppler principle. They are deployed at various locations on the sea floor where current measurements are desired.
4. Shore-based current meters use Doppler radar to measure near-shore currents using the same methodology as acoustic Doppler devises, but using radar rather than acoustics.

The U.S. National Oceanic and Atmospheric Administration (NOAA) coordinates current measurement efforts in or near the U.S. NOAA owns many of the current speed measurement stations. However other government agencies and universities own some as well. Additionally BSEE requires operators of deepwater Mobile Offshore Drilling Units (MODUs) and floating production facilities to monitor and report surface and deep, down to 3,280 ft. (1,000 m), current profiles.[8] Figure G.8 shows a map of all the Gulf of Mexico current speed detection stations.

Figure G.9 shows a snapshot of Gulf of Mexico surface currents on September 26, 2014, as the Loop Current is about to spin off a warm core eddy. In this figure, the Loop Current and clockwise-rotating warm core eddy currents are shown in yellow, orange, and red. In contrast, the counter-clockwise-rotating Cold Core Eddies are shown in green and blue.

Figure G.10 shows a snapshot of actual ADCP measurements from an actual deepwater drilling operation in the Gulf of Mexico in 5,720 ft. (1,743 m) of water. Current speed generally decreases at depth. However this snapshot shows that current speeds at depth can be as high as those at the surface.

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[8] U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, "Notice to Lessees and Operators of Federal Oil and Gas Leases and Pipeline Right-of-Way Holders on the Outer Continental Shelf, Gulf of Mexico OCS Region: Ocean Current Monitoring," NTL No. 2009-G02, Washington, D.C.

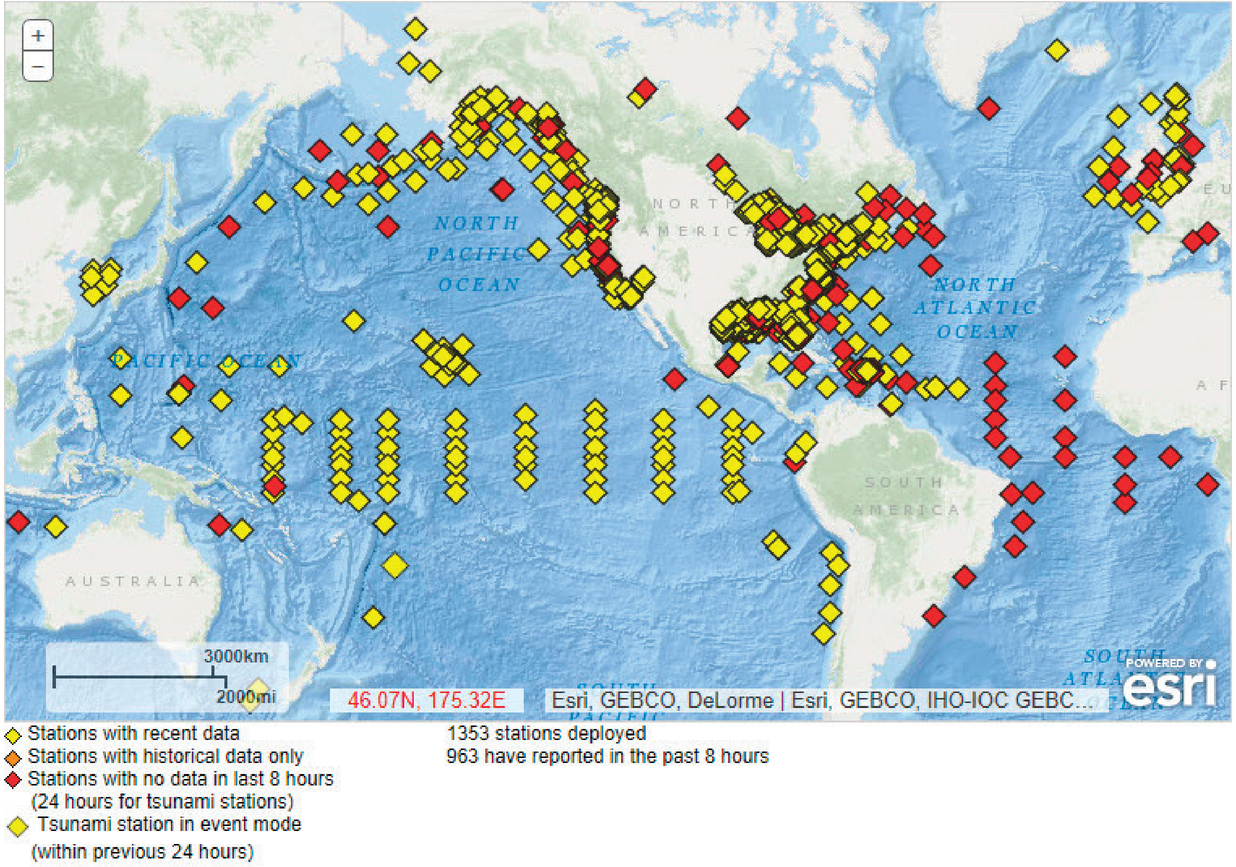

FIGURE G.8 Gulf of Mexico current speed buoy stations, June 2, 2017. SOURCE: National Oceanic and Atmospheric Administration, “National Data Buoy Center,” http://www.ndbc.noaa.gov/, accessed October 18, 2017.

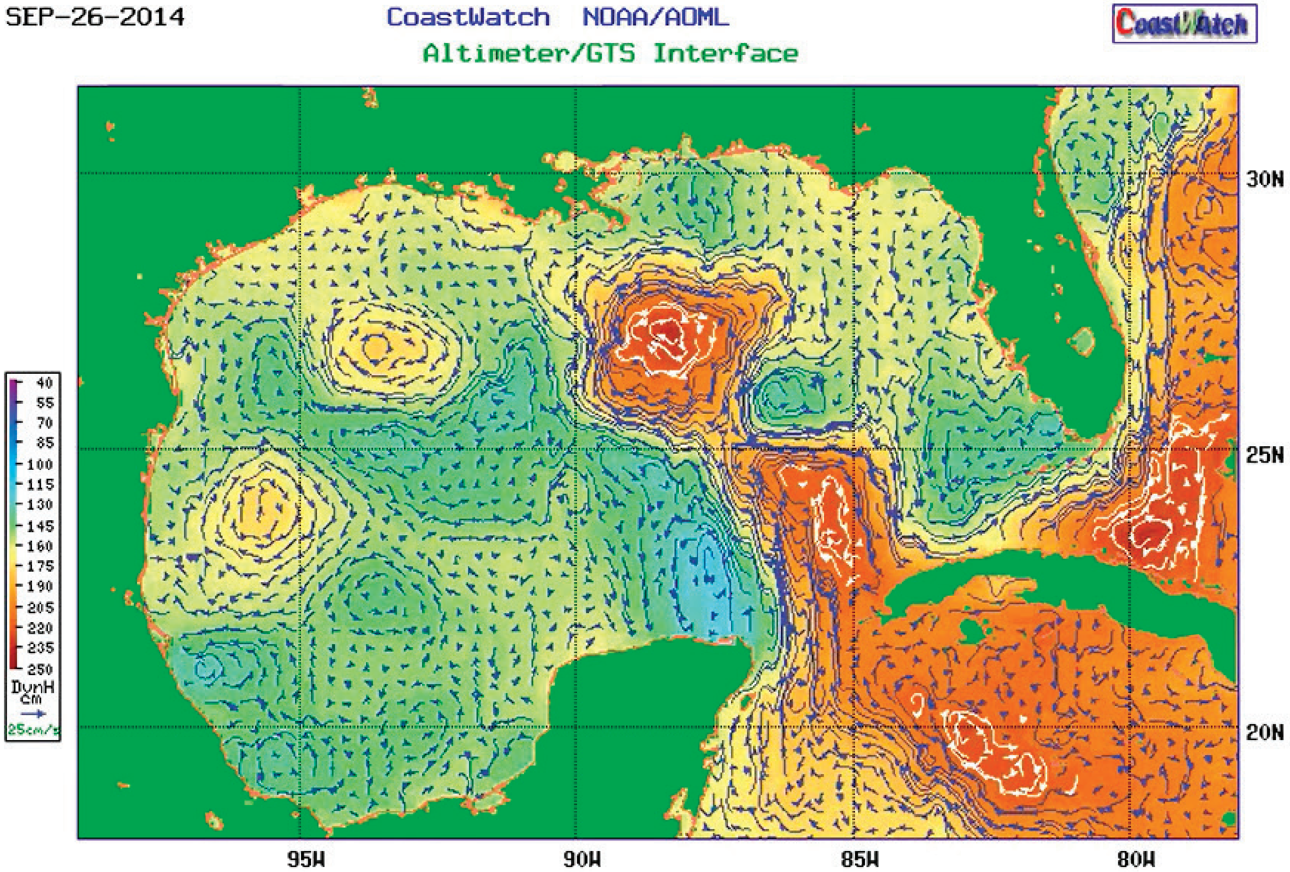

FIGURE G.9 Gulf of Mexico surface currents, September 26, 2014. SOURCE: Texas Pelagics, “Gulf of Mexico Loop Current,” http://texaspelagics.com/gom-info/gom-loop/, accessed October 18, 2017.

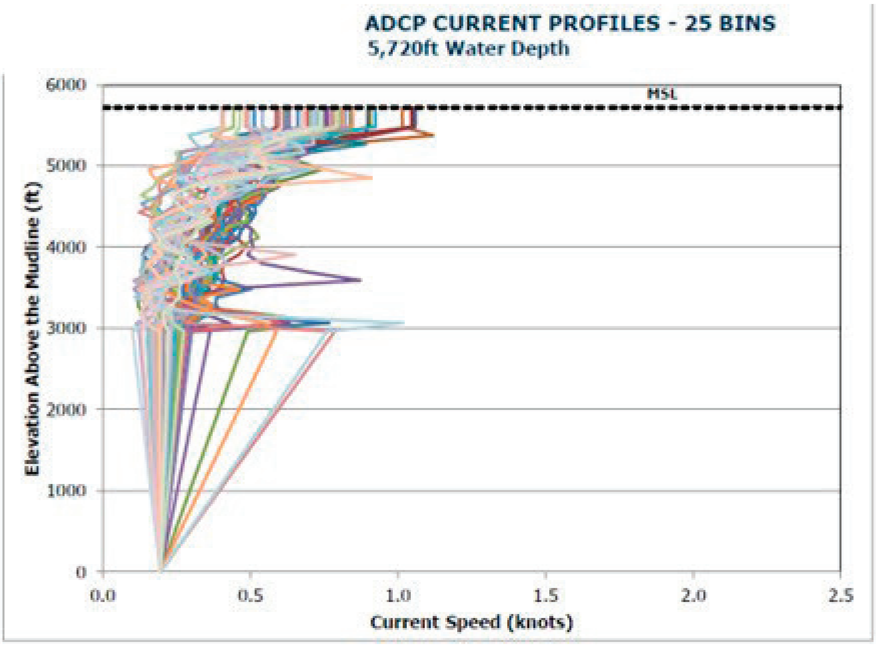

FIGURE G.10 Actual current speed profile. SOURCE: T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations on April 11, 2017.

H

Bolting Regulations and Standards

The materials and strength of bolting for subsea drilling equipment are established by Bureau of Safety and Environmental Enforcement (BSEE) regulations, which include by reference standards, specifications, and recommend practices of the American Petroleum Institute (API), American Section of the International Association for Testing Materials (ASTM), American National Standards Institute (ANSI), American Iron and Steel Institute (AISI), International Organization for Standardization (ISO), National Association of Corrosion Engineers (NACE), and other similar agencies and bodies. This section includes brief descriptions of the content of U.S. federal government's Code of Federal Regulations (CFR) Title 30, Chapter II, Subchapter B, Part 250 (30 CFR 250) and API documents that address bolted fasteners for service critical subsea equipment.

FEDERAL REGULATIONS

The U.S. federal government regulates offshore drilling and production operations through 30 CFR 250.[1] Under 30 CFR 250, BSEE is authorized to regulate oil, gas, and sulphur exploration, development, and production operations on the Outer Continental Shelf (OCS). The API publishes standards, specifications, recommended practice and technical reports for petroleum and petrochemical

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[1] U.S. Government Printing Office, *30 CFR 250—Oil and Gas and Sulphur Operations in the Outer Continental Shelf*, https://www.gpo.gov/fdsys/granule/CFR-2011-title30-vol2/CFR-2011-title30-vol2-part250.

equipment and operations. The API is a national trade organization, but does not have regulatory authority. However, 30 CFR 250 incorporates by reference many API standards, specifications, and recommended practices.

It should be recognized that the difficulties in applying the U.S. CFRs to deepwater riser systems is that drilling rigs can work in other countries that have their own specific regulations and design standards that differ from those required when working in U.S. waters.

As a result of the Deepwater Horizon incident in 2010,[2] Subpart G of 30 CFR 250 was revised to focus on, among other things, the performance of subsea safety critical equipment. Subpart G, however, does not address bolts on fasteners in particular. Rather, 30 CFR 250 incorporates by reference the following API standards, specifications and recommended practices:

- API Standard 53—Blowout Prevention Equipment Systems for Drilling Wells
- API RP 2RD—Design of Risers for Floating Production Systems and Tension-Leg Platforms
- API Spec. Q1—Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry
- API Spec. 6A—Specification for Wellhead and Christmas Tree Equipment
- API Spec. 11D1—Packers and Bridge Plugs
- API Spec. 16A—Specification for Drill-through Equipment
- API Spec. 16C—Specification for Choke and Kill Systems
- API Spec. 16D—Specification for Control Systems for Drilling Well Control Equipment and Control Systems for Diverter Equipment
- API Spec. 17D—Design and Operation of Subsea Production Systems—Subsea Wellhead and Tree Equipment
- API RP 17H—Remotely Operated Tools and Interfaces on Subsea Production Systems

The content of the above API documents relevant to the subject of bolts will be discussed in the next section. Subpart G of 30 CFR 250 became effective on July 29, 2016. In addition, the API published several new documents specifically addressing bolts as a results of bolt failures are at the foundation of this National Academies of Sciences, Engineering, and Medicine study.

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[2] NAE Report.

INDUSTRY STANDARDS, SPECIFICATIONS, AND RECOMMENDED PRACTICES

Although standards represent only minimum requirements, they must be met. An integral part of the design process should include an identification and review of all applicable, up-to-date standards that must be followed, as well as any other recommended or best practices.

This is particularly important because several organizations (i.e., API, ASME, NACE) may have promulgated many standards on the many components of a riser system, some of which over-lap or are in conflict, or have gaps.

The following standards, specifications, and recommended practices include requirements for connector bolts. Many of these documents were recently revised in response to the failures of connector bolts that motivated this National Academies study. Note that the API refers to the type of fastener bolts in this study as “closure bolting,” which are for flanges and other bolted connection on blowout preventer (BOP) equipment.

- API
  - *API Spec. 6A—Specification for Wellhead and Christmas Tree Equipment, 20th Edition, effective data April 1, 2011, Addendum 3 2013.* It should be noted that Edition 20 of API Spec 6A does not include reference to API Spec 20E or 20F, such reference will be address in the next edition. Specifications for studs and nuts are included in Section 10.3. The API requires that the dimensions and thread pitch shall be in accordance with ASTM A193/A193M for studs and ASTM A194/A194M for nuts. The mechanical properties specified in Table 62 in API Spec 6A take precedence over those required by ASTM. Recommended torque is included in Annex D. Pre-load torques are based on a bolt axial stress of 50 percent of the specified minimum yield strength of the bolt steel. The API limits the maximum allowable tensile stress, S_A, for closure bolting considering initial bolt-up, rated working pressure and hydrostatic test pressure conditions. The API specifies a safety factor of 0.83 for bolting stresses, which is based on the root area of the thread:

$$S_A = 0{,}83\ S_{bY}$$

The bolting stresses should consider all loading on the closure, including pressure acting over the seal area, gasket loads and any additional mechanical and thermal loads.

- *API Spec. 16A*—Specification for Drill-through Equipment
- *API Spec. 17D*—Design and Operation of Subsea Production Systems—Subsea Wellhead and Tree Equipment
- *API Standard 53*—Blowout Prevention Equipment Systems for Drilling Wells
- *API RP 2RD*—Design of Risers for Floating Production Systems and Tension-Leg Platforms
- *API Spec. Q1*—Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry
- *API Spec. 11D1*—Packers and Bridge Plugs
- *API Spec. 16C*—Specification for Choke and Kill Systems
- *API Spec. 16D*—Specification for Control Systems for Drilling Well Control Equipment and Control Systems for Diverter Equipment
- *API RP 16Q*—Design, Selection, Operation, and Maintenance of Marine Drilling Riser System
- *API RP 17H*—Remotely Operated Tools and Interfaces on Subsea Production Systems
- *API SPEC 20E*—Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries
- *API SPEC 20F*—Corrosion Resistant Bolting for Use in the Petroleum and Natural Gas Industries

The content of the above API documents relevant to the subject of bolts will be discussed in the next section. Subpart G of 30 CFR 250 became effective on July 29, 2016. In addition, the API published several new documents specifically addressing bolts as a result of the failures of bolts at the foundation of this study.

- ASTM Specifications
  - *ASTM A193/A193M, Standard Specification for Alloy-Steel and Stainless Steel Bolting Materials for High Temperature or High Pressure Service and Other Special Purpose Applications.* API Spec 20E incorporates specifications for bolt steel grades B7 and B7M. API Spec 6A refers to grade B7 and B7M. API Spec 17D refers to grade B7, B7M, and B16.
  - *ASTM A 194/194M, Standard Specification for Carbon and Alloy Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both.* API Spec 20E incorporates specifications for bolt steel grades 2H, 4, 7, 2HM, and 7M. API Spec 6A refers to grade 2HM.
  - *ASTM A320/320M, Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low- Temperature Service.* API Spec 20E incorporates specifications for bolt steel grades L7, L7M, and L432H. API Spec 6A

refers to grade L7. API Spec 6A refers to grade L7, L7M, and L43. API Spec 17D refers to grade L7, L7M, and L43.

— *ASTM A453/453, Standard Specification for High- Temperature Bolting, with Expansion Coefficients Comparable to Austenitic Stainless Steels.* API Spec 20F incorporates specifications for bolt steel grade 660 and grade 660 Class D. API Spec 6A refers to grade 660. API Spec 17D refers to grade 660 Class D.

— *ASTM A540, Standard Specification for Alloy Steel Bolting for Special Applications.* API Spec 20E incorporates specifications for bolt steel grades B22 and B23.

— *ASTM B633 (2011, 2007, 1998)—Standard Specification of Electrodeposited Coatings of Zinc on Iron or Steel.* The QC-FIT report states:

> This standard outlines different thickness classes with required salt spray test verification durations (See Appendix E, Table E.1 for coating finish types; ref. ASTM B633, 1998, 2007). Table E.2 specifies coating thickness classes based on the service condition (see ASTM B633, 1998, 2007, 2011). Section 6.4 recommends base metal alloys with an UTS value greater than 1700 MPa (247 ksi) should not be coated with zinc coating. The QC-FIT identified a concern about the manner that standards are applied within the supplier and manufacturer chains throughout industry. Table E.3 summarizes ASTM B633, the SC descriptions, and appropriate service conditions for each class (ASTM B633, 1998, 2007, 2011). The coating for the 2012 failed bolts manufactured 2007-2009 is a SC 2 class. SC 2 is for a moderate service condition, exposed mostly to indoor atmospheres, occasional condensation with minimum wear or abrasion. The recommended parts are tools, zippers, pull shelves and machine parts. The H4 connector bolts were coated to an SC 2 class and are used in marine subsea service blowout preventer (BOP) applications. According to GE, relevant API standards cannot be applied if a coating thicker than SC 2 is used.

— *ASTM 849 (2007)—Standard Specification of Pre-treatment of Iron or Steel for Reducing Risk of Hydrogen Embrittlement.* The QC-FIT report states:

> ASTM B849 provides recommended guidance for stress relief, pre-bake heat duration of metals prior to electroplating. Table E.6 is an overview of recommended pre-bake durations and temperatures for high strength steels based on tensile strength (to be provided by customer) (Ref. 2007 ASTM B849). As seen in Table E.6, classes are based on the UTS values.

— *ASTM 850 (2009, 2004, 1998)—Standard Guide for Post Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement.* The QC-FIT report states:

> ASTM B850 provides procedural guidance for post-baking, heat treatment duration for hydrogen stress relief of metals subjected to electroplating coating processes. Post-bake heat treatment is recommended for metals with a hardness value greater than >31 HRC and an UTS >145 ksi. The bolt design specification required a material hardness of 34-38 HRC, and a minimum UTS value of 145 ksi (ref. 2009 US Bolt MTR in 2013 Combined RCA Report, Appendix R page 335). Therefore per the 1998 edition for ASTM B850, the bolts were required to be post-baked from 2007 to 2009. If the design specification had clearly referenced ASTM B850, then the post-bake requirements would have been clear.

— *ASTM F1941 (2010, 2007)—Standard Specification for Electrodeposited Coatings on Threaded Fasteners.* The QC-FIT report states:

> This specification covers application, performance and dimensional requirements for electrodeposited coatings on threaded fasteners with unified inch screw threads. It specifies coating thickness, supplementary hexavalent chromate or trivalent chromite finishes, corrosion resistance, precautions for managing the risk of hydrogen embrittlement and hydrogen embrittlement relief for high-strength and surface-hardened fasteners. The electrodeposited coating as ordered shall cover all surfaces and shall meet the requirements prescribed. Coated fasteners, when tested by continuous exposure to neutral salt spray shall show neither corrosion products of coatings (white corrosion) nor basis metal corrosion products (red rust) at the end of the test period. The coating thickness, embrittlement, corrosion resistance, and trivalent chromite finish shall be tested to meet the requirements prescribed.

- NACE Materials Requirement

  - *NACE MR0175 (2011, 2009, 2003)—Metals for Sulfide Stress Cracking and Stress Cracking Resistance Environments (Corrosion Standard for Materials for Use in H2S Containing Environments in Oil and Gas Production-2003 edition).* NACE MR0175 specifies a maximum hardness of 32 HRC and minimum yield strength of 92,000 psi for subsea marine service. MR-0175 refers users to ASTM A193 grade B7M ASTM A320 grade L7M bolts and ASTM A194 grades 2HM and 7M nuts.

- NORSOK Standard

— *NORSOK Standard M-001 – (2004) Materials Standard.* Bolt materials are specified in Section 5.6 of M-001, "Bolting Materials for Pressure Equipment and Structural Use." For bolts, the standard includes specifications for ASTM A193 grades B7, B16, and B8M; ASTM A320 grades L7 and L43. For nuts, the standard includes specifications for ASTM A194 grades 4/S, 7/S3, 2H, 7, 8M, and 8MA. In general, the standard states,

> Carbon or low-alloyed bolting materials shall be used. Bolts with a diameter 10 mm shall be stainless steel according to ISO 3506-1, Type A4 (Type 316),

> for metal temperatures below 60 °C if the stressed parts are exposed to humid saliferous environmental conditions (for nuts, see ISO 3506-2). If other bolting materials are required due to corrosion resistance or other reasons, the material shall be selected in accordance with the general requirements of this NORSOK standard. For sub-sea applications Alloy 625 shall be used when corrosion resistant bolts are required at ambient temperature, i.e. for conditions where the bolts are exposed to natural sea water and cathodic protection cannot be ensured. It shall be verified that the materials have acceptable mechanical properties at the design temperatures. Bolts used for sub-sea application shall have a maximum hardness of 300 HB or 32 HRC. The hardness shall be positively verified by spot hardness testing for each delivery, batch and size of bolts used.

With regard to bolt coatings, M-001 specifies,

> Carbon steel and/or low alloy bolting material shall be hot dip galvanised to ASTM A153 or have similar corrosion protection. For submerged applications, where dissolution of a thick zinc layer may cause loss of bolt pretension, phosphating shall be used. For sub-sea installations the use of poly-tetra-fluoroethylene (PTFE) based coatings can be used provided electrical continuity is verified by measurements. Cadmium plating shall not be used.

It may be noted that API RP 17G also references the same ASTM standards as API Specs 6A, 16A, and 17D.

- Other
  - *Specification for Structural Joints Using High-Strength Bolts, Research Council on Structural Connections, August 1, 2014.* This specification is not directly relevant to subsea bolts, but it does describe a technique for torqueing that provides for less variance, and it incorporates some useful human factors considerations for ensuring torqueing quality.

FLANGE BOLT DESIGN SPECIFICATIONS

Flange Bolt Preloading

There have been changes in the 2011 second edition of API Spec 17D from the 1996 first edition that appear to reflect improved good industry practices for bolting for subsea drilling equipment. API Spec 17D, Section 5.1.3.5 specifies that[3]

> Closure bolting of all 6BX and 17SS flanges shall be made up using a method that has been shown to result in a stress range between 67% and 73% of the bolt's material yield stress.

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[3] API Specification 17D, ISO 1 3628-4, 2nd Edition, May 2011, Section 5.1.3.5, p. 19.

> This stress range should result in a preload in excess of the separation force at test pressure while avoiding excessive stress beyond 83% of the bolt material's yield strength.

This is a change from the 1996 first edition of API Spec 17D, in which the specified preload torque was "2/3 of the specified minimum yield stress."[4] Annex G of API Spec 17D contains the specified bolting preloads for L7, L43, B16, B7 or gr660 bolting steels, based on the 67 and 73 percent range of yield strength. Although Section 5.1.3.5 does not make it clear that the "material yield strength" refers to the minimum yield strength, this is clear in Annex G.

Regarding bolting tensile stress under service loading, API Spec 17D specified that

> The maximum allowable tensile stress for closure bolting shall be determined considering initial bolt-up, rated working pressure and hydrostatic test pressure conditions. Bolting stresses, based on the root area of the thread, shall not exceed the limits given in ISO 10423.

The reference to ISO 10432 regarding the maximum stress at the thread root is a reference to Section 4.3.4 of API Spec 6A,[5]

> The maximum allowable tensile stress, S_A, for closure bolting shall be determined considering initial bolt-up, rated working pressure and hydrostatic test pressure conditions. Bolting stresses, based on the root area of the thread, shall not exceed the limit given in Equation (9):
>
> $$S_A = 0{,}83\ S_Y \tag{9}$$
>
> where S_Y is the bolting material-specified minimum yield strength.
>
> Bolting stresses shall be determined considering all loading on the closure, including pressure acting over the seal area, gasket loads and any additional mechanical and thermal loads.

API Spec 6A, however, specifies the preload torque for bolting to only 50 percet of the minimum yield strength of the bolting steel. API Spec 6A applies more specifically to land-based operations, which API Spec 17D is for subsea equipment.

Flange Bolt Material Specifications

API Spec 17D, Section 5.1.3.5 further specifies that[6]

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[4] API Specification 17D, 1st Edition, August 1, 1996, Section 303.4, p. 22.

[5] API Specification 6A, ISO 10423:2009 (Modified), 20th Edition, October 2010, Section 4.3.4, p. 28.

[6] API Specification 17D, 1st Edition, August 1, 1996, Section 303.4, p. 22.

> Closure bolting manufactured from carbon or alloy steel, when used in submerged service, shall be limited to 321 HBN (Rockwell "C" 35) maximum due to concerns with hydrogen embrittlement when connected to cathodic protection.

This is a consistent with the first edition of the 1996 first edition of API Spec 17D, which specified a maximum hardness of "Rockwell "C" 35" for carbon and alloy steels.[7]

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[7] Ibid.

I

Drilling Riser Design

This appendix presents background information regarding bolting preload and safety factors used in bolting design.

A marine drilling riser is an unpressurized conduit through which drilling operations can be conducted in deep water. It allows the passage of tubulars (such as drill pipe) drilling tools (such as drill bits) and drilling fluid.

For the purposes of this appendix, the drilling riser system includes

1. The wellhead connector,
2. The blow-out preventer (BOP),
3. The LMRP, and
4. The riser joints.

The drilling riser system interfaces with the wellbore system, which includes

1. The surface casing and
2. The soils in which the surface casing is set

The drilling riser system interfaces with the rig system, which includes

1. The riser tensioning system
2. The rig itself, including rig performance in various ocean environment conditions

Figure I.1 depicts a typical drilling riser system and its sub-systems and components.

FORCES ACTING ON A DRILLING RISER SYSTEM

Pressure

The pressure of water increases greatly at depth. Subsea equipment must be designed to operate in these high-pressure environments. Equipment in service on the sea floor, such as marine risers and BOPs, will see much more external pressure than equipment higher up, such as drilling riser connections.

For example, at 3,000 m (9,843 ft.) the water pressure is 4,400 psig (30.3 MPa). Any connections (e.g., the space in bolt threads) made up at the surface will likely have sea water intrusion into any tiny crevices, unless the material is hydrophobic.

The design of subsea equipment must also consider the effect of differential pressure. The difference between the internal pressure and the external pressure is referred to as the "differential pressure." During deep-water drilling, the mud density can be 2157 kg/m^3 (18 ppg) or larger, while the sea-water density remains the same: 1031 kg/m^3 (8.6 ppg). Figure I.2 demonstrates that, during drilling, the pressure differential is a positive 4,888 psi (33.6 MPa).[1]

The pressure differential affects the loads on the bolts of the flanged connections of the subsea equipment. For example an internal burst pressure can add to the tensile force on a connector in the following two different two ways:

- Piston effect due to pressure acting on an end cap or
- Pipe shortening due to ballooning of the pipe.

The pressure differential loads must be included incorporated in determining the bolt pre-load (among other load sources).

In deep-water operations, the sea-water pressure can approach 5,000 psi. (34.5 MPa) The pressure and temperature of the seawater at great depth should be considered when considering corrosion mitigation strategies for flanges and bolts, such as cathodic protection and protective coatings.

Currents

As stated in Appendix D, surface and subsea currents can be significant in the Gulf of Mexico. These currents can be created by the loop current, eddy currents that are spun off the loop current, and topographical Rosby currents.

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[1] Assuming seawater specific gravity of 1.032.

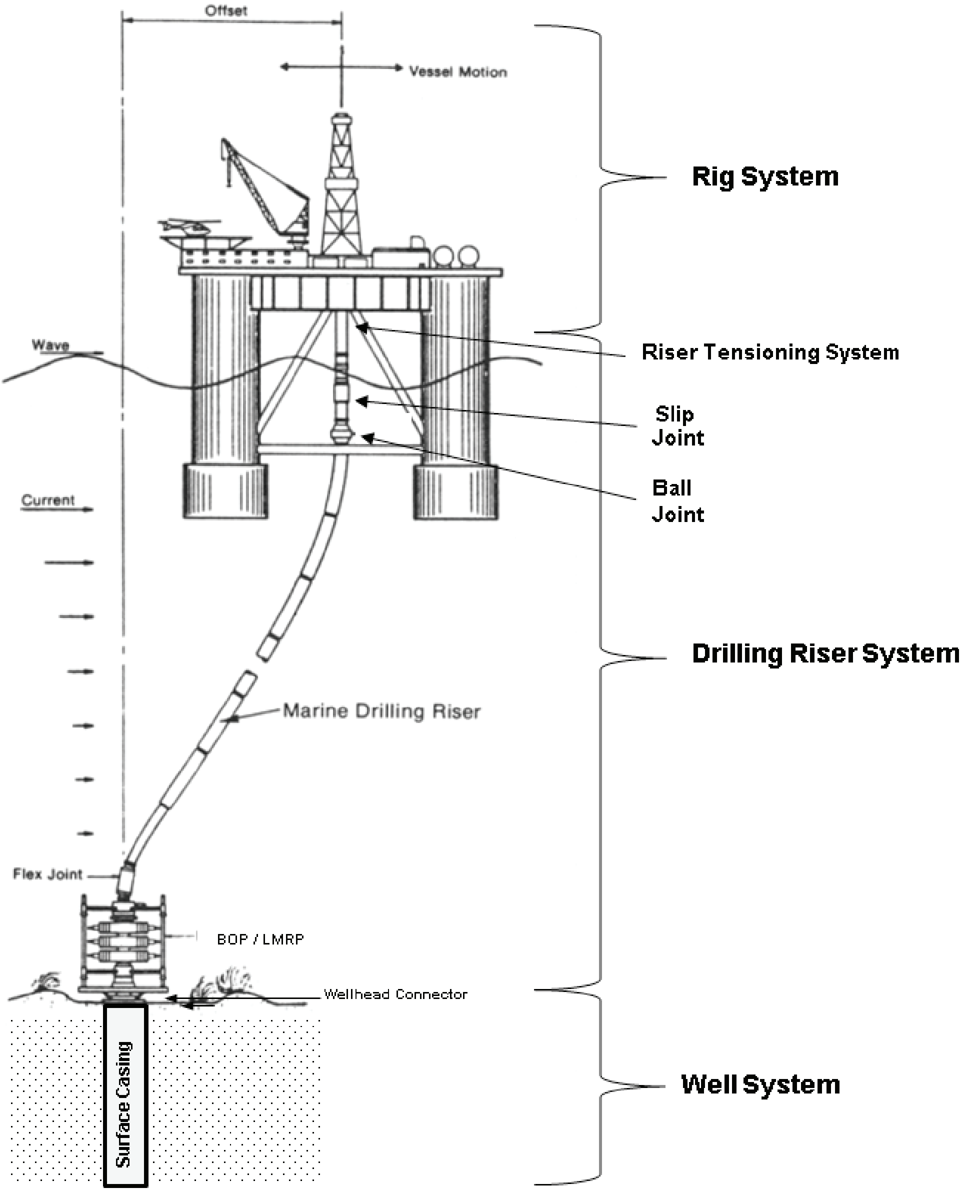

FIGURE I.1 Typical drilling riser system and its sub-systems and components. SOURCE: FESAus, "Glossary: Riser," http://fesaus.org/glossary/doku.php?id=terms:marine_drilling_riser, accessed October 22, 2017.

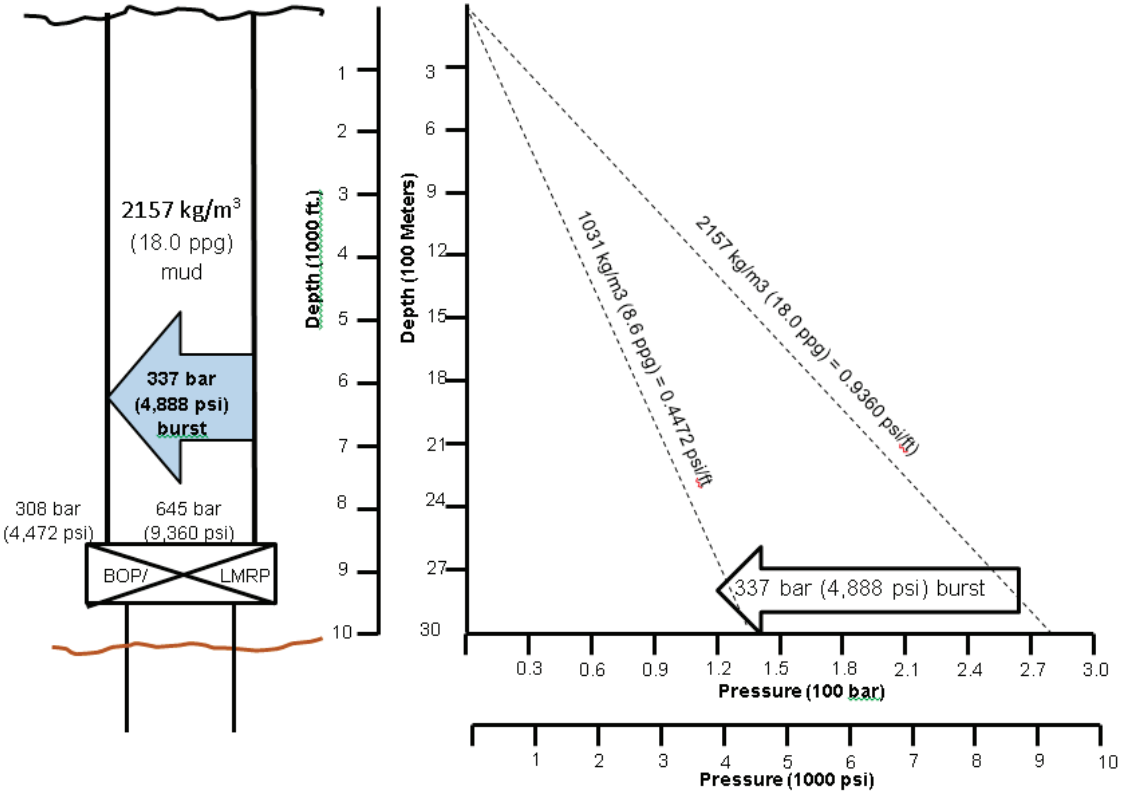

FIGURE I.2 Example of burst pressure on riser.

One of the most significant impacts on deepwater drilling and production riser design is that strong currents may occur at any time, from any direction in deepwater Gulf of Mexico—be it from the loop current, warm core eddy currents, or cold core eddy currents.

The loading these currents place on riser and BOP connectors is mainly riser displacement at depths where currents are sufficiently fast. The lateral displacement of the rig and riser caused by both waves and current will place a lateral load on the top of the BOP resulting is some seemingly minor displacement of the top of the BOP. This load will transfer as a bending moment to the wellhead connector and the wellbore casing through bottom BOP flange. This bending moment can be significant, and place tensile forces on bolts that are over and above the bolt preload. Figure I.3 depicts how currents can displace the rig and the riser.

It is possible that currents could cause VIV (vortex induced vibrations), which might cause fatigue. Fairings (see Figure I.4) may be installed on risers to prevent VIV.

Figure I.5 shows the predicted and measured bending moments for the deepwater drilling operation that captured the current speed profile shown in Figure G.10 in Appendix G.

Figure I.6 shows the actual LMRP top displacement vs. actual bending moments, with a good correlation. In this case the bending loads were within the leak and structural capacity of the 10,000 psi API-18-3/4” flange, being used. It should be noted, however, that current speeds were only 1 knot at the surface. If the currents were as high as 4 knots, which can be caused by eddy currents, the bending moments would be higher.

Wind and Waves

Ocean surface wind and waves impact deepwater drilling operations in several ways.

1. Wind speed and direction impact the amount and direction of lateral movement of the drilling rig, and resultant forces on the riser, the BOPs, and the wellhead connector. For drill ships, lateral movement can be somewhat mitigated by facing the ship into the wind.[2] Wind speed and direction also affects the sea state. A constantly high wind coming from a consistent direction for an extended area can cause relatively high seas.
2. Wave height impacts the heave (vertical movement) of the drilling rig. Unless extreme, any forces on the drill rig are mitigated by the riser slip joint at the top of the riser.

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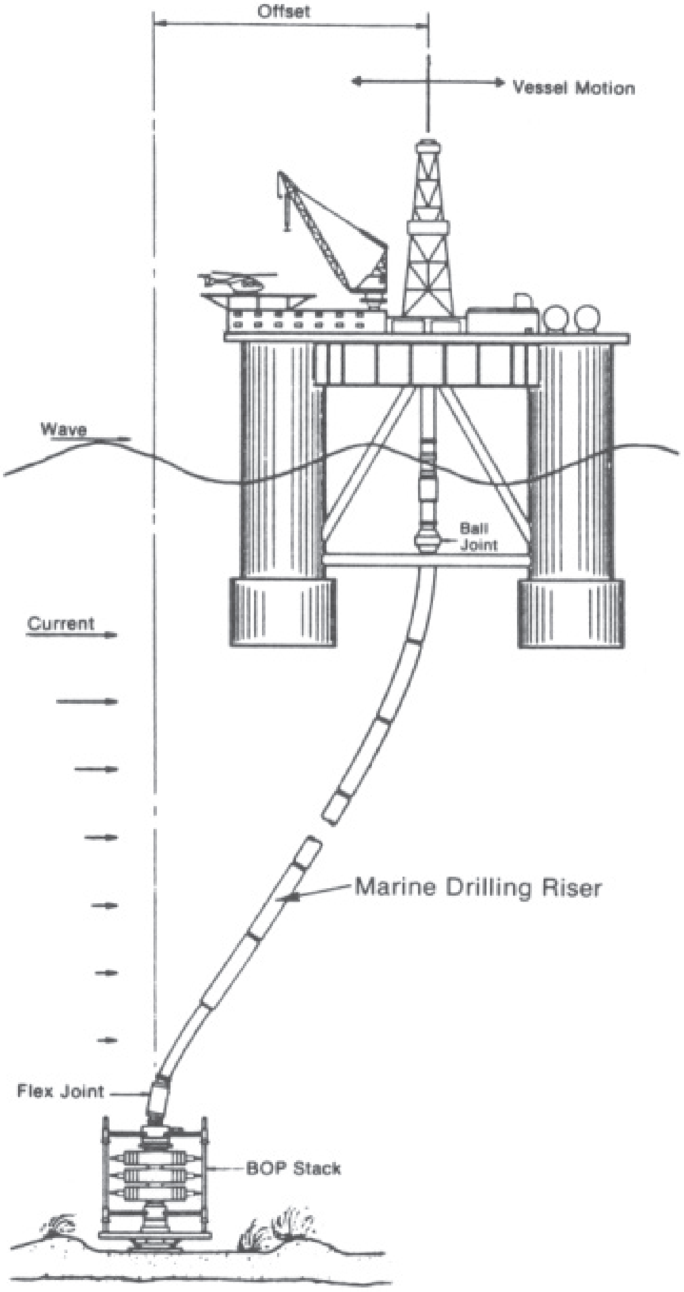
[2] Bill Capdevielle, discussions with Jim Raney and Pat Boster, May 5, 2017.



Marine Drilling Rig with Marine Drilling Riser

FIGURE I.3 Currents causing lateral offset of rig.

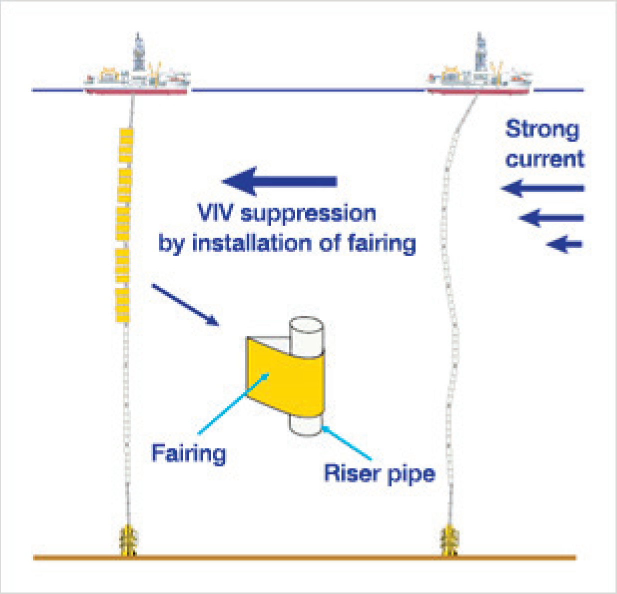


FIGURE I.4 Fairings prevent vortex induced vibrations (VIV). SOURCE: Japan Agency for Marine-Earth Science and Technology, "Vortex-Induced-Vibration (VIV)," http://www.jamstec.go.jp/cdex/e/developtec/riser/category03/.

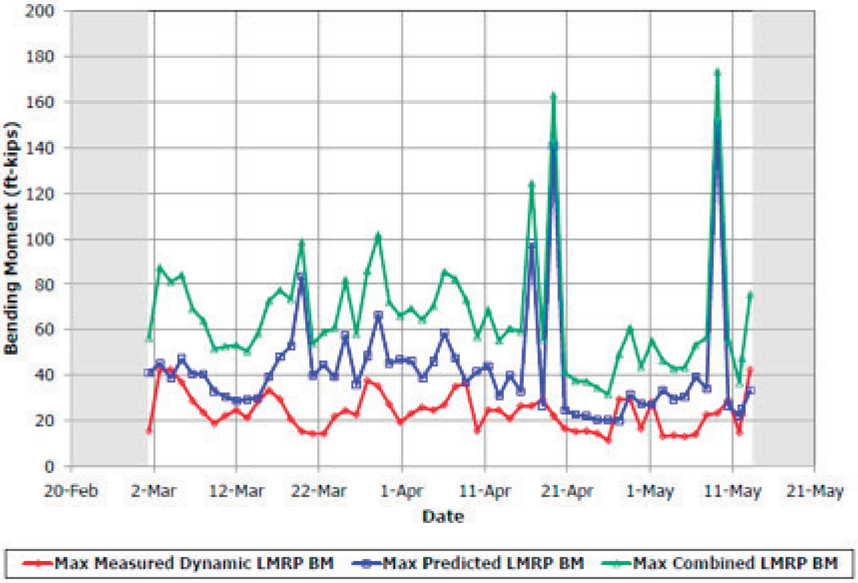


FIGURE I.5 Actual versus predicted bending moments. SOURCE: T. Fleece, BP, "Mitigating BOP Failures," presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

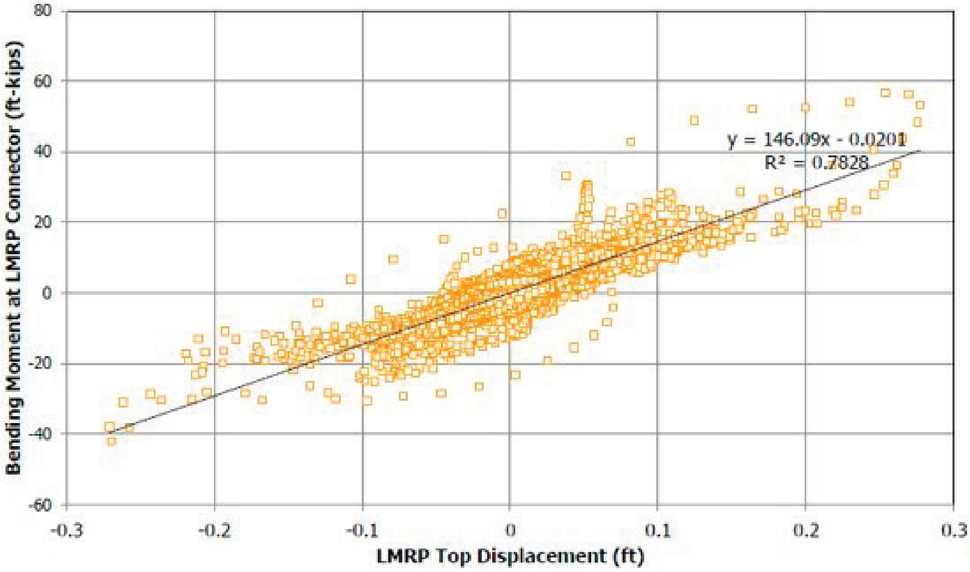


FIGURE I.6 Actual bending moments versus LRMP top displacement. SOURCE: T. Fleece, BP, “Mitigating BOP Failures,” presentation at the Workshop on Bolting Reliability for Offshore Oil and Natural Gas Operations, April 11, 2017.

3. Wave height, direction, and wave period impact the amount and direction of lateral movement of the drilling rig, and resultant forces on the riser, the BOPs, and the wellhead connector. For drill ships, lateral movement can be somewhat mitigated by facing the ship into the seas.[3]
4. Wave period may impact fatigue life of drilling riser/BOP components, but only if the forces on the riser-BOP-wellhead are significant.

The analysis of the impact of wind and waves on riser/BOP loading need to take all these factors into consideration as they all occur simultaneously. To do this one needs to understand how the top of the riser is connected to the drill rig (or ship). Figure I.7 shows a typical riser top connection configuration. The riser is supported to the rig by tensioners that come down through the moonpool (the “hole” on the rig directly underneath the drill floor). The tensioners pull up on the riser to keep it in tension. This helps keep it straight and supports it against and current loading.

The tensioners may also pull up slightly on the BOP at the sea floor. For example, the rig tensioners may keep a 500,000 pound pull on the riser, 450,000 pounds will represent the buoyant weight of the risers and 50,000 pounds will be

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[3] Willard C. Capdevielle, discussions with Jim Raney and Pat Boster, May 5, 2017.

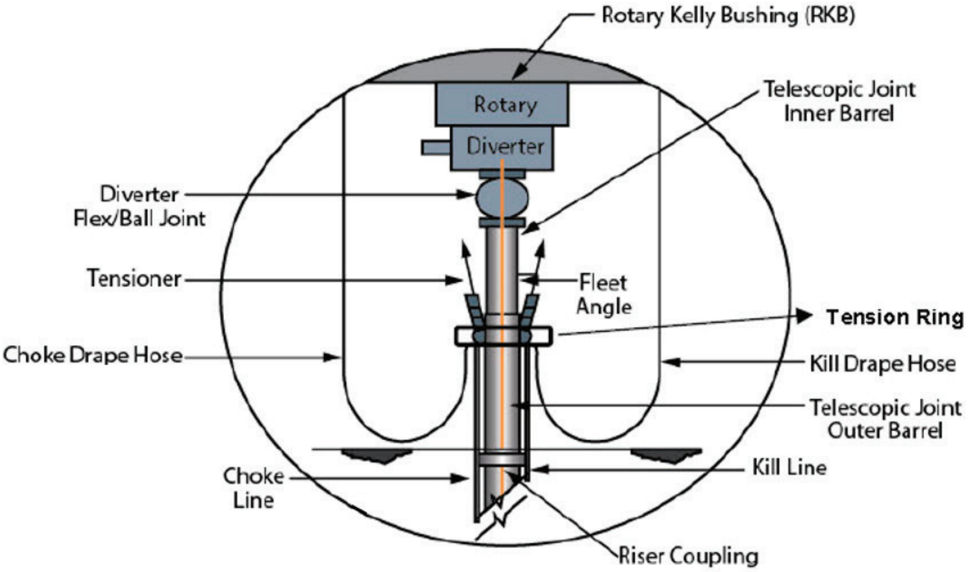

FIGURE I.7 Riser tensioning system. SOURCE: API Recommended Practice 16Q, "Design, Selection, Operations, and Maintenance of Marine Drilling Riser Systems," Figure 1.

tension pull on the LMRP.[4] In this example, the tension could increase flange bolt tension in the LMRP over and above their preload.

In normal riser operations there is very little tension placed on the LMRP and BOP stack. It is only during abnormal situations (such as rig heave exceeding slip joint travel) that significant tension will be placed on LMRP and BOP flange connectors and bolts.

Buoyancy is considered in calculating riser weight. Riser buoyance is affected by the density of the fluid inside the riser and is therefore dependent on the drilling operations being undertaken at any given time. On very heavy risers buoyancy enhancement devices may be installed.[5]

The three pieces of equipment that manage riser tension during rig operations in response to movement induced by wind and waves are

- The rig tensioner system attached to the riser tensioner ring,
- The riser slip joint, and
- The riser flex joint (or ball joint).

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[4] Les Smiles, teleconference with Willard C. Capdevielle, May 18, 2017, presented to the committee on September 28, 2017.

[5] API RP 16Q—Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems, Section 4.13.

FIGURE I.8 Extended slip joint and riser tensioners in moonpool. SOURCE: iStock Getty Images.

Figure I.8 is a photograph of riser tensioners coming down through the moonpool to hold the top of the riser, with an extended slip joint.

Consider this example of how rig heave and lateral displacement combine to potentially cause failure of the riser system. Refer to Figure I.9.

When offset is zero, then the length of the riser is the water depth (at mean sea level) minus the height of the BOP above the sea floor.

When wind, waves and current drive the rig off centerline the distance between the rig and the top of the BOP stack is increased slightly. This extra riser length is accommodated for by expansion of the slip joint(s).

Taking this example a bit further, if the slip joint bottoms out a lateral force will be placed on the BOP/LMRP. This will be in addition to the tensile load placed

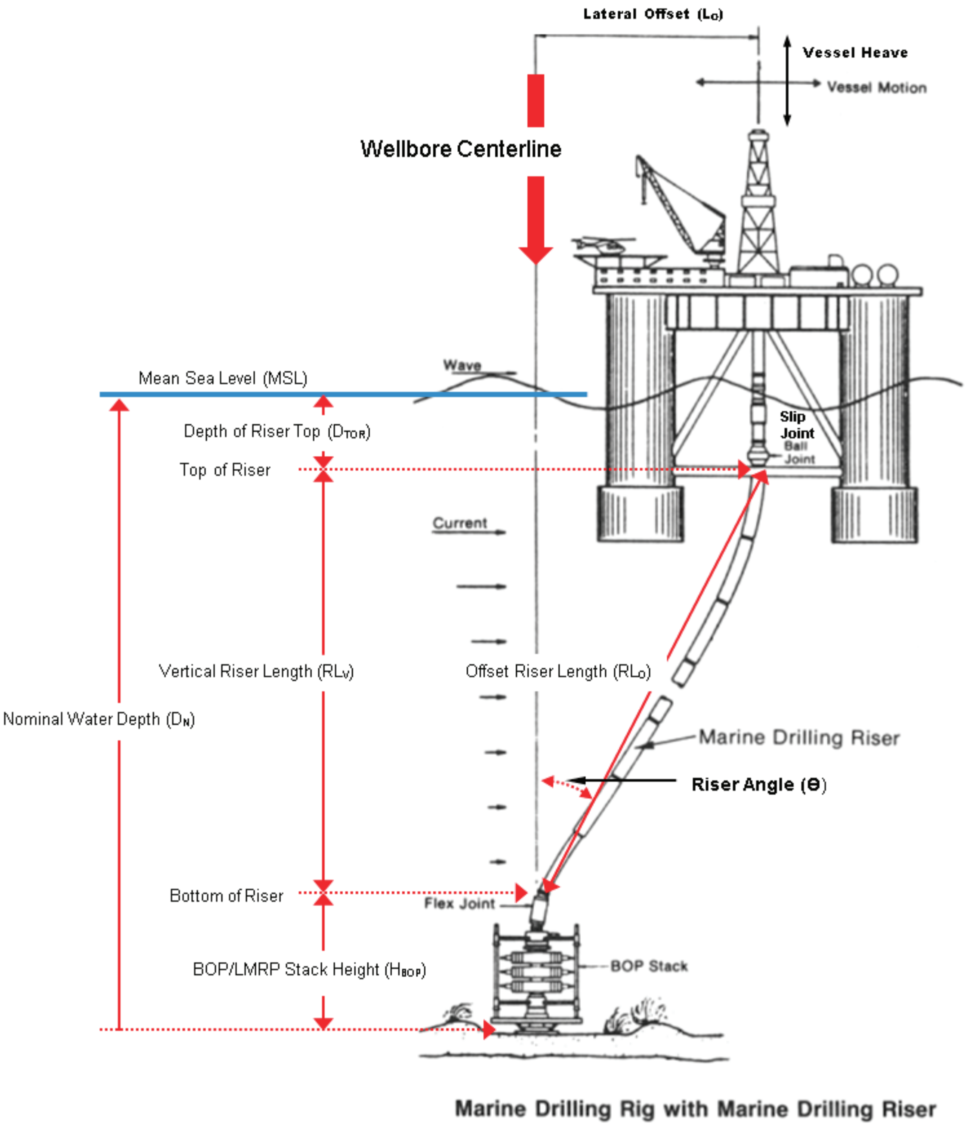

FIGURE I.9 Effect of rig offset on riser length (not to scale).

on the riser system. Refer to Figure I.10. This lateral force will produce a bending moment (M_{LF}) will be created according to the formula:

$$M_{LF} = F_H H_{BOP}$$

where M_{LF} = bending moment due to lateral force
F_H is the horizontal load on the riser just prior to riser failure
H_{BOP} is the vertical distance between the sea floor and the bottom of the riser

One more potential complication is BOP tilt. Refer to Figure I.11. BOP tilt can occur because of

1. The well's casing being installed a bit off vertical, and/or
2. The surface casing, being set in soft mud and being pulled off center by currents acting on the riser.

BOP tilt can cause a small bending moment (M_{TILT}) due to the high weight of the BOP/LMRP stack.

BOP Testing

BSEE requires that BOPs be tested every 14 days. Part of a BOP test is the pressure test program. BOPs are tested at a low pressure (several hundred psi) and at high pressure. The high-pressure test must be performed at rater working pressure (RWP) or 500 psi greater than anticipated maximum service pressure (MASP).

During these pressure tests all pressure sealing rams and annulars are closed and pressure is applied through the choke line or the kill line. For non-blind rams and annulars, a test tool (see Figure I.12 at right) is on the drill pipe. The outer surface of this test tool is sized to fit the "hole" n pipe rams. It also provides a surface on which the annulars can close.

The plug at the bottom of the test tool rest against the bottom of the pipe rams or the annular as the pressure below it acts like a piston trying to push up on the test tool.

The test pressure between BOP components creates a tensile load on the flanges between the components. This force is the test pressure times the bore area of the component being tested.

This tensile load is transferred to the flange bolts in proportion to the bolt-to-flange stiffness. This load is in addition to the bolt preload.

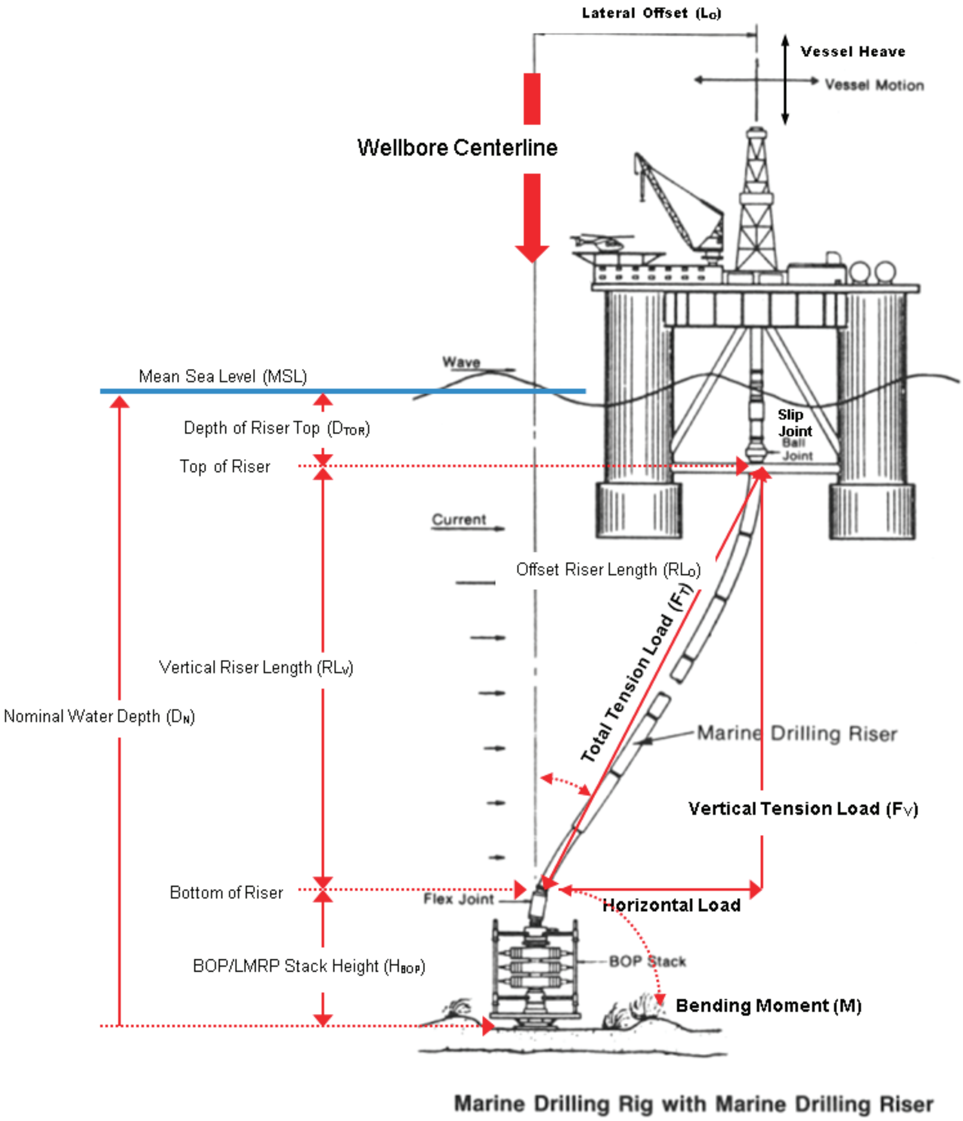

FIGURE I.10 Lateral Load on blowout preventer (BOP)/Lower Marine Riser Package (LMRP) due to offset (not to scale).

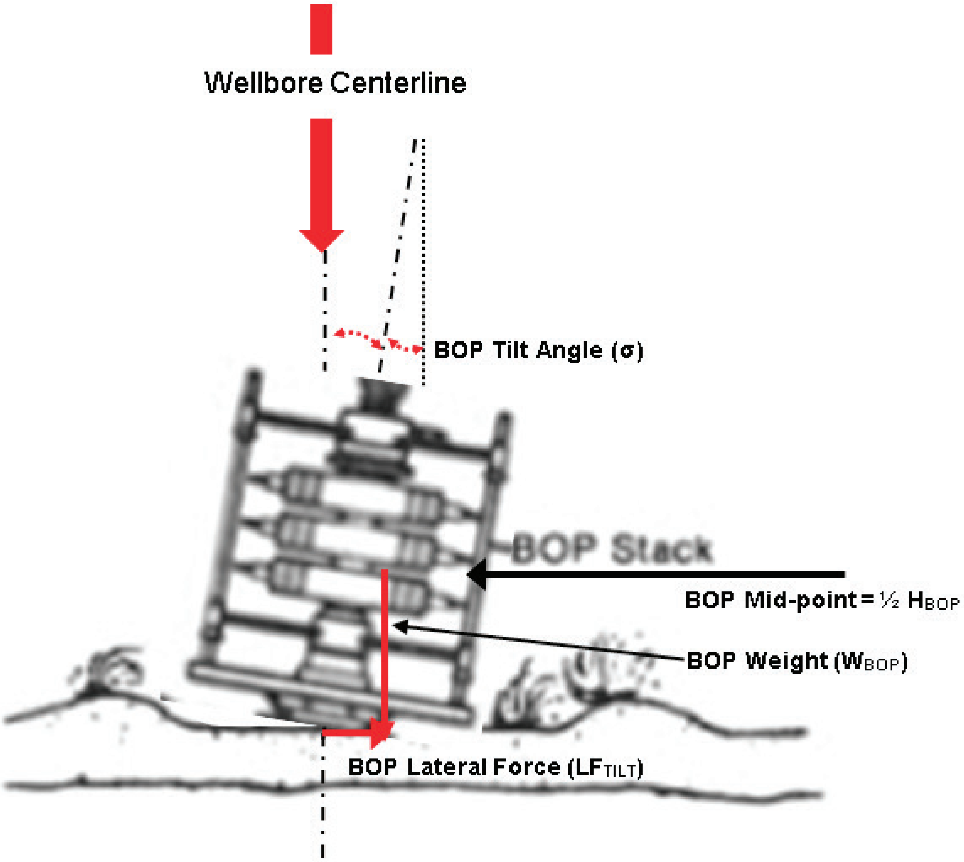

FIGURE I.11 Lateral Load on blowout preventer (BOP)/Lower Marine Riser Package (LMRP) due to BOP tilt (not to scale).

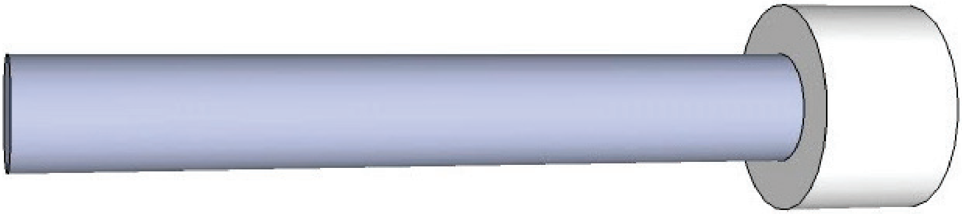

FIGURE I.12 Typical blowout preventer test tool.

Tension/Compression Cycles

In normal operations there is no significant compression loads on the riser system. Flange ring gaskets will experience normal compression loads due to flange bolt pre-loading. Unless flange bolts are pre-loaded to highly, ring gasket compression should be within design limits.

Tension in the bolts will be created by

- Bolt preloading,
- Internal pressure loads (such as pressure testing BOPs, or heavy fluids in the riser),
- Tension being pulled on the riser by the rig, and
- Bending moments on the flange connector.

DRILLING RISER SYSTEM DESIGN PROCESS

The purpose of a riser system design effort is to ensure that a drilling riser system can be successfully constructed, deployed, and operated to enable safe drilling of a well. Although this section deals with design techniques for a complete riser system, the design and construction of components must have been performed prudently so they will perform as required by the riser system. API RP 16Q states, "The marine drilling riser is best viewed as a system. It is necessary that designers, contractors, and operators realize that the individual components are recommended and selected in a manner suited to the overall performance of that system." It is for just this reason that this appendix will discuss overall riser system analysis processed before delving deeper into the design processes for flanges and flange bolts.

Because of the complexity of the design and operation of a drilling riser system, API RP 16Q presents several types of design methodologies that can be used at the discretion of the lease operator, the drilling contractor, a drill rig shipyard, or the OEM.[6] The most common are

- Operability analysis,
- Failure analysis, and
- Fatigue analysis.

Additionally API RP 16Q describes methodologies for

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[6] API RP 16Q—Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems, Chapter 5.

- Recoil analysis and
- Disconnected riser analysis.

The first three design methodologies will be discussed below.

Operability Analysis

Operability analysis is performed that a riser of a specific design can be safely deployed and operated on a specific rig, in a specific location, during a set of anticipated drilling/wellbore conditions, and under a set of assumed environmental conditions. This analysis is done to ensure the following:

- Riser can be safely run and retrieved,
- Riser can stay connected to allow safe drilling,
- Riser (LMRP) can be connected, disconnected, and re-connected,
- Riser/LMRP can be safely "hung off" the tensioner system after LMRP disconnection—until the riser can be pulled or re-connected, and
- Rig is suitable for the riser (rig tensioning system capability, moonpool configuration, DP capability).[7]

There are a series of weight and size analysis that are done regarding deploying a specific riser system. However the main thrust of the operability analysis is to communicate to the drilling contractor conditions under which the LMRP must be disconnected from the lower BOP stack to protect the structural integrity of both the riser system and the well. This is called the "drive-off/drift-off analysis."[8]

The analysis is made using a certain set of assumptions. These assumptions include ocean conditions and weight of the mud in the drilling riser. Riser system parameters evaluated include the following:

- Flex/ball joint angles,
- Tensioner stoke,
- Telescopic joint stroke,
- Riser stresses, and
- Wellhead and casing loads.

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[7] Kenneth Bhalla, discussions with Willard C. Capdevielle held on July 13, 2017, presented to the committee on September 28, 2017.

[8] API RP 16Q—Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems, Section 5.5.

This analysis establishes operational limits for the riser to be deployed. The primary operational limits are as follows:

- *Maximum tension setting* (T_{MAX})—defined in API RP 16Q as "the highest permissible tension setting with the vessel on location that provides sufficient margin so that anticipated conditions (such as wave-induced vessel motions, rig excursion, and/or tide change) do not cause any tensioner system relief valves to open, cause the tension experienced in the tensioners to exceed the limits of the design, or cause the pressure in the tensioners to exceed the limits of the design. With these considerations in mind, tension on any individual tensioner should not exceed this limit and the maximum tension setting for the riser, T_{MAX}, should not exceed this limit multiplied by the number of active tensioners. Other considerations (e.g., riser and wellhead loading, recoil, etc.) may impose additional restrictions on tension setting."
- *Minimum top tension* (T_{MIN}) —defined in API RP 16Q as "the minimum top tension required to prevent global buckling of riser in the event of the sudden loss of pressure in a tensioner or tensioner pair. The tension setting should be sufficiently high so that the effective tension is always positive in all parts of the riser even if a tensioner should fail. In most cases, the minimum effective tension is encountered at the bottom of the riser. In some cases, the minimum effective tension may occur at another location."
- *Maximum lateral offset*—the maximum rig lateral offset that can be tolerated without causing mechanical failure of the riser or any of its components by excessive tension or bending moment. Since lateral offset is the primary cause of so many failure modes for a riser/BOP system it is critical that it be accurate, conservative, and adhered to in the field. This operational limit is usually documented by a "watch circle."

The watch circle concept imposes an important safety operational limit. In practice, three (3) watch circles are established as depicted in Figure I.13.[9,10,11]

In practice, three watch circles are established:

1. The *point of disconnect (POD) circle* is the first circle to be calculated. This is the maximum lateral offset that can be tolerated by the riser system and its

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[9] Les Smiles, teleconference with Willard C. Capdevielle held on May 18, 2017, presented to the committee on September 28, 2017.

[10] Kenneth Bhalla, discussions with Willard C. Capdevielle held on July 13, 2017, presented to the committee on September 28, 2017.

[11] API RP 16Q—Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems, Section 5.5.

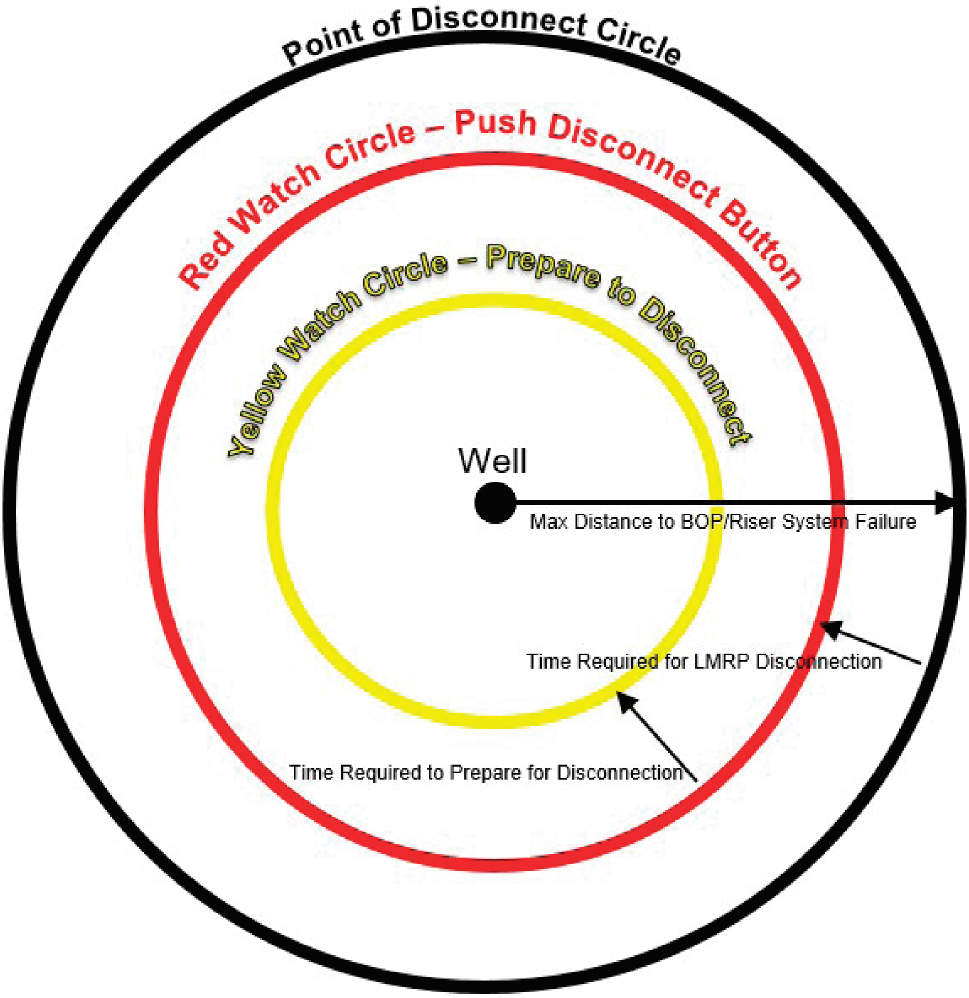

FIGURE I.13 Mobile Offshore Drilling Unit watch circle.

components without a mechanical failure at some point in the riser system. As a rig moves towards the POD limit:

- Ball joint is maxed out,
- Tension increases due to riser length at angle,
- The riser slip joint strokes out,
- The riser tensioning system reaches its lower limit,
- Tension is added to riser top,
- Bending moment on wellhead and BOP results, or
- Current could add or subtract a small amount.

2. The only way to prevent such a failure is to disconnect the LMRP for the lower BOPs, this unbounding the bottom of the riser string.
3. The *red watch circle* is calculated from the POD Circle. It represents the largest lateral offset at which the disconnect sequence should begin (i.e., the "red button" is pushed). This disconnect sequence includes operations such as closing BOP rams. The sequence may take 1 to 3 minutes, depending on the BOP.
4. The *yellow watch circle* is calculated from the red watch circle. It represents the largest lateral offset at which preparations for a disconnect should begin. These preparations may include things like pulling the drill bit off bottom to prevent it from being stuck by falling cuttings, or spacing out the drill pipe to ensure no tool joints are across the BOP shear ram(s). Spacing out in deepwater takes some time. There are critical human factors considerations here in determining the time for individual drilling crews to make these preparations.

The following observations about the watch circle should be noted:

- The condition that results in the most conservative calculation of the POD circle is the condition where the riser telescopic joint strokes out and outer barrel/tension ring is at its lowest elevation in the moonpool.
- Regarding the red and yellow watch circles, API RP 16Q states: "Both determinations rely on many assumptions about the vessel's trajectory (change in offset and heading versus time) as well as the time required to recognize and respond to the drive-off or drift-off, prepare for emergency disconnect, for the emergency disconnect to complete, and for the LMRP to separate from the lower stack prior to reaching a maximum allowable point of disconnect (POD)." In other words, there are some uncertainties in the calculation of the red and yellow watch circles:
    - — There is an assumed speed at which the rig offset is occurring. Watch circles are predetermined and are not adjusted for real-time vessel offset. Some companies specify the use of the 1-year winter storm (concurrent wind and waves) for disconnect time calculations.
    - — The activities included in "preparations for a disconnect" may vary for each rig and for different drilling operations being performed.
    - — The time to "recognize and respond to the drive-off or drift-off" situation is very dependent on the driller on the rig floor. This time is very dependent on the "human system." Operators or drilling contractors usually provide this information to the riser design engineer. The committee found no evidence that this time was benchmarked by training or drills.

- The POD circle is calculated on a set of assumptions. The POD circle is not updated for
  - — Actual wind, waves, and surface currents;
  - — Actual rig responses to wind and waves (heave, pitch, and roll; the "bottoming-out" of riser slip joints is influenced mainly by rig heave and lateral offset; neither of these parameters are used to update the POD circle);
  - — Actual riser position (angle) which can be measured, but not captured real time unless special equipment is on board;
  - — Actual underwater currents which can be measured by Acoustic Doppler Current Profilers (ADCP)[12] and were required by MMS NTL No. 2009-G02 to be measured and reported to the National Data Buoy Center. However this data is seldom used to update watch circles; and
  - — Actual loads or positions of riser components such as bottom flex/ball joints or flange bolts.

Failure (Weak Point) Analysis

Failure analysis has only one purpose: to evaluate all components of a drilling riser system as designed, manufactured, deployed, and operated and to ensure that if a failure occurs it will occur ABOVE the BOP. In other words, weak points in the riser system are calculated and the likely first component to fail is identified. A weak point failure below the BOP would disable the ability to control the well and a blowout would likely occur. This would require a re-design of the riser system. If the ability to disconnect (as assured by the watch circles) is the first line of defense, failure analysis is the second (and final) line of defense.

The assumptions that go into the calculation of the POD watch circle will also go into the failure analysis. Similarly the uncertainties go into the calculation of the POD watch circle will also go into the failure analysis.

However the riser designer must use their judgement in selecting worst and best case parameters to account for design uncertainties. For example, while POD circle calculations are most conservative when the riser slip joint strokes out and outer barrel/tension ring is at its lowest elevation, for weak point considerations the operating situation that results in the least amount of extension of the telescopic joint and the barrel/tension ring is at its highest elevation in the moonpool will typically be conservative. This is "because the eventual bottoming out occurs at a larger offset thereby producing larger bending moment and stresses."

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[12] NOAA, Ocean Explorer, "Acoustic Doppler Current Profiler," http://oceanexplorer.noaa.gov/technology/tools/acoust_doppler/acoust_doppler.html, accessed October 22, 2017.

And again, because much of the real-time performance of the riser system and its components are not measured real time, the likely point of failure cannot be updated for real-time condition.

Fatigue Analysis

It is interesting that fatigue analysis has been the least-accepted design effort by industry. Perhaps this is because there was a perception that the higher frequency load cycles due to rig heave resulted in relatively low stress levels. These higher frequency, lower-load conditions were

- Wave motion and lateral rig movement;
- Tension load cycles due to rig heave, which may occur if the riser tensioning system is not operating properly; and
- Vortex-induced-vibration (VIV) caused by surface currents that was thought be a near surface phenomenon that could be mitigated by increasing riser tension at the surface or by placing fairings on the shallow portion of the riser.

In the past, the high-load events that drove fatigue were considered to be the routine bi-weekly pressure testing of BOPs. Recent developments have indicated that riser system and component fatigue life can be finite in the dynamic ocean environment. Fatigue is most likely driven by ocean currents.[13] It is now known that there is the potential for significant currents to exist at all depths in a deepwater location. Eddy currents exist from the surface down to depths of 1,000 m (3,300 ft.). This has been confirmed by field measurements using Acoustic Doppler Current Profiler (ACDP). Figure D.12 in Appendix D shows the result from one such ACDP reading. In addition, in deepwater Gulf of Mexico locations near the Sigsbee Escarpment, Rossby Waves can produce significant currents near the seafloor.

Interestingly these is no requirement to analyze fatigue for deepwater riser systems except for HPHT wells, although fatigue can be a bigger issue in shallower water The definition for "HPHT" can be found in API TR8.[14]

Fatigue analysis looks primarily at the conductor pipe, the wellhead and wellhead connector, and the riser string. Because it is so stout, fatigue analysis is not

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[13] Les Smiles, teleconference with Willard C. Capdevielle held on May 18, 2017, presented to the committee on September 28, 2017.

[14] Brian Healey, Ph.D., and Partha Sharma, discussions with Bill Capdevielle held on July 7, 2017, presented to the committee on September 28, 2017.

performed on the BOP/LMRP or its components.[15,16] It is important to consider the conductor pipe, wellhead and wellhead connector for the following reasons:

- These are the components that bound the bottom of the riser thus cyclic loading from the riser will be transmitted these components, although likely dampened.
- These are permanent components of the well. They must survive for the entire lifetime of the well, form well construction to well abandonment. The effects of fatigue are cumulative. The fatigue life of these permanent components must be managed expeditiously.
- These components are situated below the BOP during well construction and below the subsea tree during production. Failure would likely result in a catastrophic well control event.

There is ongoing research into the VIV phenomenon. This includes methods for real-time measurement, methods for the real-time analysis of this data, and better fatigue life prediction methods.[17,18,19]

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[15] Ibid.

[16] Kenneth Bhalla, discussions with Willard C. Capdevielle held on July 13, 2017, presented to the committee on September 28, 2017.

[17] S.I. McNeill and P. Agarwal, "Efficient Modal Decompression and Reconstruction of Riser Response Due to VIV," OMAE2011-49460, 30th International Conference on Ocean, Offshore and Arctic Engineering, June 19-24, 2011, http://proceedings.asmedigitalcollection.asme.org.

[18] S. McNeill, P. Agarwal, D. Klok, K. Bhalla, T. Saruhashi, I. Sawada, M. Kyo, E. Miyazaki, and Y. Yamazaki, "Real-Time Riser Fatigue Monitoring Routine: Architecture, Data, and Results," OMAE2013-11540, 32nd International Conference on Ocean, Offshore and Arctic Engineering, June 9-14, 2013, http://proceedings.asmedigitalcollection.asme.org.

[19] S. McNeill, T. Saruhashi, I. Sawada, M. Kyo, E. Miyazaki, and Y. Yamazaki, "A Method for Estimating Quasi-Static Riser Deformation and Applied Forces from Sparse Riser Inclination Measurements," OMAE2015-41286, 34th International Conference on Ocean, Offshore and Arctic Engineering, May 31-June 5, 2015, http://proceedings.asmedigitalcollection.asme.org.

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Bolting Preload

This appendix presents background information regarding bolting preload and safety factors used in bolting design.

BOLTING PRELOAD

During assembly in the OEM shop, the BOP/LRMP stack is "built up" by placing one RAM on top of another and bolting them together at the flanges. A ring gasket is placed between the flange faces and bolts (or studs and nuts) are tightened. The procedure for tightening flange bolts must conform to various industry and OEM specifications to ensure bolts are tightened as evenly as possible.[1,2] Flange bolting procedures include the following:

- A criss-cross bolt tightening pattern,
- A bolt tightening sequence (e.g., all bolts are hand tightened, then all bolts are tightened to 25 percent of desired preload, then 50 percent, then 75 percent, then 100 percent);
- Determination of required bolt preloading, as discussed below; and
- Method of achieving and verifying bolt preload, also discussed below.

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[1] API Engineering bulletin EB 962D, March 29, 2016.

[2] John H. Bickford, "An Introduction to the Design and Behavior of Bolted Joints;" Third Edition, Revised and Expanded, John H. Bickford, Marcel Dekker, Inc., 1995.

Drilling rig contractors use the same technique when maintaining a BOP stack is on the deck of the rig. Industry also has the ability to tightening bolts and nuts when the BOP stack is deployed underwater using a remotely operated vehicle (ROV).

Determining Bolt Preload

The tensile preload for closure bolting must provide sufficient clamping force between flanges, seal rings, or component faces so that they remain sealed when flange connectors are subjected to service loading conditions.

API Spec 17D specifies the following tensile preloading of flange bolts:

- All 6BX and 17SS (types of API flanges) flange bolts be preloaded to between 67 percent and 73 percent of a bolt's yield stress.[3]
- A maximum allowable tensile loading on flange bolts, including forces from rated internal pressure, based on the root area of the thread, of 83 percent of yield strength (through API Spec 6A and ISO 10432).[4]

Thus, the bolt preload alone makes these bolts highly loaded, with little room for additional loading despite the fact that additional tensile loads on the bolts are minimal until the flange preload is exceeded.

The flange bolt installation is a process that is critical to flange performance and integrity. This is particularly true for achieving the required tensile preload on a flange bolt. API Spec 17D, Section 7.5.5 merely recommends the following regarding bolting makeup torque,[5]

> The use of calibrated torque or bolt-tensioning equipment is recommended to ensure accurate make-up tension.

Bolt Preloading Technique

There are many methods that can be used to impose the required fastener preload. These include the following:

- *Application of a controlled torque to the threaded fastener*, the method currently specified in the API standards. Applicable friction coefficients are generally not known, but approximations based on a consideration of the

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[3] API Specification 17D, ISO 1 3628-4, 2nd Edition, May 2011, Section 5.1.3.5, p. 19.

[4] API Specification 17D, 1st Edition, August 1, 1996, Section 303.4, p. 22.

[5] API Specification 17D, ISO 13628-4, 2nd Edition, May 2011, Section 7.5.5, p. 66.

surface characteristics, type of lubrication, and type of or coating have been made. Torque is applied with a torque wrench or an alternate energy source. The types of available torque wrenches include mechanical (i.e. force applied to a lever arm), electrical, pneumatic, and hydraulic. Selection of the type of torque application system to be used depends on the required torque level and specific application (e.g., above or below water).[6,7,8,9] Torque has been shown to be an inaccurate metric for assuring actual bolt preload. [10,11]

- *The RCSC technique* was developed by the Research Council on Structural Connections (RCSC). This technique is a variant of the torqueing technique with many quality control enhancements. Although the RCSC technique references ASTM standards rather than API specifications, and was developed for bolted structural connections on bridges and buildings, it may have some applicability to flange connectors. Some interesting aspects of the RCSC technique are
  - It addresses both LRFD (probabilistic) design and allowable strength (safety-factor) design.
  - It addresses protected storage requirements for bolts.
  - It only addresses bolts with diameters up to 1½ in.
  - It requires and *engineer-of-record* who is responsible for designing the joint and for proper bolting in the field.
  - It addresses bolt fatigue.
  - It requires the use of a tension calibrator to determine the "nut factor" for each manufacturing lot of bolts, studs, and nuts. The "nut factor" is an unknown variable when determining the proper torque to apply for a desired preload. The *engineer-of-record* must witness every tension calibration test to ensure the proper "nut factor" is used in the field.
  - It requires an *inspector* in the field to ensure the proper torque is applied to each bolt.
  - It requires daily calibration of wrenches used in bolt tightening.
- *Pre-tensioning* is the technique of using hydraulic pistons attached directly to the end of the fasteners. Once the desired tensile load is imparted, a restraining nut is attached preserve the length of the stretched bolt. The

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[6] J.E. Shigley, *Mechanical Engineering Design*, McGraw-Hill, New York, 1972, pp. 291-320.

[7] Tentec, "Tensioners," http://www.tentec.net/tensioners.php, accessed May 2017.

[8] Atlas Copco, "Bolt Tightening Solutions," http://www.atlascopco.co.uk/en-uk/itba/products/Bolt-tightening-solutions, accessed May 2017.

[9] Torq/Lite, "Hydraulic Torque Wrenches," http://www.torqlite.com/, accessed May 2017.

[10] K.H. Brown, C. Morrow, S. Durbin, and A. Baca, *Guideline for Bolted Joint Design and Analysis: Version 1.0*, SAND2008-0371, Sandia National Laboratories, Albuquerque, N.M., January 2008.

[11] Lester Burgess, discussions with Nancy Cooke and Bill Capdevielle, May 31, 2017, presented to the committee on August 28, 2017.

imposed tensioning force can be measured directly with an integral load cell, or it can be calculated from the imposed pressure and pressure-bearing area of the piston. One subsea equipment company uses pre-tensioning exclusively.[12]

- As an additional check, after connector installation with either a torque wrench or a direct tensioning system, the resulting stretch in the bolt can be measured by a variety of techniques including mechanically (e.g., with a set of calipers if access to both ends is available) or ultrasonically.[13] With knowledge of an appropriate spring constant for the connector, then the imposed force can be calculated if the length of the fastener under tensile load is known.

Estimates for the uncertainty range of effective bolt tensile loading when exact torque is applied is on the range of ±25 to 30 percent.[14,15,16] Uncertainty in the application of torque on fasteners is caused by several factors, some of which aren't controlled by standards and specs. Examples are the effect of thread manufacturing tolerances and friction factor (nut factor) to be used for particular lubricants and coatings.[17]

There are also some indications that the thread manufacturing technique influences bolt preload accuracy and variability. Figure J.1 shows the how the residual preload (as indicated by bolt stretch) can vary for cut threads and for rolled threads after a two-pass bolt-up procedure.[18]

Schoberg estimated the efficiency of using torque to generate bolt tension.[19] As shown in Figures J.2 and J.3, estimated that 10 percent of the applied torque resulted in elastic preloading of a bolt that clamps components together. He further

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[12] Bill Capdevielle, discussions with ITH Engineering at the 2017 Offshore Technology Conference, Houston, Tex.

[13] Boltight Limited, "Introduction to Ultrasonic Bolt Load Measurement," http://www.boltight.com/products/echometer.html, accessed May 2017.

[14] K.H. Brown, C. Morrow, S. Durbin, and A. Baca, *Guideline for Bolted Joint Design and Analysis: Version 1.0*, SAND2008-0371, Sandia National Laboratories, Albuquerque, N.M., January 2008.

[15] Lester Burgess, discussions with Nancy Cooke and Bill Capdevielle, May 31, 2017, presented to the committee on August 28, 2017

[16] J.H. Bickford, *An Introduction to the Design and Behavior of Bolted Joints*, Third Edition, Marcel Dekker, Inc., New York, N.Y., 1995.

[17] R.S. Shoberg, PE, "Engineering Fundamentals of Threaded Fastener Design and Analysis," PCB Load and Torque, Inc., Farmington Hills, Mich.

[18] J.H. Bickford and M.E. Looram, *Good Bolting Practices, A Reference Manual for Nuclear Power Plant Maintenance Personnel, Volume 1: Large Bolt Manual*, Electric Power Research Institute, Palo Alto, Calif., 1987.

[19] R.S. Shoberg, PE, "Engineering Fundamentals of Threaded Fastener Design and Analysis," PCB Load and Torque, Inc., http://www.hexagon.de/rs/engineering%20fundamentals.pdf.

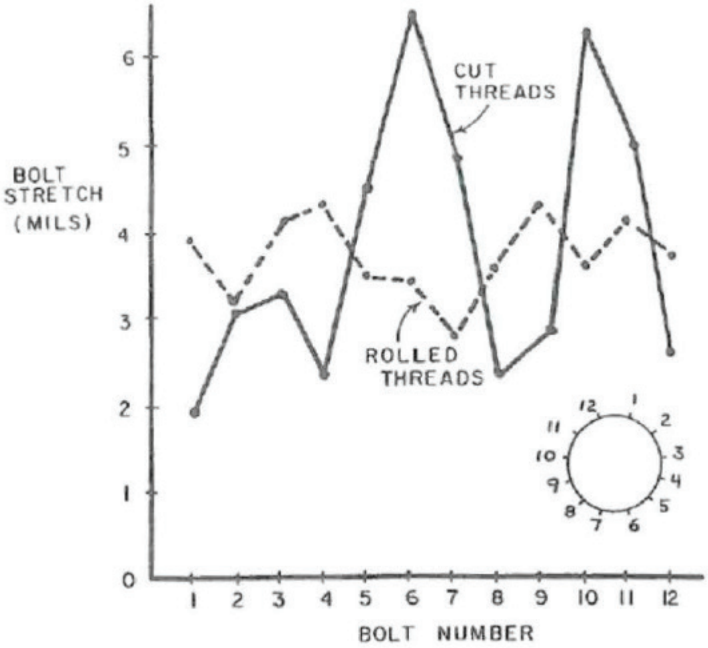

FIGURE J.1 Variation in bolt stretch after two-pass bolting for cut and rolled threads. SOURCE: J.H. Bickford and M.E. Looram, *Good Bolting Practices, A Reference Manual for Nuclear Power Plant Maintenance Personnel, Volume 1: Large Bolt Manual*, Electric Power Research Institute, Washington, D.C., 1987.

estimated that 50 percent of the torque was consumed by underhead friction and 40 percent of the torque is consumed by thread friction. He concludes that, "an increase in either friction component of 5 percent can reduce pre-load tension by half."[20]

Safety Factors for Flange Bolts

The maximum allowable design loads for flange bolts is decreased by a factor of safety. "Factor of safety (FoS), also known as safety factor (SF), is a term describing the structural capacity of a system beyond the expected loads or actual loads. Essentially, how much stronger the system is than it usually needs to be for an

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[20] Ibid, p. 5.

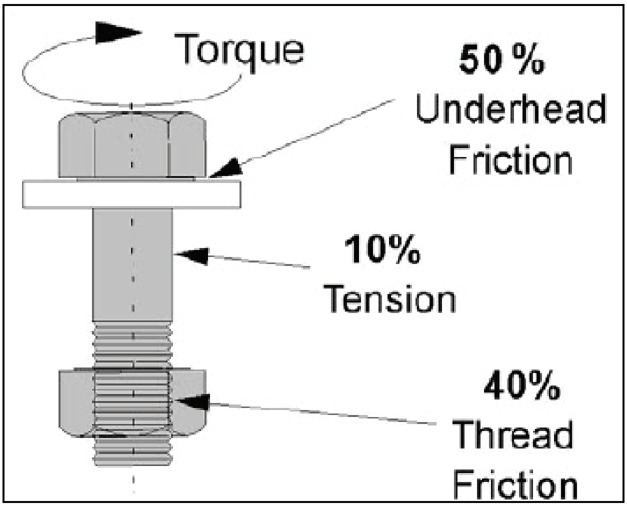

FIGURE J.2 Torque and its contribution to friction and tension. SOURCE: Ralph S. Shoberg, PE, *Engineering Fundamentals of Threaded Fastener Design and Analysis*, PCB Load & Torque, Inc., Farmington Hills, Mich.

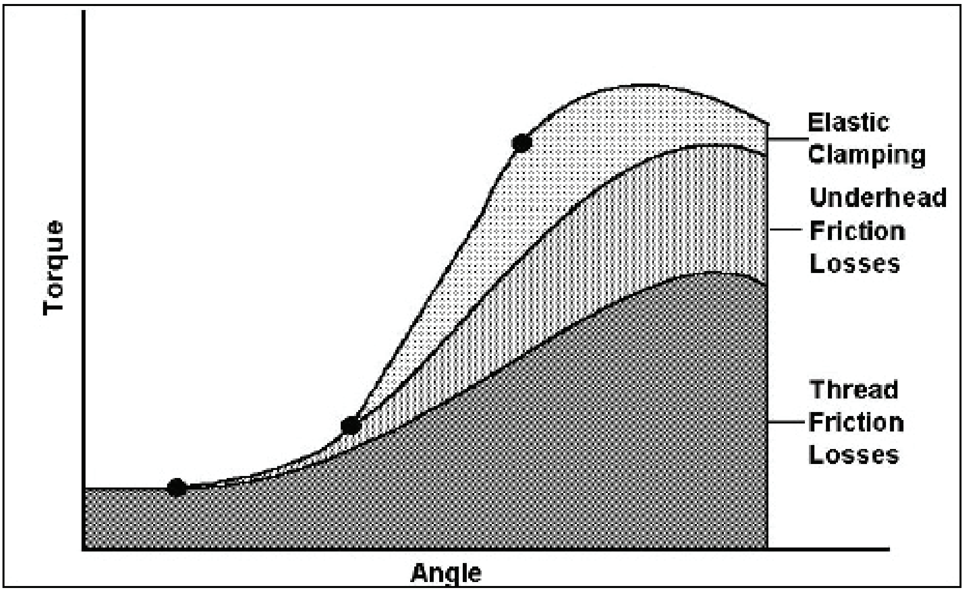

FIGURE J.3 Torque vs. angle and the claping to friction relation. SOURCE: Ralph S. Shoberg, PE, *Engineering Fundamentals of Threaded Fastener Design and Analysis*, PCB Load & Torque, Inc., Farmington Hills, Mich.

intended load."[21] The purpose of a safety factor is to accommodate any variations or uncertainties regarding actual loads and bolt properties.[22] The safety factor is determined by the following equation:[23]

$$\text{Factor of Safety} = \frac{\text{Design Strength}}{\text{Design Load}}$$

Design Strength can be defined in several ways, but two commonly used are:

- *Nominal ultimate tensile strength*, which is the stress at which the bolt's material would be expected to fail by breaking or fracturing based on the load and original cross-sectional area; and
- *Yield strength*, which is the stress which will cause the bolt to plastically deform, usually defined as nominal 0.2 percent strain from its original length.

The traditional factor of safety is based on ultimate tensile strength. However, on ductile metals in a pressure connection it is not inappropriate to check the factor of safety on both ultimate tensile strength and yield,[24] since a flange connection whose bolts yield enough can fail to maintain pressure boundary, even if they have not fractured. As discussed later in this appendix there does not appear to be any industry practice to examine bolts for plastic deformation unless they have deformed enough to leak, or fractured entirely.

API Specification 17D, "Specification for Subsea Wellhead and Christmas Tree Equipment," specifies bolt loading limits as a percentage of yield stress (not ultimate tensile strength), because plastic deformation of bolts is as undesirable an event as an actual bolt failure if it leads to failure of the connector to maintain the pressure boundary of the well.

A similar design parameter is the margin of safety (MoS),[25] sometimes referred to as the safety margin. The margin of safety describes "ratio of the strength of the structure to the requirements." The margin of safety can be calculated by the following equation:[26]

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[21] Mechanical 360, "Factor of Safety and Margin of Safety," https://www.mechanical360.net/updates/factor-of-safety-and-margin-of-safety, accessed November 10, 2017.

[22] E.A. Avallone, T. Baumheister III, and A.M. Sadegh, *Marks Standard Handbook for Mechanical Engineers*, 11th edition, McGraw-Hill, New York, N.Y., 2007.

[23] Mechanical 360, "Factor of Safety and Margin of Safety," https://www.mechanical360.net/updates/factor-of-safety-and-margin-of-safety, accessed November 10, 2017.

[24] Ibid.

[25] Ibid.

[26] Ibid.

$$\text{Margin of Safety} = \frac{\text{Failure Load}}{\text{Design Load}}$$

or

$$\text{Margin of Safety} = \text{Factor of Safety} - 1$$

Similarly, a yield margin of safety could be defined substituting the yield load for the failure load.

The yield margin of safety for flange bolts can be derived from the working stress limitations specified in API Spec 17D, which recommends the following:

- For bolt preload (the initial "tightening of a flange bolt to achieve flange face closure force), the bolt should be placed in a tensile loading state of 67 to 73 percent of maximum yield stress.[27]
- For bolt in-service loading (the bold preload plus any additional working loads such as pressure, externally-applied tension, or bending moments on the connector) the tensile loading on the bolt shall not exceed 83 percent of maximum yield stress.[28] This equates to a yield margin of safety of .205.

It is useful to compare the safety margins for subsea wellhead and Christmas tree equipment, as specified in API Spec 17D, to the safety margins for surface wellhead and Christmas tree equipment, as specified in API Spec 6A.[29] For surface wellheads bolt preloading is specified at only 50 percent of yield; the operational bolt loading remains at 83 percent of yield.

Consider that the operational loading on the onshore Christmas tree bolts would be mainly from internal pressure on the connector, which is known to a high degree of certainty. Piping support systems would virtually eliminate any external loads on the connectors such as tension or bending moments. Additionally, the flange bolts themselves are not exposed to the potentially corrosive underwater environments (including cathodic protection) as the subsea flanges being considered in this study report.

Subsea wellhead and Christmas tree bolts suffer additional and greater integrity risks, including:

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[27] API Specification 17D, ISO 1 3628-4, 2nd Edition, May 2011, Section 5.1.3.5, p. 19.

[28] API Specification 6A, ISO 10423:2009 (Modified), 20th Edition, October 2010, Section 4.3.4, p. 28.

[29] API Specification 6A, ISO 10423:2009 (Modified), 20th Edition, October 2010, Section 4.3.4, p. 28.

- Service in high-pressure salt water—sometimes hypersaline
- Exposure to H_2S, CO_2, hydrogen, and cathodic protection
- Potential tensile forces coming from the rig through the riser
- Potential bending moments caused by deep water currents

The above four factors place significant and often uncertain environmental stress and loading on subsea bolts.

Perhaps the most critical factor in considering the appropriateness of the safety factors implied by API RP 17D is the accuracy of the bolt preloading technique—for both surface and subsea applications. As discussed above in the section on Bolt Preloading, torqueing is a very inaccurate method for achieving bolt preload. The ±25 to 30 percent accuracy range of using torque to preload bolts and nuts should be considered when determining the suitability of 20.5 to 50 percent (preload and operating) safety margins. It is problematic to consume 50 to 60 percent of a very narrow bolt preload safety margin with preload variability. This margin should be set accounting for uncertainty.

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Threaded Fastener Failure Modes

FAILURE OF LOW ALLOY STEELS

Since the majority of the bolts used in undersea connections are made of low alloy steels with carbon concentrations in the range of 0.3-0.4 wt.%, this appendix will focus on failure modes for this type of material. Hydrogen embrittlement in Ni-based alloys is briefly discussed since a limited number of bolts are made from nickel based superalloys.

The general characteristics of low alloy steels that relate to fracture response are reviewed to provide background information for a discussion of hydrogen embrittlement. These materials undergo a transition from brittle to ductile failure with increasing temperature. The temperature at which this occurs, referred to as the ductile-to-brittle transition temperature (DBTT), is usually defined as the midpoint in a range of temperatures, spanning approximately 50°, during which the fracture mode transitions from 100 percent brittle to 100 percent ductile. The transition temperature is most commonly determined through Charpy testing, although a notched fracture test in which the sample is loaded in tension can be used. The latter type of test reports a fracture toughness value for crack propagation (K_{IC}), whereas the Charpy test simply gives integrated fracture energy. The transition temperature is usually well below room temperature for steels that have been tempered in the range of 600°C to 700°C and then rapidly cooled. For applications such as the one considered in this appendix and for steels heat treated according to the current standards, the fasteners should fail in a ductile manner.

Ductile failure in low alloy steels is generally associated with a high fracture energy, which implies that significant stress must be applied to the material for it to occur. The mode of fracture is often described as micro-void nucleation and coalescence and evolves in the following way. As the sample is loaded in tension, the interface between the steel matrix and large inclusions, the most common of which are manganese sulfides, separates and creates microvoids that grow with increasing applied stress. This growth reduces the cross-sectional area over which the stress is applied. When the stress reaches a critical value the material between these large voids rips apart and failure occurs. The fracture path between these large voids is often populated with much smaller voids that form around the carbides produced during tempering and is usually transgranular.

Low energy ductile fracture can be observed in some situations as a result of material processing. This low energy fracture can occur as a result of a high density of sulfides and alignment of the sulfides in a particular direction in the material that is also parallel to the fracture path. It can also result from a process referred to as overheating which causes precipitation of the sulfides on the grain boundaries.[1,2] In the latter case the ductile fracture mode is intergranular.

Brittle fracture occurs with much lower energy absorption. The general model for this type of fracture, often referred to as the Griffith model, is that a microcrack is nucleated at a second phase particle or defect and then, once it reaches a critical size, propagates rapidly across the sample.[3] In steels that have been quenched from the tempering treatment, the most common sites of nucleation are cracked carbides or cracked inclusions.[4] However, if the sample is not rapidly quenched and the steel contains impurity elements such as phosphorus or tin at levels above approximately 100 wt ppm, the grain boundaries can become weak and serve as the sites of crack nucleation and propagation.[5] In this case, brittle fracture can be observed at much higher temperatures than expected. This phenomenon is referred to as temper embrittlement.

Unpredicted brittle fracture can also be caused by a specific environment. Many types of environments can be listed that can cause low energy fracture in steel, but here the discussion is limited to hydrogen embrittlement. Hydrogen embrittlement

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[1] T.B. Cox and J.R. Low, An investigation of the plastic fracture of AISI 4340 and 18 Nickel-200 grade maraging steels, *Metallurgical Transactions* 5(6):1457-1470, 1974.

[2] A.M. Ritter and C.L. Briant, "The Effect of Second-Phase Particles on Fracture in Engineering Alloys," pp. 59-123 in *Embrittlement of Engineering Alloys* (C.L. Briant and S.K. Banerji, eds.), Academic Press, New York, N.Y., 1983.

[3] A.A. Griffith, *Philosophical Transactions of the Royal Society A* 221:163, 1920.

[4] C.J. McMahon, Jr., and M. Cohen, Initiation of cleavage in polycrystalline iron, *Acta Metallurgica* 13:591, 1965.

[5] C. L. Briant and S.K. Banerji, Intergranular failure in steel: The role of grain-boundary composition, *International Metals Reviews* 23:164, 1978.

has, in general, been described by three broad mechanisms which are important because they point to certain dependencies, triggers, and drivers. Hydrogen induced decohesion (HEDE) relates to a lowering of the metal-metal bond strength and Griffiths fracture toughness in response to hydrogen. HEDE can be exacerbated by the impurity segregation described above. Hydrogen induced local plasticity relates to hydrogen enhanced deformation that results in a variety of effects such as enhanced plastic slip, greater dislocation planarity and slip band cracking, and large local accumulations of dislocation bands such that detrimental pile-ups occur at interfaces like grain boundaries which in turn trigger intergranular fracture. The third mechanism involves hydriding where a metal-hydrogen phase forms that has a low intrinsic fracture toughness. The first two mechanisms are the most likely operative in ferrous and nickel base alloys used as oil and gas marine connectors. It should be noted that nickel and nickel alloys such as Ni-Cu may hydride albeit not at typical cathodic potentials used in marine service.

The source of hydrogen in marine applications can arise from a combination of factors. These include processing such as pickling, coatings, or post-coating bake-outs at the OEM, long term field exposure where water is reduced electrochemically by galvanic coupling, impressed current or sacrificial anode based cathodic polarization, or anoxic freely corroding conditions at high sensible pressures.

Hydrogen embrittlement has several characteristics that should be noted.[6,7,8,9,10,11]

- The crack growth is time dependent. A crack can propagate in a stable fashion, once it reaches a critical threshold stress intensity, and continue until it reaches a length such that, for a given applied stress, rapid fracture takes over. Thus, it is not a failure that will necessarily occur immediately after a part is loaded or put into service. It is generally assumed that this

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[6] R.P. Gangloff and R.P. Wei, Gaseous hydrogen embrittlement of high strength steels, *Metallurgical Transactions A* 8:1043-1053, 1977.

[7] J.R. Pickens, J.R. Gordon, and J.A.S. Green, The effect of loading mode on the stress-corrosion cracking of aluminum alloy 5083, *Metallurgical Transactions A* 14:925, 1983.

[8] H.K.D.H. Bhadeshia, "Extremely Strong Steels—The Mechanism and Prevention of Hydrogen Embrittlement," Lecture, *AISTech 2017*, Association for Iron and Steel, May 8, 2017.

[9] Z.D. Harris, J.D. Dolph, G.L. Pioszak, B.C.R. Troconis, J.R. Scully, J.T. Burns, The effect of microstructural variation on the hydrogen environment-assisted cracking of Monel K-500, *Metallurgical and Materials Transactions A* 47:3488, 2016.

[10] R.P. Gangloff, H. Ha, J. Burns, and J.R. Scully, Measurement and modeling of hydrogen environment-assisted cracking in Monel K-500, *Metallurgical and Materials Transactions A* 45(9):3814-3834, 2014.

[11] J.H. Ai, H.M. Ha, R.P. Gangloff, and J.R. Scully, Hydrogen diffusion and trapping in a precipitation-hardened nickel-copper-aluminum alloy Monel K-500 (UNS N05500), *Acta Materialia* 61(9):3186-3199.

time dependence occurs because hydrogen must continue to diffuse to the crack tip as the crack propagates. Hence the hydrogen diffusion coefficient at the crack tip is critical. This parameter is subject to modifications by the details of the plastic and fracture process zones; hydrogen trapping and concentration dependent diffusion are critical factors.

- The threshold stress intensity for cracking is reduced and the crack growth rate is increased by the diffusible hydrogen concentration to a different degree for a given material. However, the sensitivity of a material to a given hydrogen content depends on many material factors such as strength, Griffiths fracture toughness (in a decohesion model), and the potency factor for hydrogen which may in turn be related to grain boundary structural or chemical factors such as interface impurity and metalloid content.
- A critical hydrogen content for fracture is often observed. A subtle detail is that hydrogen may affect ductile cracking processes, although this type of fracture is a much higher energy fracture than brittle failures caused by hydrogen embrittlement. At greater hydrogen contents these fracture modes may transition with appropriate tensile stress, microstructure and local hydrogen content to increasing brittle modes such as intergranular and lath boundary cracking. Hence the notion of a threshold may correspond to any detectable embrittlement or mode transition.
- Cracking and susceptibility may be strain rate dependent and affected by dynamic plastic strain during or after hydrogen charging. The mechanistic effects of strain are debated and may alter surface effects such as hydrogen production and uptake (e.g. enhanced by film rupture) versus internal effects such time for diffusion controlled transport to the fracture process zone, dynamic trap creation, and dislocation transport from the tip into the fracture process zone.
- The rate of crack growth is temperature dependent. For steels, a maximum in crack growth rate is often near or slightly below room temperature. This observation is often related to a balance between trapping and diffusion where detrapping and outgassing occur at high temperatures and transport is very slow at cold temperatures.
- A tensile stress is required to cause the failure. Hydrogen diffuses to regions of high tensile stress in a material, such as those at a crack loaded in tension, and concentrates there.
- The fracture mode can be either transgranular or intergranular. The details of the fracture mode depend on the concentration of hydrogen and also the susceptibility of the grain boundaries to fracture as discussed below.
- Traps in the material, such as precipitates or dislocations, can increase the amount of hydrogen required to cause failure. Some strong traps effectively pin the hydrogen and keep it from diffusing to areas of high tensile stress

> in a closed system. This only works for low crack tip stress fields. This can only delay cracking in an open system as trap filling and saturation will allow hydrogen to eventually accumulate. Reversible traps of intermediate and low strength can impede diffusion even in an open system where a slower effective diffusivity can be affected by intermediate strength cracks to limit stage II steady state crack growth rates even in open systems.[12]

In the next section, detailed aspects of HAC in steels that relate to the topic of this appendix are discussed. In particular, these examples will show that the hydrogen concentration in the sample, and particularly at the crack tip, plays a critical role in determining the degree of embrittlement. *If this concentration is sufficiently high, most steels will be susceptible to hydrogen embrittlement.*

General HE Susceptibility

Of all the steel types used in subsea connectors, many are susceptible to hydrogen embrittlement in seawater at free corrosion potentials, with a common denominator being strength level in excess of about 80-110 ksi (560 to 800 MPa). These include bainitic, martensitic and martensitic and aged steels with the precise details of embrittlement depending on microstructure, interface cleanliness and strength. This behavior is shown in Figure K.1 where exposure of pre-cracked specimens to 3.5 percent NaCl is shown to lower the fracture toughness of low alloy steels, that range in strength from 115 to over 260 ksi (800 to over 1800 MPa), from over 55 ksi(in)$^{1/2}$ to 9-18 ksi(in)$^{1/2}$ (60 MPa(m)$^{1/2}$ to 10-20 MPa(m)$^{1/2}$).[13] It should be noted that similar behavior[14] occurs in quenched and tempered reactor steels.[15]

The root cause of SCC of steels in seawater has been shown to be diffusible hydrogen concentration within the alloy regardless of source.[16] The stress intensity dependence of subcritical crack growth rate produced in a tempered martensitic

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[12] Open systems have continual hydrogen production while closed systems does not.

[13] R.P. Gangloff, A Review and Analysis of the Threshold for HEE of Steel, in *Corrosion Prevention and Control, Proceedings of the 33rd Sagamore Army Materials Research Conference* (S. Isserow, ed.), U.S. Army Materials Technology Laboratory, Watertown, Mass., 1986.

[14] An exception to this well-established trend is in the case of extreme sour gas charging seen in the NACE MR 0175 test solution. In so-called, "sulfide induced stress corrosion cracking," cracking may be controlled by inclusion density and shape and be independent of yield strength. Only in this highly specialized case is the strong yield strength correlation is absent.

[15] W.E. Erwin and J.G. Kerr, "The Use of Quenched and Tempered 2 1/4Cr-1Mo Steel for Thick Wall Reactor Vessels in Petroleum Refinery Processes: An Interpretive Review of 25 Years of Research and Application," Welding Research Council, 1982.

[16] R.P. Gangloff, "Hydrogen Assisted Cracking of High Strength Alloys," pp. 31-101 in *Comprehensive Structural Integrity* (I. Milne, R.O. Ritchie, B.L. Karihaloo, eds.), Elsevier/Pergamon, Amsterdam, Boston, 2003.

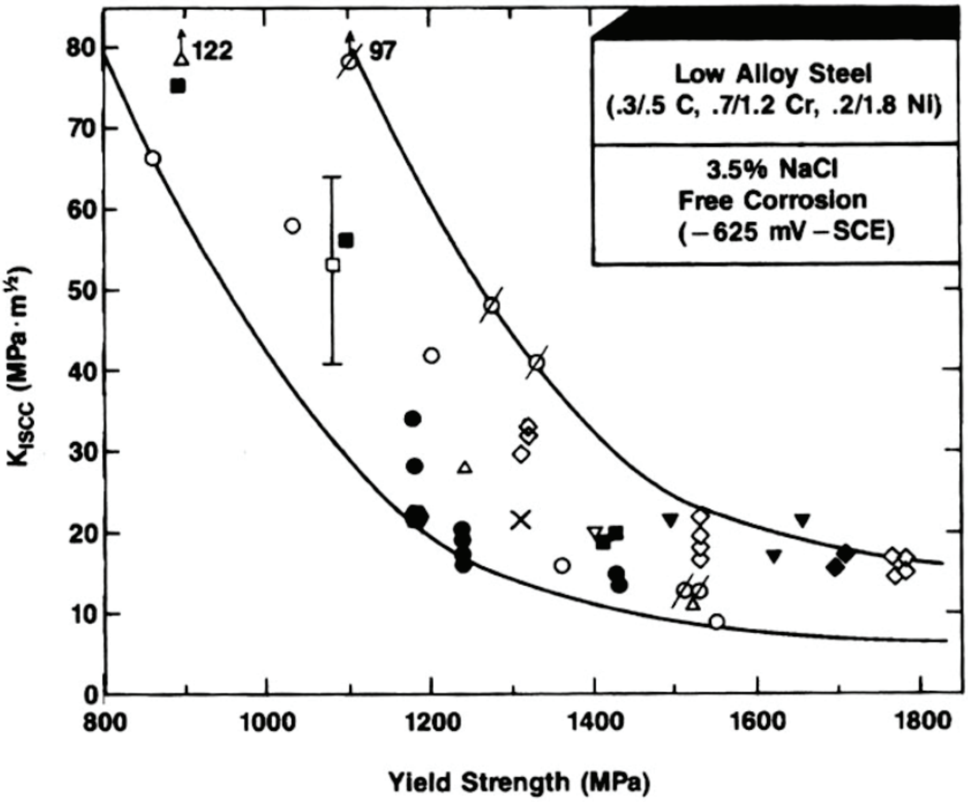

FIGURE K.1 The yield strength dependence of the threshold stress intensity factor for SCC in tempered martensitic steels cracked quasi-statically during stressed exposure in near-neutral NaCl solution at corrosion or open circuit potentials and 23°C. Permission requested Elsevier. SOURCE: R.P. Gangloff, "Corrosion Prevention and Control" pp. 64-111 in *33rd Sagamore Army Materials Research Conference*, (M. Levy and S. Isserow, eds.), U.S. Army Laboratory Command, Watertown, Mass., 1986.

steel exposed in three separate environments that produce atomic hydrogen at the crack tip are shown in Figure K.2.[17] Here H_2S and H_2 gas are more severe than 3.5 percent NaCl and an overall toughness decreases to the range of 10-20 MPa $(m)^{1/2}$ is observed at applied stress intensities above these thresholds, a stage I region is typically followed by a stage II region of crack growth rate that strongly depends on the environment and potential and, in turn, the hydrogen concentration at the crack tip. Thus the H_2S environment is more severe than seawater because the hydrogen

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[17] G.E. Kerns, M.T. Wang, and R.W. Staehle, pp. 700-733 in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys* (R.W. Staehle, J. Hochman, D.R. McCright, and J.E. Slater, eds.), National Association of Corrosion Engineers, Houston, Tex., 1973.

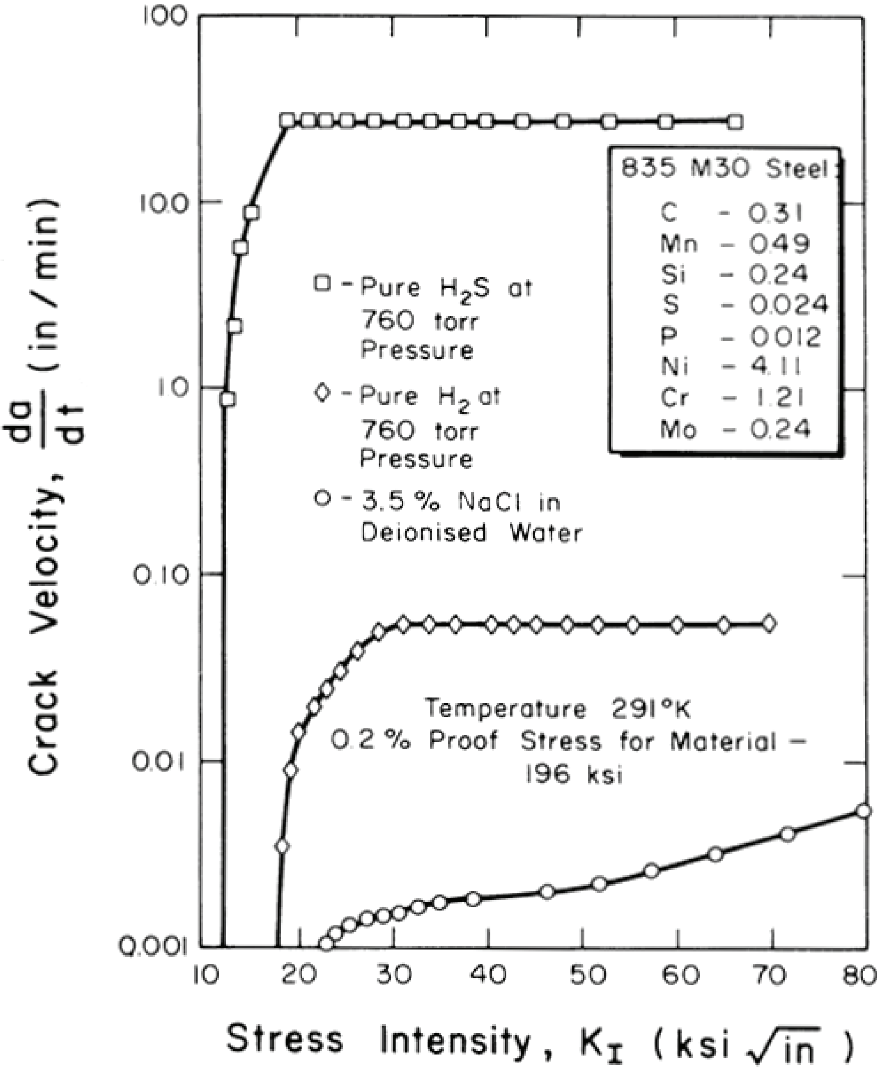

FIGURE K.2 The stress intensity dependence of sub-critical crack growth rate produced in a tempered martensitic steel exposed in three separate environments that produce atomic hydrogen at the crack tip during stressing under slow rising CMOD. SOURCE: G.E. Kerns, M.T. Wang, and R.W. Staehle, "Stress Corrosion Cracking and Hydrogen Embrittlement in High Strength Steels," pp. 700-735 in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys* (R.W. Staehle, ed.), NACE International, Houston, Tex., 1973. © NACE International 2012.

concentration is likely greater. This extreme susceptibility is not encountered at lower strength levels as shown in Figure K.2 but immunity is not observed.

It is notable that while at very high strength levels, maraging steels are also susceptible to stress corrosion cracking in seawater, they are less susceptible than quenched and tempered 4340 steel at the same strength level due to differences in the microstructure.[18,19] Vacuum melted, quenched, and tempered steels with low amounts of trace elements compare even more favorably with maraging steels in resisting stress corrosion at high-strength levels. For example, modern clean UHSS such as Aermet 100^{TM} do not crack from prior austenite grain boundaries but instead exhibit cracking at lath interfaces.[20] Unfortunately the drop in toughness with hydrogen content even with a carefully controlled microstructure is still significant.

Dependence on Applied Potential

Electrode potential is of great importance in the behavior of steels because these alloys are often coated with a sacrificial anodic material such as zinc for corrosion protection which creates a galvanic couple and/or are cathodically protected by either sacrificial anodes or impressed current cathodic protection systems. One of the key factors in the type and severity of hydrogen induced cracking of high strength steels is the electrode potential. This is shown in Figures 2.10 through 2.12.[21,22] Brown first reported the effect of applied potential on crack growth rate in high strength steels.[23] Crack growth rate was found to increase at both highly anodic and highly cathodic applied potentials with a reduced susceptibility at intermediate

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[18] D.G. Enos and J.R. Scully, A critical-strain criterion for hydrogen embrittlement of cold-drawn, ultrafine pearlitic steel, *Metallurgical and Materials Transactions A* 33:1151-1166, 2002.

[19] R.N. Parkins, A.J. Markworth, J.H. Holbrook, and R.R. Fessler, Hydrogen gas evolution from cathodically protected surfaces, Paper 47 in *Corrosion 84*, National Association of Corrosion Engineers, Houston, Tex., 1984.

[20] Y. Lee and R.P. Gangloff, Measurement and modeling of hydrogen environment-assisted cracking of ultra-high-strength steel, *Metallurgical and Materials Transactions A* 38:2174-2190, 2007.

[21] B.A. Kehler and J.R. Scully, Predicting the effect of applied potential on crack tip hydrogen concentration in low-alloy martensitic steels, *Corrosion* 64:465-477, 2008.

[22] B.F. Brown, *Stress-Corrosion Cracking in High Strength Steels and in Titanium and Aluminum Alloys*, Naval Research Laboratory, Washington, D.C., 1972, p. 3.

[23] C.T. Fujii, "Stress-Corrosion Cracking Properties of 17-4 PH Steel," p. 430 in *Stress Corrosion—New Approaches: A Symposium Presented at the Seventy-Eighth Annual Meeting of the American Society for Testing and Materials* (H.L. Craig, ed.), American Society for Testing and Materials, Philadelphia, Pa., 1976.

potentials.[24] This behavior was seen in K92580 and 300M and ESR 4340 steels.[25,26] PH 15-5 stainless steel,[27] PH 13-8,[28] maraging steels,[29] eutectoid cold drawn and heat treated steels,[30] C1045 steel,[31,32] PH 17-4, 9-4-45 and 4340 high strength steels and AISI 1080 steel,[33] and in modern variants of UHSS such as Aermet 100. It is clear that a broad range of different high strength steel alloys exhibit this behavior.

This effect is shown in the potential dependent fracture toughness data in Figure K.3. HEAC susceptibility is strongly potential dependent on both cathodic and anodic potentials in many UHSS alloys; applied potential (E_{App}) affects both threshold stress intensity (K_{TH}) and stage-II subcritical crack growth rate (da/dt_{II}). Figure 2.11 shows da/dt_{II} in AerMet® 100 as a function of E_{App} in 0.6 M NaCl and the open circuit potential for various coatings in chloride solutions. The root cause is the diffusible hydrogen concentration at the crack tip developed as a function of external applied potential and crack chemistry as examined and modeled by Turnbull and modeled/predicted by Kehler.

Figure K.4 also indicates the predicted diffusible hydrogen concentration at the crack tip as a function of applied potential. The cause of HE is the establishment of a high $C_{H,diff}$ at the crack tip governed by chemical and electrochemical factors, as well as crack tip metallurgy, where $C_{H,diff}$ is the diffusible hydrogen content or

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[24] B.F. Brown, "Stress Corrosion Cracking of High Strength Steels," p. 471 in *The Theory of Stress Corrosion Cracking in Alloys* (J.C. Scully, ed.), North Atlantic Treaty Organization, Scientific Affairs Division, Brussels, Belgium, 1971.

[25] E.U. Lee, H. Sanders, and B. Sarkar, "Stress Corrosion Cracking of High Strength Steels," *Proceedings of the Tri-Service Conference on Corrosion* (J.V. Kelley and B. Placzankis, eds), U.S. Army Research Laboratory, Aberdeen, Md., 2000.

[26] P.F. Buckley, R.H. Brown, B. Placzankis, and J. Beatty, Paper 547 in *Corrosion 94*, National Association of Corrosion Engineers, Houston, Tex., 2004.

[27] K.B. Das, W.G. Smith, R.W. Finger, and J.N. Master, "Hydrogen Embrittlement of Cathodically Protected 15-5PH Stainless Steel," in *Proceedings of the Second International Congress of Hydrogen in Metals*, International Association of Hydrogen Energy, Pergamon, Paris, France, 1977.

[28] P.S. Tyler, M. Levy, and L. Raymond, Investigation of the conditions for crack propagation and arrest under cathodic polarization by rising step load bend testing, *Corrosion* 47:82-87, 1991.

[29] D.P. Dautovich and S. Floreen, "The Stress Corrosion and Hydrogen Embrittlement Behavior of Maraging Steels," pp. 1210, 1215 in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys* (R.W. Staehle, ed.), National Association of Corrosion Engineers, Houston, Tex., 1977.

[30] V.S. Galvez, L. Caballero, and M. Elices, "The Effect of Strain Rate on the Stress Corrosion Cracking of Steels for Prestressing Concrete," p. 603 in *Laboratory Corrosion Tests and Standards: A Symposium by ASTM Committee G-1 on Corrosion of Metals* (G.S. Haynes and R. Baboian, eds.), ASTM, Philadelphia, Pa,, 1985.

[31] C.F. Barth, E.A. Steigerwald, and A.R. Trojano, Hydrogen permeability and delayed failure of polarized martenstic steels, *Corrosion* 25:353, 1969.

[32] C.F. Barth and A.R. Troiano, Cathodic protection and hydrogen in stress corrosion cracking, *Corrosion* 28:259, 1972.

[33] R.M. Schroeder and I.L. Muller, Stress corrosion cracking and hydrogen embrittlement susceptibility of an eutectoid steel employed in prestressed concrete, *Corrosion Science* 45:1969-1983, 2003.

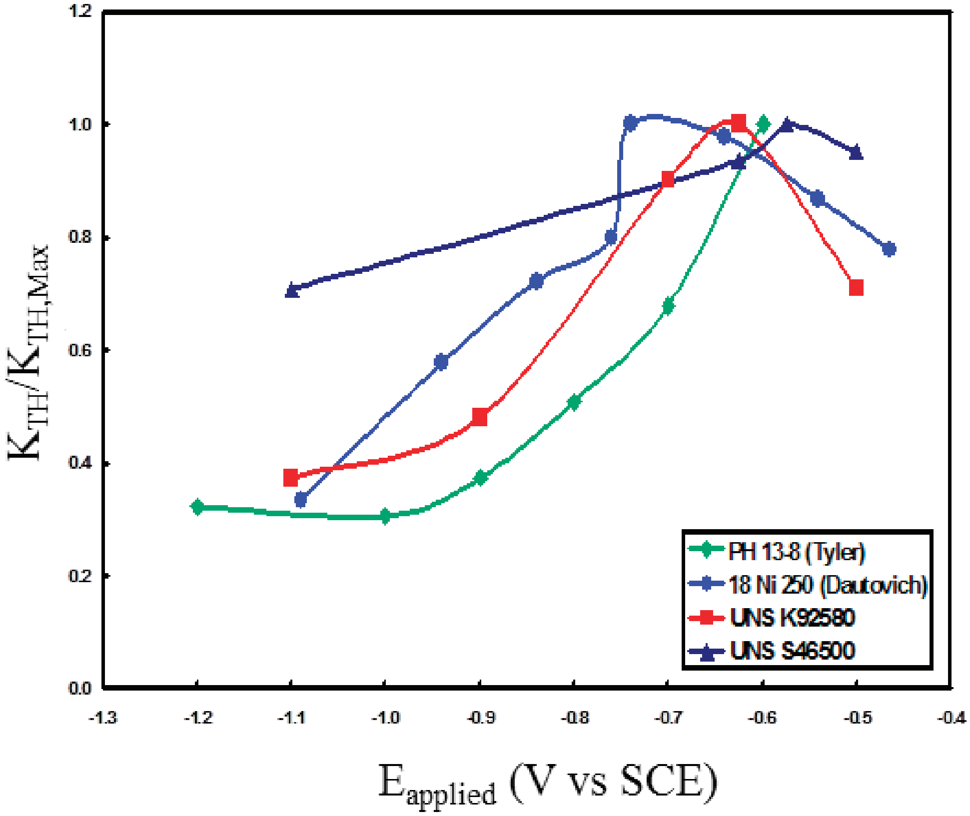

FIGURE K.3 Normalized K_{TH} versus $E_{applied}$ for four high strength steels (PH 13-8, 18 Ni 250, UNS K92580, and UNS S46500. © NACE International 2012. SOURCE: Kehler, CORROSION Soruce data: [Dautovich, 1977 #5; Tyler, 1991 #96; Lee, 2006 #144] b) K_{TH} versus $E_{applied}$ for UNS K92580 showing scanning electron images of the fracture surfaces for applied potentials of $-1.1\ V_{SCE}$ and $-0.5\ V_{SCE}$, respectively. [Lee, 2006 #144]. From B. Kehler and J.R. Scully, after Y. Lee, and R.P. Gangloff, Measurement and modeling of hydrogen environment-assisted cracking of ultra-high-strength steel, *Metallurgical and Materials Transactions A* 38A:2174, 2007.

concentration (moles/cm^3 or wt. ppm) consisting of the sum of both the perfect lattice hydrogen for a given hydrogen fugacity obtained through the cathodic hydrogen overpotential and the hydrogen concentration associated with weak and intermediate reversible hydrogen traps. The hydrogen occluded at these traps is in equilibrium with hydrogen in lattice sites. The diffusible hydrogen is mobile and in general can repartition to the tensile tri-axial stress field of the crack tip.

Figure K.5 details the strong effect of hydrogen concentration on threshold stress intensity in H_2 gas and in aqueous solutions. Unlike the IHE situation that involves a fixed amount of hydrogen in a closed system, a continuous supply of

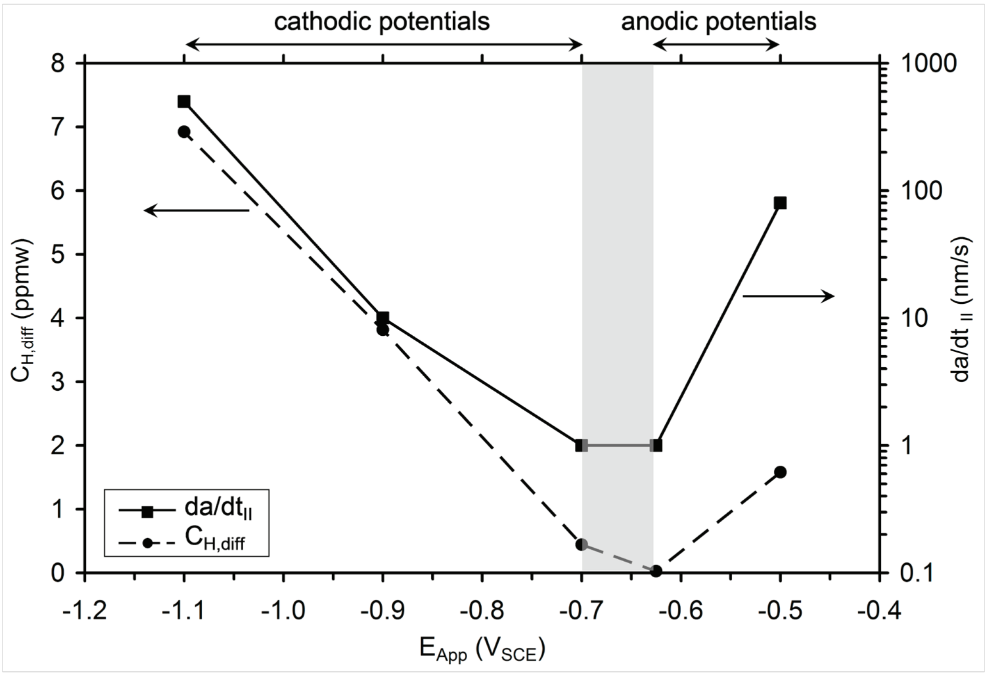

FIGURE K.4 The dependence of stage-II crack growth rate (da/dt$_{II}$) and diffusible hydrogen concentration ($C_{H,diff}$) on the applied potential (E_{App}) for AerMet®100 in 0.6 M NaCl. SOURCE: Data from Y. Lee and R.P. Gangloff, Measurement and modeling of hydrogen environment-assisted cracking of ultra-high-strength steel, *Metallurgical and Materials Transactions A* 38A:2174, 2007.

hydrogen at the crack tip in such an open system presents a greater challenge to mitigation of TG HEE. Thus, degradation of fracture toughness is a strong function of applied electrode potential which enables the continual supply of hydrogen in marine environments.

Under cathodic polarization, the crack becomes increasingly alkaline relative to the bulk as a result of proton discharge and water reduction. In addition, the crack tip potential is shifted to more positive potentials due to ohmic voltage drop. Therefore, the overpotential for hydrogen production may actually be smaller at the crack tip than on the boldly exposed surfaces in the cathodic case. Thus, the hydrogen overpotential is lower and the pH is high and hydrogen uptake is lower. This is confirmed through visual inspection of the fracture surface. When the overpotential for hydrogen production is greater on the bulk surfaces than at the crack tip, the crack grows faster on the sample edges than at mid thickness. That is, the sample edge corresponds to higher values of $C^{H,diff}$, while the sample center corresponds to lower $C^{H,diff}$ values. Therefore, cathodic polarization may lead to greater hydrogen uptake at less occluded sites, with faster near surface

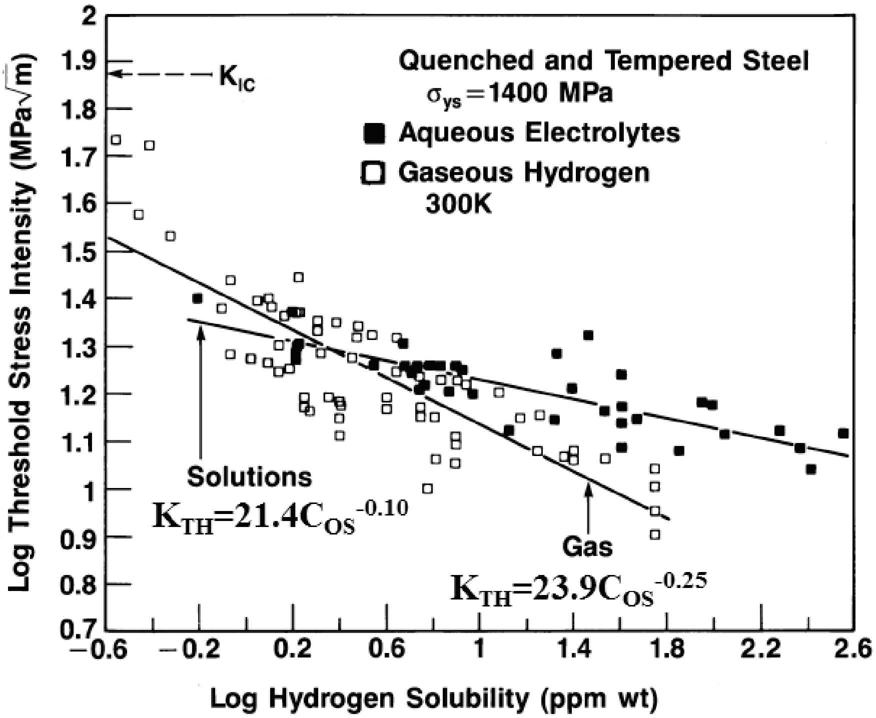

FIGURE K.5 Threshold stress intensity versus hydrogen solubility determined through permeation measurements for high-strength steel exposed to various electrolytes and gaseous hydrogen. SOURCE: R.P. Gangloff, "Corrosion Prevention and Control" pp. 64-111 in *33rd Sagamore Army Materials Research Conference*, (M. Levy and S. Isserow, eds.), U.S. Army Laboratory Command, Watertown, Mass., 1986.

cracking even though the stress intensity and hydrostatic stress may be lower at such locations. It should be further noted that anodic potential produce hydrogen embrittlement in high strength materials and not a switch in mechanism towards stress corrosion cracking by anodic dissolution.

It is readily shown that acidification and crack tip hydrogen uptake occurs in anodically polarized high strength steels. When normalizing to hydrogen content such as $C_{H,diff}$, it can be seen that in cases of both anodic and cathodic polarization cracking is similar. Also, hydrogen absorption characteristics could be markedly different on an actively corroding or plastically strained surfaces compared to unstrained metal in corroded condition or covered with calcareous deposits.[34,35]

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[34] J.R. Scully, M.J. Cieslak, and J.A. Vandenavyle, Hydrogen embrittlement behavior of palladium modified PH 13-8 Mo stainless steel as a function of age hardening, *Scripta Metallurgica et Materialia* 31:125-130, 1994.

[35] J.R. Scully and P.J. Moran, The influence of strain on hydrogen entry and transport in a high strength steel in sodium chloride solution, *Journal of the Electrochemical Society* 135:1337-1348, 1988.

The above analysis points out that the level of cathodic or anodic polarization, affected by impressed current cathodic protection level, galvanic coupling material or corrosion protection coating is extremely important. Consequently, the danger of hydrogen embrittlement must be kept in mind during the application of cathodic protection to alloys, such as martensitic stainless and other high strength steels, known to be susceptible to hydrogen embrittlement. For instance, cathodic protection with zinc is usually more severe than with aluminum, and corrosion protection coatings such as zinc or cadmium or other heavy metals not only can promote hydrogen uptake at crack tips but they enable co-deposition of hydrogen during deposition.

In studies on propagation of stress corrosion cracks in 18 percent nickel maraging steel Peterson and his associates found that when the steels was polarized to a potential of −0.77 V by coupling with a cadmium anode, the stress required for crack propagation in seawater was raised to a value close to that for crack propagation in air. However, when zinc at a potential of about −1.03 V was used as the source of the protective current, the stress value for crack propagation was reduced considerably below that for crack propagation in the absence of cathodic protection. This result suggests that caution should be exercised in applying cathodic protection in seawater to high strength steels of this type.

Moreover, UHSS components are usually coated for corrosion protection from environmental factors such as high humidity, changing ambient temperatures, salt spray, processing and operational chemicals. Sometimes these coatings may function as H permeation barriers. However, in operational service, coated components are seldom free of scratches that expose the bare steel to a galvanic couple potential. Sacrificial coatings cathodically polarize steel at the scratch producing hydrogen that could be absorbed at these sites. Low alloy UHSS suffer from hydrogen environment assisted cracking which can limit their use in marine environments.

FAILURE OF NICKEL BASE ALLOYS

There are at least eight nickel alloy systems of major commercial importance. These include pure nickel, nickel–copper alloys, nickel-chromium alloys, nickel-iron alloys, nickel–molybdenum alloys, nickel-chromium-molybdenum alloys, Ni-Cr-Mo-Fe-Cu alloys, and nickel based superalloys.[36,37,38] Superalloys contain up to a dozen alloying elements. Many alloys were developed for high strength at high

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[36] Ibid.

[37] K.G. Budinski and M.K. Budinski, *Engineering Materials: Properties and Selection*, 8th edition, Pearson, Upper Saddle River, N.J., 2005.

[38] J. Kolts, "Environment Embrittlement of Nickel-Base Alloys," p. 647 in *ASM Metals Handbook*, ASM International, Metals Park, Ohio, 1987.

temperature and low thermal expansion, but have also been adapted for seawater use due to good corrosion resistance. Some nickel base alloys are age hardenable while none respond to allotropic transformation type quench hardening. Nickel and copper are completely soluble in each other (Monels) and nickel exhibits good solubility with iron, chromium, manganese. Alloy 718 and Monel K-500 are two examples of alloys often used as high strength fasteners in seawater. Each alloy is based on a face-centered cubic austenitic matrix with good intrinsic corrosion resistance and often procured in the form of various studs and bolts in the solution annealed, cold worked and aged conditions.

Strength levels vary by alloy type and heat treatment but are 150 ksi (1034 MPa) yield strength and 180 ksi (1275 MPa) ultimate tensile strength with a Rockwell hardness of minimum R_C 35-36 for aged 718. Cold work, annealing temperature and age hardening are crucial features of each alloy that affect hydrogen uptake, trapping, strength, and fracture resistance. For instance, the time-temperature-transformation curve for Alloy 718 illustrates how aging is performed after annealing. The annealing temperature is critical in that a grain boundary phase known as δ, Ni_3Nb, can be formed if annealed below a certain temperature. The alloy is aged hardened by formation of γ' and γ" in the metallic matrix. Monel Alloy K-500 (UNS N05500) is a precipitation-hardenable nickel-copper alloy that combines the corrosion resistance of Monel Alloy 400 with greater strength and hardness. It is strengthened by a combination of cold work and precipitation age hardening to form fine coherent intermetallic $Ni_3(Ti,Al)$ phases.

General HE Susceptibility

Nickel-chromium-iron alloys containing more than about 40 percent nickel are not susceptible to stress corrosion cracking by concentrated chloride solutions such as magnesium chloride. A number of nickel base alloys have been observed to crack in boiling $MgCl_2$, salt brines, seawater, HCl and H_2S environments. These are reviewed in the ASM Metals Handbook, Volume 13, and the references therein.[39]

The principal type of EAC of nickel base alloys in seawater occurs when there is exposure to cathodic protection and hydrogen production. However, lab testing involving cathodic charging, the NACE solution, hydrogen gas, or other hydrogen producing environments can also cause susceptibility. The rule of thumb regarding the notion that hydrogen embrittlement in seawater requires a strength level greater than about 100 ksi (690 MPa) generally applies to nickel based alloys.

The hydrogen embrittlement assisted cracking (HEAC) behavior of Ni-based superalloys in gaseous H_2 and aqueous exposure has been reviewed in detail. The potential severity of this cracking problem is apparent in nickel base alloys such

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[39] *ASM Metals Handbook*, Volume 13, ASM International, Metals Park, Ohio, Table 16.

as Alloy 718.[40] Subcritical environment-assisted cracking in high strength superalloys can be equivalent for gases and electrolytes as long as the dissolved hydrogen concentration is the same. This assumption is justified as the microscopic cracking modes were similar for each environment and involved a mixture of IG and TG slip-plane based cracking. However, occluded-crack chemistry analysis must be considered for exposure in seawater.

Figure K.6 shows that these thresholds are defined by a single function of the crack tip H concentration for alloy 718 stressed in aqueous-acidified chloride solution (•) as well as high pressure H_2 (o). The K_{TH} declines with increasing crack tip H concentration, above 20 ppm and independent of the crack tip environment that produced this H.

Similar data have been developed for solution heat treated and aged Monel K-500.[41] The trend is the same but the details differ and must be understood to evaluate suitability in a given exposure environment. It should be noted that the crack growth rate slows considerably as the applied potential becomes less cathodic. In fact, at −0.7 V the crack growth rate is not detected in a lab test. Nickel-copper alloy bolt failures have also been observed numerous times in age hardened Monel Alloy K-500 (UNS N05500) subjected to normal cathodic polarization when coupled to aluminum anodes in seawater.[42,43] Failures by intergranular cracking have been attributed to hydrogen production, uptake and embrittlement as a result of cathodic polarization and was first attributed to high thread root hardness of HRC 39 due to age hardening after threading. It was recommended that first annealing and then age hardening be conducted after threading to limit hardness below the acceptable hardness (HRC 35) of Monel Alloy K-500 (UNS N05500) recommended as a limit in sour systems. However, additional failures have occurred in roll-threaded Monel Alloy K-500 (UNS N05500) bolts annealed at 980-1050°C, water quenched, and precipitation age hardened at 500-600°C for 16 h producing a Rockwell C hardness of only 25. Embrittlement failures occurred in bolts after about one year under load to about 59 percent of the tensile yield strength and cathodically protected with anode grade aluminum. These failures have continued, and the root cause remains elusive.

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[40] L. Raymond, *Fracture and Stress Corrosion Cracking Resistance of C465 (46 HRC), BioDur 108 (39 HRC), SpT 13-8 (37 HRC), SpT 13-8 (35 HRC), K-Monel 500 (31 HRC), and Zeron 100 (23 HRC)*, LRA Report #CTC'071024, L. Raymond and Associates, Newport Beach, Calif., 2008.

[41] R.P. Gangloff, H.M. Ha, J.T. Burns, and J.R. Scully, *Metallurgical and Materials Transactions A* 45(10):3814-3834, 2012.

[42] K.D. Efird, Failure of Monel® Ni-Cu-Al alloy K-500, *Materials Performance* 24:37-40, 1985.

[43] L.H. Wolfe and M.W. Joosten, Failures of nickel/copper bolts in subsea application, *SPE Production Engineering* 3:382-386, 1988.

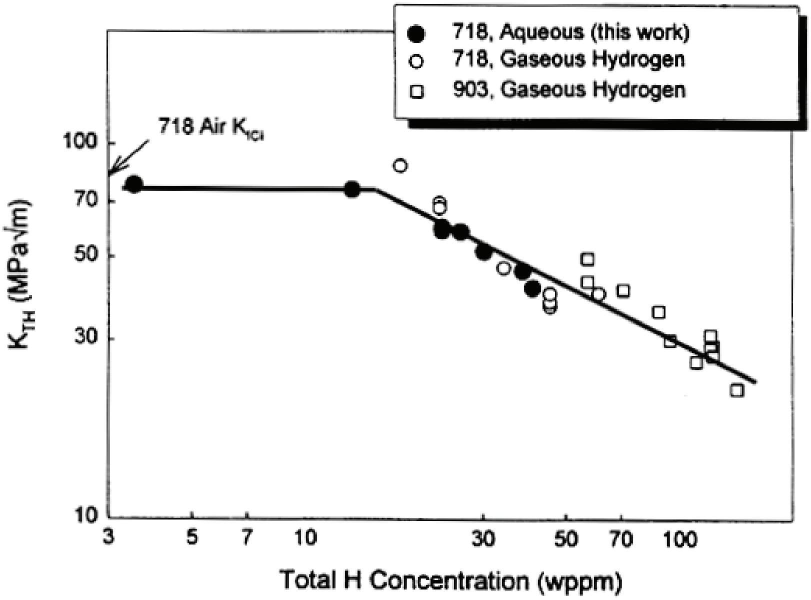

FIGURE K.6 Threshold stress intensity for HEAC in peak aged alloys 718 and 903, stressed in either high pressure H_2 (□,○), or acidified chloride solution with cathodic polarization at –1.0 V_{SCE} (●), *versus* calculated H content produced at the crack tip. H-free superalloys cracked by microvoid processes at high K_{IC}. SOURCE: R.P. Gangloff, "Hydrogen Assisted Cracking of High Strength Alloys," pp. 31-101 in *Comprehensive Structural Integrity* (I. Milne, R.O. Ritchie and B. Karihaloo, editors-in-chief; J. Petit and P. Scott, eds.), Volume 6, Elsevier Science, New York, N.Y., 2003. Data from J.A. Lillard, "Environment Assisted Cracking of a Nickel-Based Superalloy in Hydrogen-Producing Solutions," Ph.D. Dissertation, University of Virginia, Charlottesville, Va., 1998.

Dependence on Applied Potential

Hydrogen embrittlement under cathodic polarization in seawater follows a similar trend to steels and has been investigated for Alloy 718 (55Ni-20Fe-18Cr-5Nb-2(Al+Ti), (UNS N07718), and Monel K-500 (63Ni-27Cu-3Al-0.5Ti). An example of the combination of hydrogen concentration versus applied cathodic potential to predict K_{th} has been reported. The C_H versus E_{app} data was used to predict K_{th} and could also be adjusted to take into account the IR drop and alkalinity of cathodic crack tips leading to the family of curves relating hydrogen concentration to potential for various recess depths labeled as 0, 10, 5, and 100 mm in a rescaled recess with a 1 mm gap as shown in Figure K.7. K_{th} can then be predicted as a function of crack depth and applied potential in seawater for aged Alloy 718.

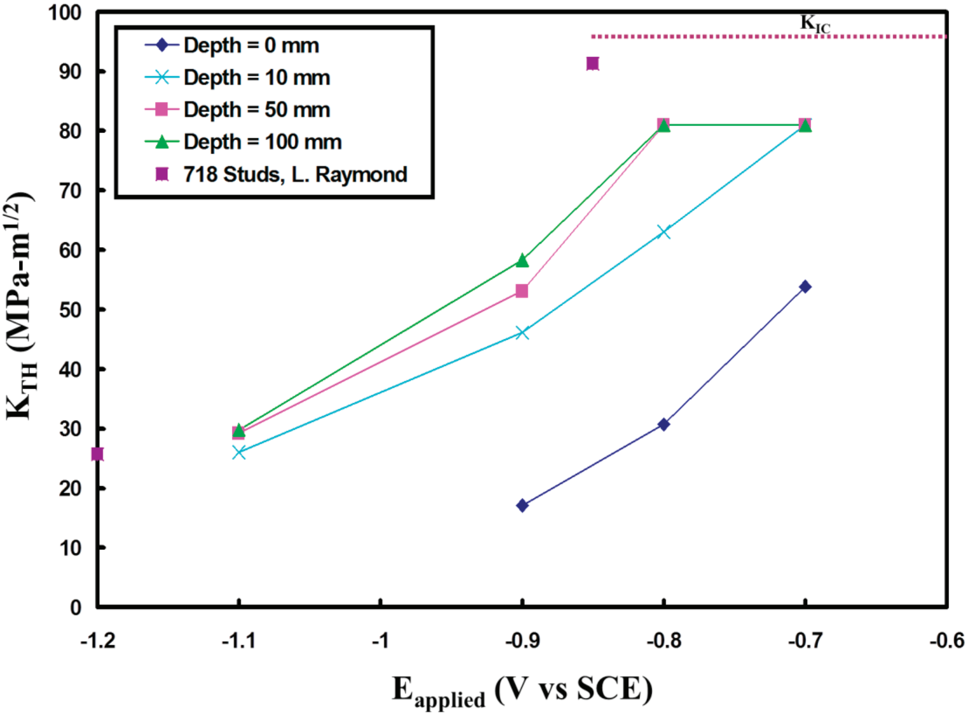

FIGURE K.7 Predicted K_{TH} as a function of crack depth and applied potential for aged alloy 718 based on the empirical expression by Grandle and Gangloff. The experimental data of Raymond are included for comparison. SOURCE: Data from Scully, unpublished following the methods of Kehler utilized for steel.

The predicted K_{th} within a crevice matches experimental data. K_{th} decreases as the cathodic potential decrease. The results for Monel K-500 show a similar trend and increased hydrogen production and uptake is seen at more cathodic potentials. Other high strength nickel base alloys are expected to display the same trends and is regulated by the details of the crack or occlude site geometry. This thinking can be applied to cracks and threaded geometries with confined spaces.

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Committee Biographies

ROBERT SCHAFRIK, *Chair*, is a professor in the Industrial, Manufacturing, and Systems Engineering Department at the University of Texas, Arlington, beginning in January 2018; he is currently focused on additive manufacturing. He retired in 2014 as general manager of the Materials and Process Engineering Department at GE Aviation. After retiring from GE Aviation, he served as a consultant on advanced materials and processes. While at GE Aviation, he was responsible for developing advanced materials and processes used in GE's aeronautical turbine engines and their marine and industrial derivatives. He oversaw materials application engineering activities supporting GE Aviation's global design engineering, manufacturing, and field support activities. He also operated a state-of-the-art in-house laboratory for advanced materials development, characterization, and failure analysis. Prior to joining GE in 1997, he served in two concurrent positions within the National Research Council, which he joined in 1991: staff director of the National Materials Advisory Board and staff director of the Board on Manufacturing and Engineering Design. Under his direction, 33 final reports for studies were issued that addressed significant national issues in materials and manufacturing. Dr. Schafrik also served in the U.S. Air Force in a variety of R&D and system acquisition capacities; he retired as a Lieutenant Colonel. Dr. Schafrik is a member of the National Academy of Engineering (NAE), and he recently served as member of the Air Force Scientific Advisory Board (2009-2013). He received his Ph.D. in metallurgical engineering from Ohio State University in 1979, an M.S. in information systems from George Mason University in 1996, an M.S. in aerospace engineering from the Air Force Institute of Technology in 1974, and a B.S. in metallurgy from Case Western Reserve University in 1967.

ROBERT POHANKA, *Vice Chair*, was the director (retired) at National Nanotechnology Coordination Office. He received his Ph.D. from Pennsylvania State University in 1972. He served from 2012 until 2014 as the director of the National Nanotechnology Coordination Office (NNCO) within the National Science and Technology Council, Office of Science and Technology Policy, Executive Office of the President. From January 2009 to March 2012, he served as the research director for the Hybrid Complex Warfare Sciences within the Expeditionary Maneuver Warfare and Combating Terrorism Science and Technology Department, Office of Naval Research (ONR). Dr. Pohanka served as the director of the Defense Venture Catalyst Initiative (DeVenCI), on assignment from ONR to the Office of the Under Secretary of Defense, Science and Technology. He led and directed the strategy for finding private sector technologies, developed independently of the Department of Defense (DoD), and transitioned them to DoD Research, Development, and Acquisition. From June 2004 to May 2006, he was head of the Engineering Materials and Physical Sciences Department at ONR. During this period, Dr. Pohanka also served as director for the Materials Science and Technology Division and as director for the Ship, Hull, Mechanical, and Electrical Division. Dr. Pohanka is a recipient of the U.S.-Japan Electroceramic Bridge Building Award (2005), presented the E.F. Osborn Memorial Lecture (2001), selected as a Senior Executive Service Meritorious Executive (2000), and Centennial Fellow from Pennsylvania State University (1996). He is a fellow of the American Ceramic Society (ACerS) and a life member of the American Physical Society. He has chaired international symposia for the ACerS, the Institute of Electrical and Electronics Engineers, SPIE, and Materials Research Society.

CLYDE L. BRIANT is a professor of engineering at Brown University, where he was the former Otis E. Randall University Professor. He received his Ph.D. in materials science from Columbia University in 1974 and was a post-doctoral researcher at the University of Pennsylvania from 1974 to 1976. From 2003 to 2006, he served as dean of engineering at Brown University, and from 2006 to 2013 he served as vice president for research. His primary research interest has been in the area of structural materials and, more recently, has begun to study engineering design and the evolution of innovative technological systems. In engineering education, he seeks to provide an education for the public engineer that is an engineer who is extremely well-versed technically and who is also concerned about the societal impact and public understanding of engineering achievements. He is a member of the National Academy of Engineering.

WILLARD CAPDEVIELLE is a professional petroleum engineer registered in Texas and Louisiana. He is a semi-retired upstream oil and gas professional with over 40 years of experience. Mr. Capdevielle has served in many technical and managerial roles in Mobil, Exxon-Mobil (contractor), and Hess Corporation. He has spent approximately one-fourth of his career in upstream technology centers, one-fourth of his career in operations and operations support, and one-fourth of his career in major capital project support. Mr. Capdevielle has spent significant time working on offshore drilling rigs and production platforms, including 4 years as an offshore installation manager on one of Mobil's North Sea platforms. He has been a member of the Society of Petroleum Engineers for over 45 years, having served as a chapter officer, on conference committees, on one of the forum committees, and as a peer reviewer for technical papers.

HOMERO CASTANEDA is an associate professor and the director at the National Corrosion and Materials Reliability Center within Texas A&M University (TAMU). He received his bachelors in chemical metallurgical engineering and his masters in materials science from the National Autonomous University of Mexico in 1994 and 1997, respectively. He then got his Ph.D. in materials science and engineering from Pennsylvania State University in 2001. Dr. Castaneda has 15 years of experience using electrochemical and nondestructive techniques to monitor interfacial phenomena in materials and theoretical modeling of corrosion processes for different industries. He has been a principal investigator (PI) for multiple projects on corrosion science and engineering for the Department of Energy (DOE), DoD, the Department of Transportation, and several companies. Before joining TAMU, he worked for 5 years at the University of Akron (2011-2015) as an assistant professor and before that at Battelle Memorial Institute as a senior scientist (2006-2010) in the Advanced Materials and Pipelines Center in Columbus, Ohio. Before Battelle, he was the technical director of Corrosion, Materials and Pipelines in the Mexican Petroleum Institute for 5 years. He has authored and co-authored over 70 peer-reviewed papers in the areas of corrosion science and engineering, coatings degradation and reliability, materials characterization, and electrochemical impedance spectroscopy. He has nine patents and copyrights.

NANCY COOKE is a professor of human systems engineering and the science director of the Cognitive Engineering Research Institute at Arizona State University. Dr. Cooke received a B.A. in psychology from George Mason University and received her M.A. and Ph.D. in cognitive psychology in 1983 and 1987, respectively, from New Mexico State University. Currently, she supervises post-doctoral, graduate and undergraduate research on team cognition with applications in design and training for military command-and-control systems, emergency response, medical systems, cyber security systems, and remotely piloted aircraft systems. In particular, Dr. Cooke specializes in the development, application, and evaluation of methodologies to elicit and assess individual and team cognition. Her most recent work includes the development and validation of methods to measure team coordination, team communication, and team situation awareness and research on translating the science of teams to human-robot teaming. Dr. Cooke was editor-in-chief of *Human Factors* from 2005 to 2009 and is the 2006 recipient of the Human Factors and Ergonomics Society's O. Keith Hansen Outreach Award. Dr. Cooke has served as a member of the Board on Human-Systems Integration (2007-2016) and chaired the board from 2012-2016. She served the National Academies of Sciences, Engineering, and Medicine as a member of the panel on Human Factors Science at the Army Research Laboratory, as well as two study panels on Human-System Design Support for Changing Technology (2005-2007) and the Safety and Security of Spent Nuclear Fuel Storage (2004-2005). Dr. Cooke chaired the study panel on the Science of Team Science (2013-2014).

THOMAS W. EAGAR is a professor of materials engineering and engineering management at the Massachusetts Institute of Technology. Dr. Eagar's past research has involved welding and joining, but an increasing amount of work involves other aspects of materials manufacturing and engineering systems, such as product design and development, alternate manufacturing processes, manufacturing management, materials systems analysis, selection of materials, and failure analysis. Recent research includes fundamentals of transient liquid phase diffusion bonding, control of melting during gas metal arc welding, effects of welding fume on health of workers, stresses generated during joining of dissimilar materials, improved methods of dimensional analysis of materials processing, design, forming and assembly of automotive body components, and methods for successful product design and development. Dr. Eagar is a member of the NAE.

L. BRUN HILBERT, JR., is a principal engineer at Exponent. He received his bachelor's degree in mathematics and his master's degree in mechanical engineering from the University of New Orleans in 1979 and 1981, respectively; he received his Ph.D. in materials science and mineral engineering from the University of California, Berkeley, in 1995. Dr. Hilbert has been consulting at Exponent since 1996 in the fields of mechanical and petroleum engineering, with special applications to engineering mechanics and geomechanics. He has worked in the petroleum exploration and production industry for 30 years. Dr. Hilbert has expertise in stress analysis, solid mechanics, fluid mechanics, heat transfer, and structural component design. In the area of petroleum engineering, he has expertise in oil and gas well design and integrity, hydraulic fracturing, well production and wellhead equipment, well stability and sand production, well stimulation, drilling mechanics, petroleum rock mechanics, reservoir geomechanics, fixed and floating offshore platforms, and gas and liquid hydrocarbon storage in solution-mined salt caverns and hydrocarbon formations. In the area of geomechanics, Dr. Hilbert has expertise in evaluating the structural integrity of oil and gas wells in compacting or deforming reservoir rocks, in the stability of underground storage structures and nuclear waste repositories and he assists clients in failure analysis involving soil-structure interaction, including pipelines. He has highly specialized expertise in the structural integrity and leak resistance of the threaded connections used to join high-pressure pipe. Dr. Hilbert has conducted failure analyses of steel, rubber, and plastic structures. Prior to joining Exponent, he was employed as an engineering specialist for Exxon Production Research Company, where he performed research and taught courses in Well Completions and Workers in the Middle East, Southeast Asia, Australia, and North America. Dr. Hilbert has been selected as a Society of Petroleum Engineers Distinguished Lecturer for 2015-2016.

DEREK J. HORTON is a materials research engineer at the Navy Research Laboratory. He has worked with Naval materials compatibility programs for subsea applications covering nickel-based, cobalt-based superalloys, titanium, stainless steels, and other materials for use as high-strength fasteners and structural materials. Dr. Horton also has additional experience with fracture mechanics based investigation of high-strength fasteners materials, greater than 175 KSI yield, for subsea applications. He also served on the Railgun Corrosion Working Group whose purpose was to provide guidance for high-strength material use in novel marine atmospheric and alternate immersion environments as well as a basic research study of optimizing the composition of titanium fastener materials to reduce galvanic corrosion in airframe aluminum alloys. Prior to being a materials research engineer, Dr. Horton was a research engineer in the Navy's Vision Point Systems group where he studied environmental effects on fracture, including hydrogen embrittlement on a series of alloy systems including stainless steels, Ni-based superalloys, and titanium, including several forensic analyses of material failures, including high-strength environmental fracture induced failures. As a research associate at University of Virginia, he conducted a hydrogen embrittlement-based failure analysis of line pipe steel used in ocean water, including electrochemical measurements of hydrogen diffusion, hydrogen concentration, and in situ measurements of hydrogen embrittlement, and he studied Cu-based antimicrobial alloys, including E. coli kill rate, cation release, and resistance to tarnishing.

DAVID W. JOHNSON, JR., is a senior advisor at Stevens Institute of Technology and an editor-in-chief of the *Journal of the American Ceramic Society*. He earned a B.S. in ceramic technology and a Ph.D. in ceramic science from the Pennsylvania State University in 1964 and 1968 respectively. Dr. Johnson is retired from Bell Laboratories where he served as director of the applied materials research department. He is a member of the NAE, an ACerS fellow, a past chair and member of the Electronics Division, a member of the Basic Science and Glass and Optical Materials divisions and the National Institute of Ceramic Engineers. Dr. Johnson served as president of ACerS in 1994-1995 and is the recipient of numerous awards, including Distinguished Life Membership in ACerS.

DAVID K. MATLOCK is a university emeritus professor at Colorado School of Mines (CSM). He received his bachelors in engineering science from the University of Texas, Austin, in 1968 and his masters and Ph.D. in materials science and in engineering from Stanford University in 1970 and 1972, respectively. He joined the CSM faculty in 1972 as a member of the physical and mechanical metallurgy program. Dr. Matlock is a registered professional engineer in Colorado. From 1981 until his retirement in 2013, he held the Armco Foundation Fogarty Professorship at CSM. He is one of the co-founders of the Advanced Steel Processing and Products Research Center, an industry-university cooperative research center established at CSM in 1984. Dr. Matlock served as center director from 1993 until his retirement in May 2013. In retirement, he continues to be an active participant in all center operations. At CSM, Dr. Matlock has taught courses in mechanical properties of materials, fracture and fatigue, metallurgical failure analysis, and strengthening mechanisms in metals. He continues active in research in a variety of metallurgy programs which emphasize both fundamental and applied studies. Some of his current programs include deformation behavior and formability of steel, including coated sheet products; evaluation of the deformation behavior at interfaces in forming operations; and the analysis of fracture toughness in new bar and forging steels. In addition to his continuing activities at CSM, Dr. Matlock is currently a member of the technical management team of Lightweight Innovations for Tomorrow (LIFT) and is a co-leader of the Thermo-Mechanical Processing (TMP) Pillar, one of the six technology pillars on which LIFT is based. LIFT is a public-private partnership operated by the American Lightweight Materials Manufacturing Innovation Institute and is one of the National Network of Manufacturing Institutes established by the federal government. Dr. Matlock is a member of the NAE.

JYOTIRMOY MAZUMDER is the Robert H. Lurie Professor of Engineering at University of Michigan. He has a D.I.C. in process metallurgy from Imperial College, 1978 and a Ph.D. in process metallurgy from Imperial College, 1978, and a B.E. in metallurgical engineering from Calcutta University, 1972. He is interested in transforming the field of materials processing by laser from a technological art to scientifically based engineering; laser aided manufacturing; atom to application; technical approach including on-line optical diagnostics, transport phenomena modeling, non-equilibrium synthesis of materials with tailored properties, and their evaluation and characterization. Some of his honors and awards are as follows: Distinguished University Innovator, Office of the Vice President for Research, 2012; member, NAE, 2012; Thomas A. Edison Patent Award, American Society of Mechanical Engineers (ASME), 2010; fellow, ASME, 2008; 22nd Arthur L. Schawlow Award, Laser Institute of America, 2003; and 2001 Inventor Recognition, UM Technology Transfer, Celebrate Invention, 2001.

ROGER L. McCARTHY is a consultant at McCarthy Engineering. He received his bachelors in mechanical engineering from the University of Michigan in 1972, and his Ph.D. in mechanical engineering from the Massachusetts Institute of Technology in 1977. Dr. McCarthy specializes in mechanical, machine, and mechanism design analysis, including issues related to fabrication, manufacturing, fire and explosion, warnings, risk analysis, and hazards evaluation. His research has focused on the safety and risk analysis of mechanical designs, and the engineering of the man/machine interface, particularly on issues related to information transfer, such as on-product warnings. He also has experience in the intellectual property issues associates with these areas. Dr. McCarthy has investigated some of the major disasters in modern times that were precipitated by the failure of a bolted connection, so as the collapse of the Hyatt Walkways in Kansas City that killed 116, or the steering gear failure on the Amoco Cadiz that ultimately led to its grounding and loss. Dr. McCarthy is the founder and owner of McCarthy Engineering. He serves on the Board of Shui on Land (SOL), Ltd., which is publicly traded (stock code 0272) on the Hong Kong Exchange. SOL won the Hong Kong Corporate Governance Excellence Award in 2007. Dr. McCarthy a member of the NAE.

JOHN R. SCULLY is the interim department chair, the Charles Henderson Chaired Professor of Materials Science and Engineering, and co-director for Center for Electrochemical Science and Engineering at University of Virginia (UVa). He received his bachelors, masters, and Ph.D. in materials science and engineering from Johns Hopkins University in 1980, 1982, and 1987, respectively. He had appointments with the Naval Ship R&D center and Sandia National Laboratories prior to joining the faculty at UVa. Dr. Scully's work is closely linked to technological advancements that improve the standards of living, safety, and the quality of life. His primary research interest is to understand the relationships between a material's structure and composition and properties related to environmental degradation, aging and life prediction. He is technical editor-in-chief of *Corrosion*, the journal of science and engineering. Technical focus includes most forms of corrosion and environment assisted cracking in numerous environments including seawater focusing on a wide variety of materials ranging from high-strength steels and precipitation aged hardened alloys to metallic glasses and high-entropy alloys. Dr. Scully has served on numerous government review boards and for industries concerned with materials reliability, aging, and failure, including either spent nuclear fuel engineered waste canisters, aircraft, and bolt failures for five different countries.

POL D. SPANOS is the Lewis B. Ryon Professor of Mechanical Engineering and Materials Science at Rice University. He received his M.S. in civil engineering in 1974 and Ph.D. in applied mechanics from the California Institute of Technology in 1976. Dr. Spanos's research efforts focus on the dynamics and vibrations of structural and mechanical systems under a variety of loads. He develops primarily analytic and numerical methods that often require advanced scientific computation packages and supercomputers. He is a fellow of the American Academy of Mechanics, the American Society of Civil Engineers (ASCE), the ASME, and the Alexander von Humboldt Association of America. He is a member (by invitation) of the Earthquake Engineering Research Institute, the International Association for Structural Safety and Reliability, the American Society of Engineering Education, and the American Association for the Advancement of Science. He is a corresponding member of the National Academy of Greece (Academy of Athens), a member of Academia Europaea (Academy of Europe), a foreign member of the Indian National Academy of Engineering, and a member of the NAE (USA). He has served, both, as the chair of the ASCE Engineering Mechanics Division and as the chair of the ASME Applied Mechanics Division. He has held distinguished visiting professor positions in numerous prestigious institutions, worldwide. Further, he has served in leadership/mentorship positions for a plethora of diversity enhancing initiatives and organizations.

NEIL G. THOMPSON is senior vice president of Det Norske Veritas (USA) (DNV-GL) and head of the Pipeline Services Department, including the Materials and Corrosion Technology Center (MCTC) located in Dublin, Ohio. Dr. Thompson is a graduate of University of Alabama and Vanderbilt University with a Ph.D. in materials science engineering. He has worked in corrosion and materials research and forensic analysis for over 30 years. He is past president of NACE International and the NACE Foundation. He directs and oversees forensic investigations in a variety of business segments including pipelines, oil and gas, and petrochemical/chemical processing. Dr. Thompson was the project manager for the forensic investigation of the blowout preventer recovered from the Deep Water Horizon drilling rig failure (2010 Gulf oil spill) for the Department of the Interior and Department of Homeland Security Joint Investigation Team and contracted through the Bureau of Ocean Energy Management, Regulation, and Enforcement. Dr. Thompson has directed 32 major research projects and numerous field studies and testing projects examining various aspects of corrosion science, corrosion monitoring, and cathodic protection. He is co-author of *DC Electrochemical Test Methods*, published by NACE Press, and has co-author of over 70 technical publications. A large portion of his research has been in the area of underground corrosion and CP for the pipeline industry with numerous projects performed for the Pipeline Research Council International, the Gas Research Institute, and the Gas Technology Institute.

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Disclosure of Conflict of Interest

In accordance with Section 15 of the Federal Advisory Committee Act, the "Academy shall make its best efforts to ensure that no individual appointed to serve on [a] committee has a conflict of interest that is relevant to the functions to be performed, unless such conflict is promptly and publicly disclosed and the Academy determines that the conflict is unavoidable." A conflict of interest refers to an interest, ordinarily financial, of an individual that could be directly affected by the work of the committee. As specified in the Academy's policy and procedures (http://www.nationalacademies.org/coi/index.html), an objective determination is made for each provisionally appointed committee member whether or not a conflict of interest exists given the facts of the individual's financial and other interests and the task being undertaken by the committee. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

We have concluded that for this committee to accomplish the tasks for which it was established its membership must include among others, at least one person who possesses current industry experience and expertise in the areas of forensic analysis of corrosion and corrosion control for metal alloys in the extreme subsea environments encountered by the fasteners that are the focus of this study.

To meet the need for this expertise and experience, Dr. Neil Thompson is proposed for appointment to the committee even though we have concluded that he has a conflict of interest because he is an employee of a company with financial interests in the oil and gas industry.

Dr. Thompson is senior vice president of Det Norske Veritas (USA) (DNV) and head of the Pipeline Services Department, including the Materials and Corrosion Technology Center, with over 30 years of experience in corrosion and materials research and forensic analysis. He directs and oversees forensic investigations in a variety of business segments, including pipelines, oil and gas (both onshore and offshore), and petrochemical/chemical processing. For example, Dr. Thompson was the project manager for the forensic investigation of the blowout preventer recovered from the Deep Water Horizon drilling rig failure (2010 Gulf oil spill) for the Department of the Interior (DOI) and Department of Homeland Security (DHS) Joint Investigation Team (JIT). He has directed over thirty major research projects and numerous field studies and testing projects examining various aspects of corrosion science, corrosion monitoring, and cathodic protection. Dr. Thompson also has considerable experience in managing research and testing on Strength Nickel Based Alloy Fasteners. Research under his management includes characterizing the resistance of key nickel based alloys to hydrogen embrittlement as a function of metallurgical variables, (ii) evaluating the performance of alternate materials that may be considered for subsea fastener applications and (iii) developing guidelines on use of PH Ni-Based alloys for fasteners in seawater environment and (iv) evaluating fasteners for sensitivity to Hydrogen Induced Stress Cracking (HISC). We believe that Dr. Thompson can serve effectively as a member of the committee and that the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the work.

After an extensive search, we have been unable to find another individual with the equivalent experience and expertise in forensic analysis of corrosion and corrosion control for metal alloys in extreme subsea environments who does not have a similar conflict of interest. Therefore, we have concluded that this potential conflict is unavoidable.