QC-FIT EVALUATION of FASTENERS FAILURES ADDENDUM II

Office of Offshore Regulatory Programs

QC-FIT Report # 006
July 2017

Bureau of Safety and Environmental Enforcement

EXECUTIVE SUMMARY

On October 13, 2015, while conducting initial latch-up blow out preventer (BOP) pressure and function testing on the Garden Banks block 216 Well Number 5 in 1,450 feet of water in the Gulf of Mexico (GOM); the Noble Paul Romano[1] rig was unable to actuate the BOP high pressure blind shear ram (BSR) shear function. After several attempts to actuate the rams, the Noble crew discovered that the failure to operate the BOP BSR actuator was a result of failed actuator fasteners.[2] Upon inspection of the BOP stack on the deck, Hess, Noble, Subsea Solutions and the Original Equipment Manufacturer (OEM) (National Oilwell Varco (NOV)) crew identified six of the eight fasteners fractured on the BOP BSR assembly. Prior to the failure, the BOP was in service from April 28 to September 20, 2015, then went through an overhaul and reinstated into service September 21-28, 2015. There were no reported personnel injuries or hydrocarbon spill related to the failure of these fasteners.

All of the fasteners in the same manufacturing batch would have similar material properties and be at risk for potential failure. The OEM informed BSEE of another Mobile Offshore Drilling Unit (MODU) operating in the GOM, the Amos Runner, with a BOP using fasteners from the same batch. The Amos Runner was actively performing well work on Mississippi Canyon 794 Well number 001 at a water depth of 1,462 feet. The impacted fasteners were replaced on the BOP after NOV issued a product information bulletin[3]. There were no reported fastener failures for the Amos Runner.

Following the discovery on October 29, 2015 of the BSR fastener failures on the Noble Romano MODU, BSEE convened the Quality Control Failure Incident Team (QC-FIT) to conduct a technical evaluation of the equipment involved in this incident. The team needed to determine if there were global quality assurance/quality control (QA/QC), technology, safety, or environmental concerns that needed to be addressed by the BSEE and/or industry related to the design and use of subsea fastener equipment on the Outer Continental Shelf (OCS). This QC-FIT technical evaluation consisted of meetings with the operator, contractor, and OEM, and review of applicable reports, technical documents and industry standards. These activities provided significant information about the fasteners' design, material properties, manufacturing processes, protective coatings, and corrosion fracture behavior, to determine their fitness for service. A comprehensive list of recommendations is included at the end of this report.

The QC-FIT's key concerns raised during the technical evaluation included the following:

- The Root Cause Analysis (RCA) conducted by the OEM revealed that the BOP BSR fasteners had material hardness values greater than 35 Rockwell Hardness Scale C (HRC) which could lead to hydrogen embrittlement issues.
- The OEM used an older version of ASTM B633 (1998 Edition)[4], "*Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel,*" which specified an inadequate post electroplating heat treatment bake temperature of 190^{o}C (374^{o}F) for a minimum of 3 hours. Zinc electroplated fasteners with material hardness values greater than 32 HRC have an increased risk of hydrogen embrittlement failures when subjected

[1] The Noble Paul Romano is a semi-submersible anchored Mobile Offshore Drilling Unit
[2] Bolts and connectors are referred to as fasteners throughout this report.
[3] NOV Product Information Bulletin: D4516545916-PIB-001 Rev 02, February 24, 2016
[4] ASTM B633, 1998 Edition is not incorporated into BSEE regulations.

to the specified inadequate post electroplating bake heat treatment time of 3 hours or less. The 3 hour post bake heat treatment time is insufficient time for hydrogen molecules to dissipate out of the fastener's surface.

- OEMs should review their bolt design, and evaluate the requirements for bolt hardness and material property values for subsea applications. After reviewing BSEE's QC-FIT Evaluation of Connector and Bolt Failures Summary of Findings Report #2014-01[5] the OEM decided to lower the fasteners' required yield strength from 167 ksi to 130 ksi with material hardness values to less than 35 HRC. The OEM also specified a longer, 8 hour minimum post electroplating bake heat treatment duration for fasteners per ASTM B850[6] 1998 Edition (reapproved 2015), "*Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement,*" to reduce hydrogen embrittlement concerns. BSEE agrees with the OEM's recommendation to replace fasteners with higher hardness values of 37-42 HRC with fasteners with lower hardness values of 31-34 HRC. Fasteners with lower hardness values and longer post electroplating bake duration of 8 hours or more, provides sufficient time for hydrogen molecules to dissipate out of the steel fastener material surface thereby reducing susceptibility to hydrogen embrittlement.
- The OEM should review and follow the appropriate sections from the latest version of API Specification 20E[7], ASTM B633[8], ASTM B849[9] and ASTM B850[10]. This review will aid in specifying appropriate material properties, including the pre and post electroplating bake heat treatment temperature and duration for fasteners used for subsea critical equipment.
- The OEM's finite element analysis (FEA) on the door assembly revealed that the maximum allowable tensile stress exceeded 83% of the bolting material's specified minimum yield strength as referenced in Section 5.4.3 of API Specification 16A Third Edition[11], reaffirmed in August 2016, "Specification for Drill-Through Equipment. This indicates that the applied stresses were beyond the normal limit of design requirements.
- BSEE contracted National Aeronautical and Space Administration (NASA) as an independent third party test laboratory to conduct additional evaluation of the fastener failures. The NASA's metallographic evaluation of the fasteners identified a crack at the root of the fastener thread. Inadequate heat treatment of high strength materials can potentially cause cracks to form at the root of the fasteners' threads. These cracks may continue to propagate inward towards the center of the fasteners' diameter, resulting in premature failure of the fasteners under normal loading conditions.

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[5] QC-FIT Evaluation of Connector and Bolt Failures Summary of Findings Report#2014-01 can be found on the following website: https://www.bsee.gov/sites/bsee.gov/files/ge-bolt-report-final-aug2014.pdf

[6] ASTM B850 1998 Edition and 2015 Edition *"Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement"* is not incorporated into BSEE regulations.

[7] API Specification 20E Second Edition, February 2017, "*Alloy and Carbon Steel Fastening for Use in the Petroleum and Natural Gas Industries"* is not incorporated into BSEE regulations.

[8] ASTM B633, 1998, 2007, 2011, and 2015 Edition, *"Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel" is not incorporated into BSEE regulations.*

[9] ASTM B849, 2002 Edition (reapproved 2013), *"Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement" is not incorporated into BSEE regulations.*

[10] ASTM B850, 1998 Edition (reapproved 2015), *"Standard for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement" is not incorporated into BSEE regulations.*

[11] API Specification 16A Third Edition, June 2004, Reaffirmed August 2010, is incorporated by reference in BSEE regulation §250.730.

As a result of these findings, in the interest of safety and environmental protection on the OCS, BSEE recommends the following:

- Operators and inspectors should understand that the fastener failures are not limited to BOP BSR fasteners. There have been failures with fasteners with higher hardness values in other BOP locations e.g. shear blades, connectors, lower marine riser package (LMRP) assemblies, etc. Inspections should be performed on these locations during maintenance when the BOP stack is retrieved to the surface.
- BSEE should send copies of the QC-FIT report to OEMs to review the impact of system design, material selection, manufacturing, installation, and maintenance on the functional performance of fasteners in critical equipment locations such as the BOP, BSR shear blades, connectors, LMRP assemblies, etc.
- Industry should perform a comprehensive review of manufacturing best practices, environmental service conditions, and relevant industry standards such as API, ASTM, ASME, NACE, NORSOK, ISO, etc. to develop consistent guidance for ideal material property requirements for the manufacture of fasteners used for critical subsea equipment.
- Industry has initiated a repository for fastener failures and should continue to collectively share and review the following information on fasteners: failure data; research; failure testing and analysis; material selection; design; performance; manufacturing processes; industry standards; human factors; and best practices. The collected data and information should be able to assist industry with fastener design for critical subsea equipment.
- Industry has addressed supply sub-tier vendor manufacturing QA/QC concerns in API 20E for fastener manufacturing. Efforts to address manufacturing QA/QC concerns for fasteners and other critical subsea equipment should continue since existing industry practices and BSEE regulations related to QA/QC and quality management systems (QMS) may not be robust enough to ensure that all manufactured components are "fit for service" throughout the supply chain. QA/QC practices should include controls for identifying non-conformities to industry standards and OEM specifications.
- Industry should evaluate API Specification Q1, Ninth Edition, June 2014 including the addendums, "*Specification of Quality Management Systems Requirements for Manufacturing Organizations for the Petroleum and Gas Industry*" for the following:
  - Consider including oversight and auditing of subcontracted second-tier, third-tier and lower tiered vendors who perform a manufacturing process into API Specification Q1. This requirement would ensure that all components manufactured throughout the supply chain are "fit for service."
  - Ensure that the API monogram program provides a sufficient auditing mechanism such that the OEMs are in full compliance with API Specification Q1 Ninth Edition.
  - Consider including fasteners for critical equipment in the API monogram program.
- BSEE should review the latest edition of API Specification Q1 for consideration to be incorporated into regulations.
- API has funded a plating subcommittee to develop a matrix of various coatings and hardness levels to evaluate fasteners' susceptibility to hydrogen embrittlement performance. Industry should consider conducting a joint industry research project on fasteners to determine the ideal material and coating properties, design, torque specification based on the lubricant, installation, maintenance, human factors, fatigue loading, fastener thread manufacture, load capacity, cathodic protection, environment,

and the impact of the stress load conditions on fastener performance and reliability during subsea service.

- BSEE should closely monitor the industry's adoption of API Specification Q2, First Edition, June 2016, "*Specification for Quality Management System Requirement for Service Supply Organizations for the Petroleum and Gas Industries*" and consider whether this specification should be incorporated into regulations. This specification defines the QMS process, risk based QMS requirements and provides guidance to ensure that a piece of equipment is manufactured per the OEM's requirements.
- BSEE should review API Specification 18LCM (Life Cycle Management), First Edition, April 2017, "*Standard for Product Lifecycle Management for the Petroleum and Natural Gas Industry*" for consideration to be incorporated into regulations. This specification provides guidance for maintaining and demonstrating continued conformance of products to original and/or current product definition requirements from inclusion into a lifecycle management program to the end of its usable life.
- BSEE should consider incorporating API Specification 20E Second Edition, February 2017, "*Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry*" into BSEE regulations. This specification establishes the requirements for the qualification, production, and documentation of alloy and carbon steel bolting used in the petroleum and natural gas industries. API 20E also specifies various bolting specification levels (BSL) and that manufacturers' qualification process shall be based on QMS evaluations in accordance with API Specification Q1 Ninth Edition, June 2014.

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BACKGROUND

On October 13, 2015, while conducting initial latch-up blow out preventer (BOP) pressure and function testing on the Garden Banks block 216 Well Number 5 in 1,450 feet of water in the Gulf of Mexico (GOM); the Noble Paul Romano rig was unable to actuate the BOP high pressure blind shear ram (BSR) shear function. After several attempts to actuate the shear rams, the Noble crew discovered that the failure to operate the BOP BSR actuator was a result of failed actuator fasteners. Upon inspection of the BOP stack on the deck, it was found that six of the eight fasteners fractured on the BOP BSR assembly. The BOP was in service from April 28 to September 20, 2015, then went through an overhaul and reinstated into service September 21-28, 2015. There were no reported personnel injuries or hydrocarbon spill related to the failure of these fasteners.

All of the fasteners in the same manufacturing batch would have similar material properties and be at risk for potential failure. The OEM (NOV) informed BSEE of another MODU with a BOP that had fasteners from the same batch operating in the GOM, the Amos Runner. The Amos Runner was actively performing well work on Mississippi Canyon 794 Well number 001 at a water depth of 1,462 feet. The impacted fasteners were replaced on the BOP, after NOV issued a product bulletin. There were no reported fastener failures for the Amos Runner.

Figure 1 on the right is a schematic of a typical BOP with the BSR assembly circled in blue. Figure 2 shows a schematic of the BSR assembly which is located on the BOP that is secured by eight fasteners. Six of the eight fasteners fractured during BOP testing [12] allowing pressurized hydraulic fluid to leak to the sea. Figure 3 shows the BOP subsea with some of the fractured fasteners at the door interface. Figure 4 shows the BOP subsea with one of the eight fasteners fractured at the nut end. Figure 5 shows the BOP on deck and the upper BSR Assembly with fractured fasteners. Figures 6, 7, and 8 are images of the fractured fastener at the thread.

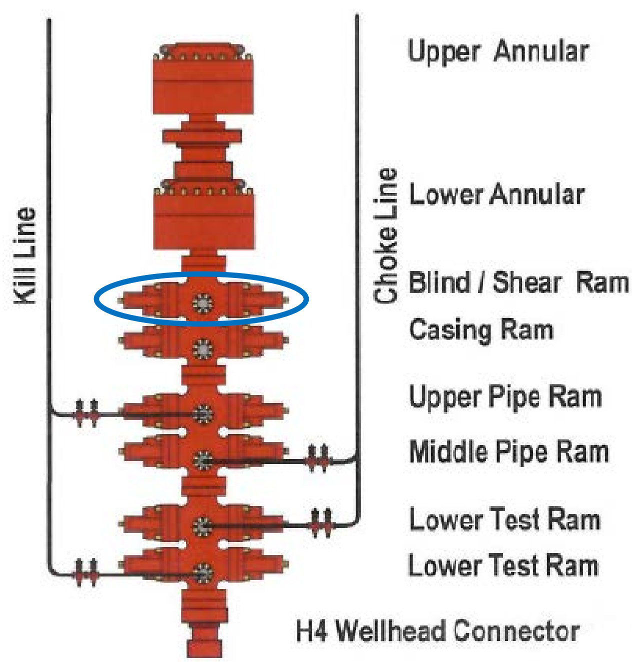

FIGURE 1: BOP SCHEMATIC

[12] §250.737 (D) - Additional BOP test requirements

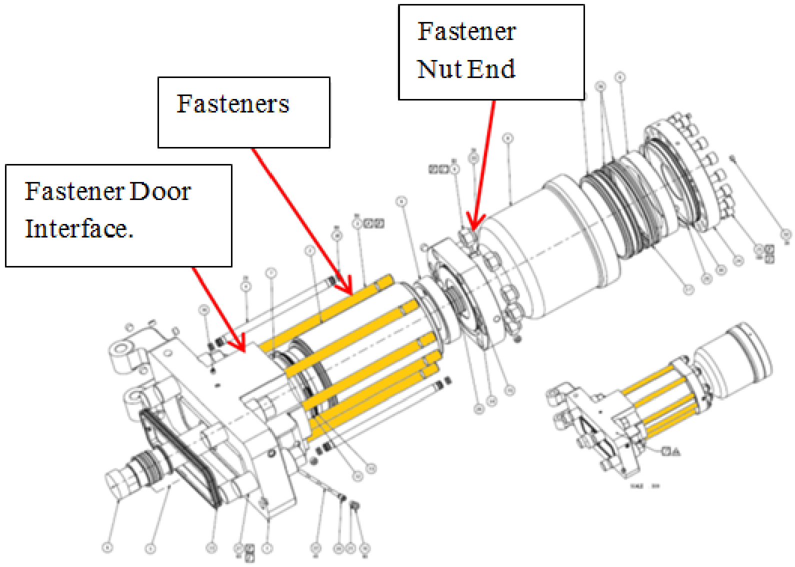

FIGURE 2: BOP BSR ASSEMBLY SCHEMATIC (OEM RCA)

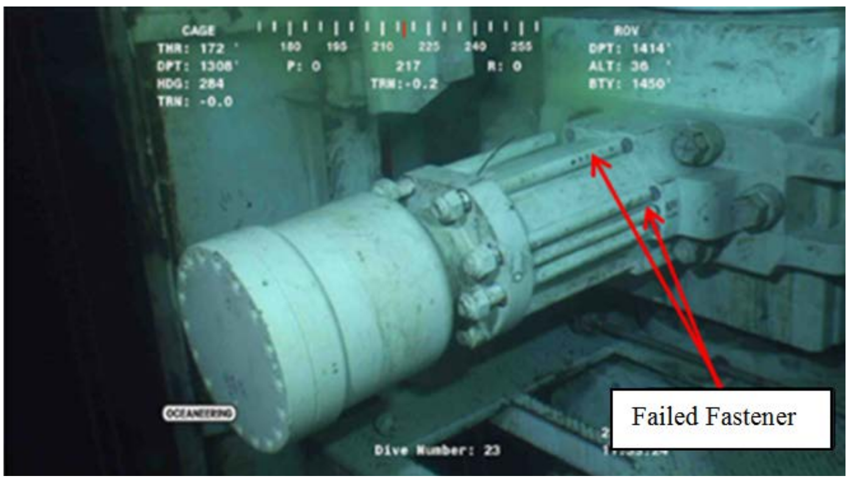

FIGURE 3: DOOR INTERFACE FASTENER FAILURE - BOP BSR ASSEMBLY (OEM RCA)

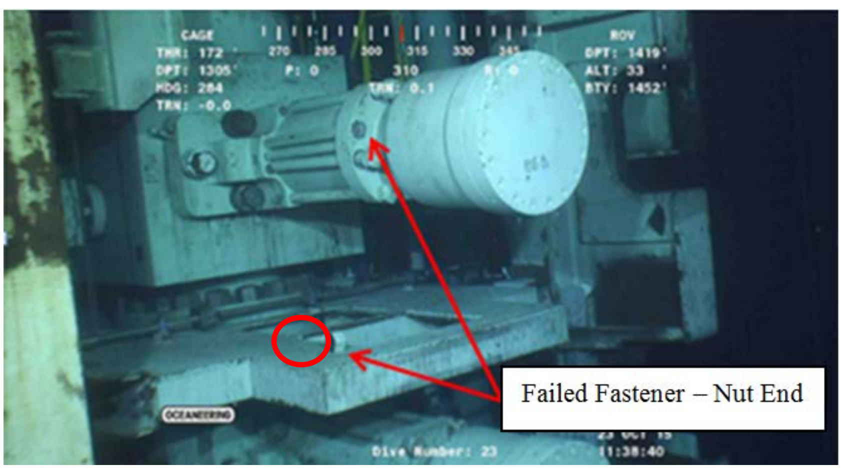

FIGURE 4: NUT END FASTENER FAILURE - BOP BSR ASSEMBLY (OEM RCA)

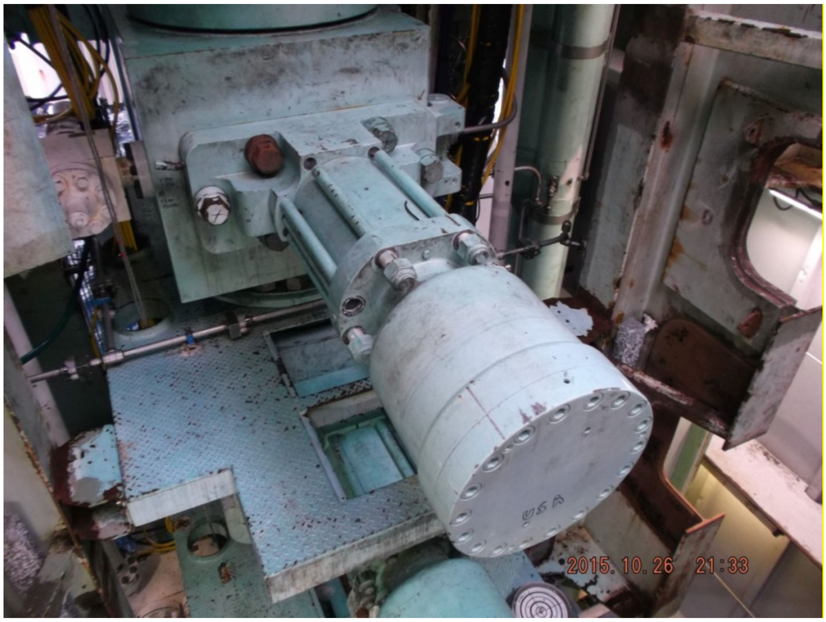

FIGURE 5: UPPER BSR FASTENER FAILURES

FIGURE 6: UPPER BSR FASTENER FAILURES – CLOSE-UP OF SHEARED THREADS

FIGURE 7: UPPER BSR FASTENER FAILURES – CLOSE-UP OF SHEARED FASTENER

FIGURE 8: UPPER BSR FASTENER FAILURES – CLOSE-UP OF FRACTURED FASTENER

In response to the BSR assembly fastener failures, the OEM conducted an RCA to determine the root cause of the failures. Listed below are the OEM's RCA findings:

- Chemical compositional analysis and mechanical properties testing was conducted on the failed fasteners. The fasteners were 4340 steel and confirmed by optical emission spectroscopy (OES) to meet the OEM's chemical composition requirement for ASTM A540[13] Grade B23 2011 Edition, "*Standard Specification for Alloy-Steel Bolting for Special Applications.*"
- A post bake heat treatment after electroplating is required for base material hardness values greater than 32 Hardness Rockwell Scale C. The OEM specified an older version

[13] ASTM A540 2011 Edition, "*Standard Specification for Alloy-Steel Bolting for Special Applications*" is not incorporated by reference in BSEE's regulations.

of ASTM B633 1998 Edition, "*Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel*" which required a post electroplating bake treatment temperature of 190^{o}C (374^{o}F) for a minimum of 3 hours. This inadequate post-bake duration increased the risk of hydrogen embrittlement for the fasteners.

- The measured hardness values of the fractured fasteners ranged from 34.4 to 42.8 HRC across the cross-section of the fastener shank[14] and 44.6 to 45.1 HRC in the banding[15] region. Segregation of the carbides in the banded areas results in different material hardness between the banded and the non-banded areas across the cross-section of the fastener diameter. This higher material hardness increases the fastener materials' susceptibility to hydrogen embrittlement.
- The microstructure revealed the appearance of intergranular fracture combined with micro-pores and grain separation, indicative of a fastener failure due to hydrogen embrittlement.

After reviewing BSEE's QC-FIT Report #2014-01 the OEM lowered the fasteners' yield strength requirement to 130 ksi and material hardness values of less than 35 HRC to reduce the risk of hydrogen embrittlement as specified in NORSOK M-001 and the latest API 20E standards. The OEM also specified a longer, 8 hour minimum post electroplating bake treatment duration for fasteners per ASTM B850 1998 Edition (reapproved 2015), "*Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement,*" to reduce hydrogen embrittlement concerns.

ASSESSMENT

In response to the fastener failures on the Noble Paul Romano MODU, BSEE convened the QC-FIT to conduct a technical evaluation of the equipment involved and determine if there were QA/QC, technology, safety, and/or environmental concerns that needed to be addressed by the BSEE and/or industry related to the design, manufacture and use of these fasteners on the OCS or globally. This QC-FIT technical evaluation consisted of meetings with the operator, contractor, and OEM, and review of applicable reports, technical documents and industry standards. These activities provided significant information about the fasteners' design, material properties, manufacturing processes, and protective coatings to ensure that the fasteners' design was fit for service. The OEM initiated an RCA to determine the root cause for the BOP BSR fastener failures. This BSR fastener failure was isolated to a single rig operating on the OCS. However, this failure could impact safety of oil and gas operations globally due to the MODU's ability to travel.

OEM ROOT CAUSE ANALYSIS

The OEM contracted an independent third party test laboratory to conduct an engineering RCA to determine the root cause of the fasteners' failures. The OEM RCA's included a review of the fasteners' design, material specifications, material properties, load conditions, manufacturing and

[14] Shank – See figures in Appendix II.

[15] Banding is defined as alternating layers of two different microstructures in steel. Banding is caused by deposits of alloying elements during the solidification of the metal alloy.

maintenance procedures, chemical composition, and microstructure. In summary, the OEM concluded the following:

- Chemical compositional analysis and mechanical properties testing were conducted on the failed fasteners. The fasteners were 4340 steel and confirmed by OES to meet the OEM chemical composition requirement for ASTM A540[16] Grade B23 2011 Edition, "*Standard Specification for Alloy-Steel Bolting for Special Applications.*"
- As evaluated by OEM, the measured hardness values of the fastener shank material ranged from 34.4 HRC to 42.8 HRC (Table 1) which exceeded NORSOK M-001 Fifth Edition, September 2014, "Materials Selection" section 6.1 requirement, "hardness of any components shall not exceed 328 Brinnell Hardness Scale B (HRB) or 35 HRC."

Table 1: Measured Hardness Values of Fractured Fasteners[17] (OEM RCA)

Rockwell Hardness Scale C (HRC)			
Fastener	**Minimum**	**Maximum**	**Average**
1	40.4	41.8	41.1
2	40.2	41.4	40.8
3	40.2	41.1	40.6
4	39.8	41.1	40.5
5	41.3	42.3	41.8
6	34.4	39.6	37.0
7	40.8	42.8	41.8
8	40.4	41.3	40.8

- The fasteners used on this BSR were specified to an older version of ASTM B633 1998 Edition, which required a post electroplating bake treatment at a temperature of 190^{o}C (374^{o}F) for a minimum of 3 hours. For the replacement fasteners the OEM specified a longer, 8 hour minimum post electroplating bake treatment duration for fasteners with tensile strength greater than 1,000 MPa, as referenced in ASTM B850 1998 Edition (reapproved 2015), "*Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement.*" Fasteners with lower hardness values and longer post electroplating bake duration of 8 hours or more, provides sufficient time for hydrogen molecules to dissipate out of the steel fastener material surface thereby reducing susceptibility to hydrogen embrittlement.
- The original fasteners design had a higher material yield strength value of 167 ksi to contain the forces of the BSR actuator. The OEM conducted an FEA on the BSR assembly, which showed that the maximum allowable tensile stress exceeded 83% of the bolting material's specified minimum yield strength as referenced in Section 5.4.3 of API Specification 16A Third Edition, reaffirmed in August 2016. The OEM lowered the fastener's material yield strength from 167 ksi to 130 ksi and conducted a second FEA which showed that the maximum allowable tensile stress values were within 83% of the bolting material's specified minimum yield strength.

[16] ASTM A540 2011 Edition, "*Standard Specification for Alloy-Steel Bolting for Special Applications*" is not incorporated by reference in BSEE's regulations.
[17] Measured hardness values were taken from the shank area of the fasteners.

- Figure 9 shows fluorescent dye penetrant test identifying the crack propagated across multiple threads of the fastener. Cracks in the fastener indicate that the in-service load exceeded the fastener material design requirements.

FIGURE 9: CRACK PROPAGATION THAT EXTEND INTO MULTIPLE THREADS BELOW THE FRACTURE FACE (OEM RCA)

- Figure 10 shows a microscopic image of an intergranular 'Rock Candy' style fracture surface with micro-pores and grain separation typical of Hydrogen Embrittlement.

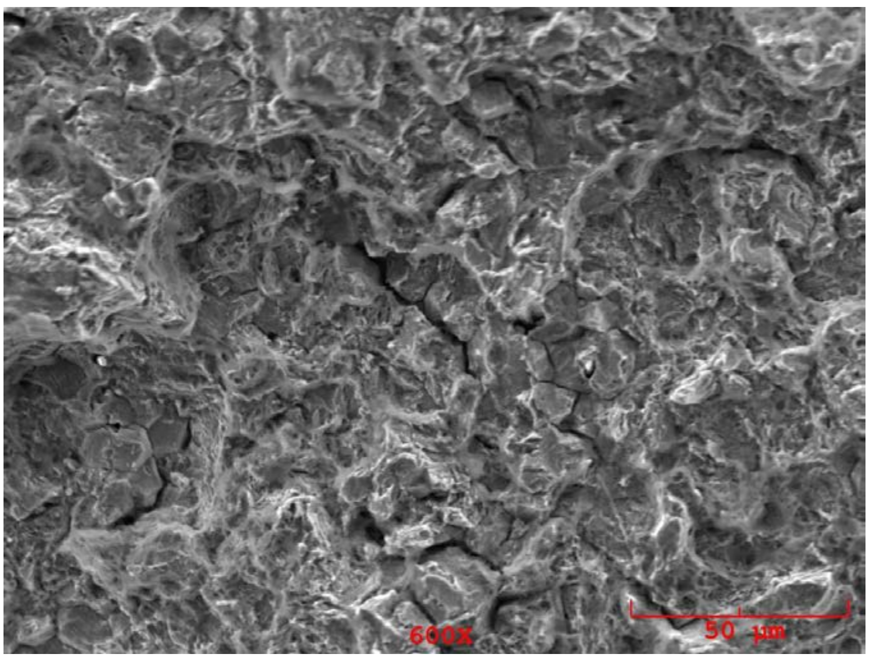

FIGURE 10: SEM IMAGE OF INTERGRANULAR FRACTURE SURFACE (OEM RCA)

In response to the OEM's RCA analysis, BSEE recommends the following:

- The OEM should conduct an FEA on all newly designed fasteners to ensure that operational stress concentrations and load levels remain within the designed load limits.
- The OEM should verify that the vendor's material test certificates meet the OEM's material properties requirements (e.g. alloy chemical composition, coatings, and mechanical properties – yield strength, ultimate tensile strength, hardness, etc.).
- The OEM should specify fasteners material with their material properties to be manufactured to the latest industry standards revision.

POTENTIAL CONTRIBUTING FACTORS

The OEM's RCA identified the following potential contributing factors to fasteners' failures:

- After the fasteners fractured, the OEM conducted an FEA on the door assembly, which revealed that the maximum allowable tensile membrane stress exceeded 83% of the bolting material's specified minimum yield strength as referenced in Section 5.4.3 of API Specification 16A Third Edition, reaffirmed in August 2016. This indicates that the applied stresses were beyond the normal limit of design requirements.
- The OEM specified an older version of ASTM B633 1998 Edition, which required a post electroplating bake treatment at a temperature of 190^{o}C (374^{o}F) for a minimum of 3 hours. This inadequate post bake time increases the risk of hydrogen embrittlement.

NASA ROOT CAUSE ANALYSIS

BSEE contracted NASA as an independent third party test laboratory to conduct evaluation of the fractured fasteners. NASA RCA included testing of the failed fasteners' material properties, chemical composition, and microstructure analysis. Based on NASA's evaluation, the QC-FIT concluded the following:

- NASA verified that the chemical composition of the failed BSR fastener material met ASTM A540 B23 (4340 alloy), 2011 Edition standard as specified by the OEM.
- As evaluated by NASA, the measured hardness values of the fastener shank material ranged from 37 HRC to 42 HRC (Table 2). According to NORSOK M-001 Fifth Edition, September 2014, "Materials Selection" section 6.1, "For submerged parts that may be exposed to cathodic protection (CP), for martensitic carbon, low-alloy and corrosion resistant alloy (CRA), the hardness of any components shall not exceed 328 Brinnell Hardness Scale B (HRB) or 35 HRC."

Table 2: Measured Hardness Values of Fractured Fasteners[18] (NASA RCA)

Rockwell Hardness Scale C (HRC)			
Fastener	**Minimum**	**Maximum**	**Average**
1	40	42	41
2	40	41	40.5
3	40	42	41
4	40	42	41
5	37	39	38
6	38	40	39
7	40	41	40.5
8	41	41	41

- NASA conducted a metallographic evaluation by macroscopic and microscopic optical and scanning electron microscopy (SEM) observation methods to identify the failure mechanism for the fasteners' failure. Optical microscopy was used to characterize the microstructures of the failed fasteners' fracture surface, multiple threaded areas, and thread root.
  - Figure 11 shows a microscopic image of a failed fasteners' thread cross-section. Stress cracks were observed in the thread root areas identified by yellow arrows indicating the load exceeded the fastener material design requirements. These cracks are prime sites for hydrogen diffusion into the material grain boundaries leading to failures due to hydrogen embrittlement. The fracture surface in Figure 11 was further evaluated under a higher magnification.

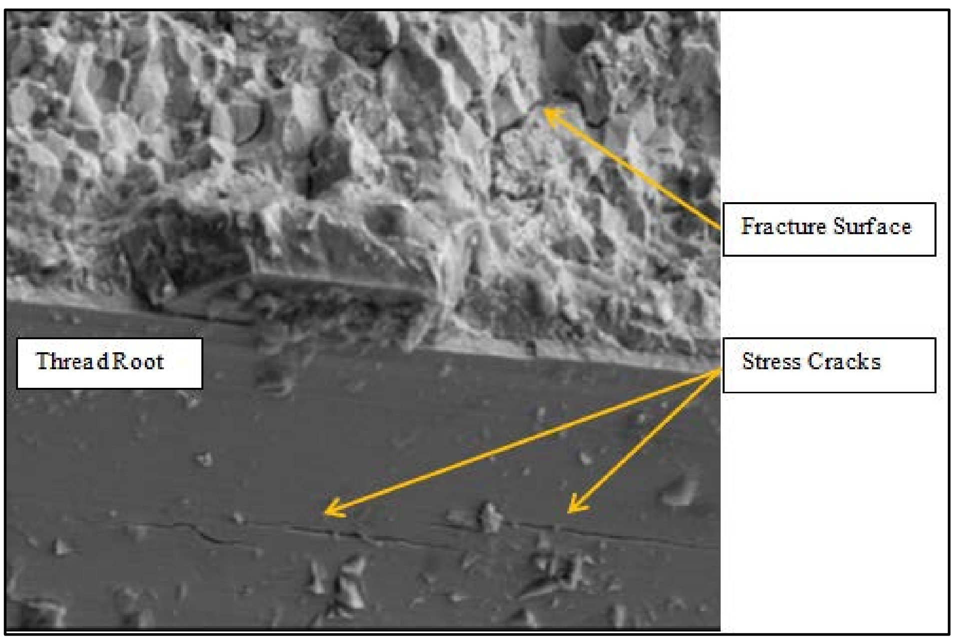

FIGURE 11: PARALLEL CRACKS OBSERVED IN THREAD AND THREAD ROOT NEAR FRACTURE (NASA RCA)

  - Figure 12 shows a microscopic image of a failed fastener cross-section with a crack at the root of a thread. High material strength properties and inadequate heat treatment can lead to pre-existing cracks at the root of the threads. Thread root cracks can continue inwards towards the centerline of the fastener's diameter, resulting in

[18] Measured hardness values were taken from the shank area of the fasteners.

premature failure of fasteners under normal loading conditions. The measured crack length was 0.336 inches of the 1.852 inch fastener diameter.

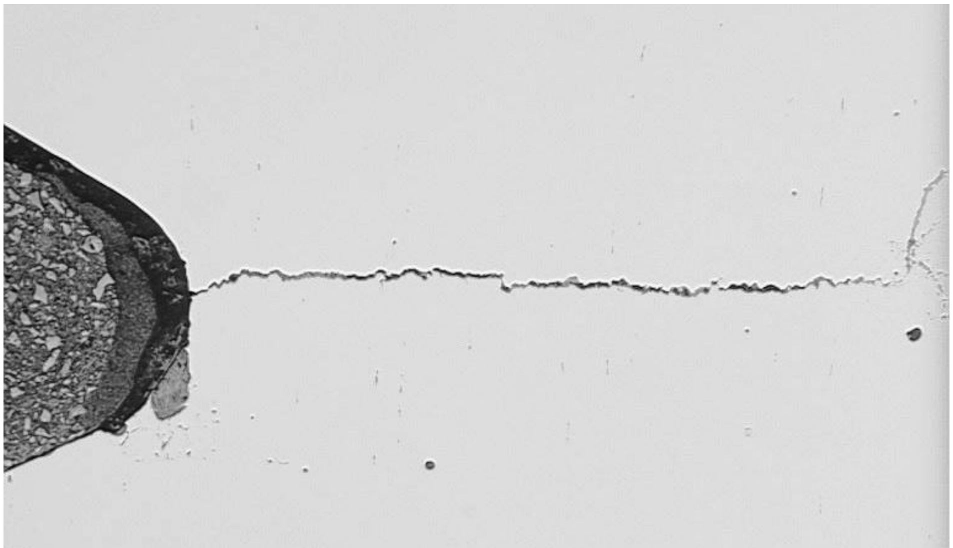

FIGURE 12: CRACK INITIATION AT THE THREAD ROOT (INTACT OTHER END OF THE FRACTURED FASTENER – NASA RCA)

- In Appendix 1 are Figures 13 and 14 showing micro-photographs of the fractured surface with details for the crack initiation and the propagation across the thread diameter of the fastener.
- In Appendix 1 are Figures 15 and 16 showing SEM micro-photographs with details of the intergranular fracture typical of hydrogen embrittlement.

APPLICABLE INDUSTRY STANDARDS

MATERIAL PROPERTIES

The API Specification 20E, Second Edition, February 2017, *"Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry."* specifies the requirements for the qualification, production, and documentation of alloy and carbon steel bolting used in oil and gas applications. This standard provides guidance for consistency in material property requirements for fasteners to be used for the required design load conditions, manufacturing processes for the reproducibility, and verification of the fasteners' function. The recent additions to API 20E include quality management system (QMS) requirements for the sub-contracted vendors at all levels of the manufacturing process. If the fasteners were manufactured per the API 20E requirement for a maximum hardness of 35 HRC, the risk of hydrogen embrittlement may have been reduced.

API Specification 16A, Third Edition, reaffirmed in August 2016, *"Specification for Drill-through Equipment,"* specifies hardness measurements on parts manufactured from carbon low alloy and martensitic stainless type steels shall exhibit maximum values of 35 HRC in accordance with NORSOK M-001 Fifth Edition, "Materials Selection." September 2014. API Specification 16A Third Edition, reaffirmed in August 2016, specifies that OEMs shall have a documented procedure for the qualification of bolting manufacturers, by referencing the requirements of API Specifications 20E and API 20F, First Edition, 2015, *"Corrosion Resistant Bolting for Use in the Petroleum and Natural Gas Industries."* Bolting manufactured from alloy steel or carbon steel shall be limited to 34 HRC maximum due to concerns with hydrogen embrittlement. Exposed bolting shall meet the requirements of 22 HRC maximum when exposed to sour environments per NACE MR0175/ISO15156, 2015, *"Petroleum, petrochemical, and natural gas industries - Materials for use in H_2S containing environments in oil and gas production."* These fractured fasteners material hardness values were greater than the listed standards recommended maximum hardness values.

QUALITY ASSURANCE

API Specification Q1 Ninth Edition, June 2014:*"Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry,"* API Specification Q2, First Edition, June 2016: *"Specification for Quality Management System Requirements for Service Supply Organizations for the Petroleum and Natural Gas Industry"* and API Specification 18LCM First Edition, 2017, *"Standard for Product Lifecycle Management for the Petroleum and Natural Gas Industry"* recently published April 26, 2017, address quality management, equipment traceability and service risk for manufacturing organizations and service supply organizations, covering both products and services used in the oil and gas industry. The goals of these standards are to improve the manufacturing processes, overall quality and reliability of the equipment being used.

API Specification Q1 Ninth Edition was developed to address QMS for organizations that manufacture products or provide manufacturing-related processes under a product specification for use in the petroleum and natural gas industry. API Specification Q1 Ninth Edition emphasizes the following:

- Supplier's QMS should be effectively implemented, maintained and conform to the requirements of API Specification Q1 Ninth Edition.
- API may perform additional audits of any subcontractors to ensure their compliance with the requirements of the applicable API product specifications and/or standards.
- Ensures that the manufacturer's design and development outputs should meet the OEM's design and development input requirements.
- The criteria for the initial evaluation of suppliers by the OEM shall include verification that the supplier's QMS conforms to the quality system requirements specified for suppliers by the OEM.
- The OEM shall maintain documented procedures to identify the controls and related responsibilities by identifying, documenting and reporting non-conformities of the product delivered.

In the case of this evaluation, the fastener failures fall under API Specification Q1 Ninth Edition, June 2014, section 5.10 "Control of Nonconforming Product." This specification outlines guidance for identifying product failures after delivery and appropriate actions to address the effects of nonconformance. If the design and risk assessment criteria were followed as per API Specification Q1 design and development guidelines, the associated risk of the fastener failure may have been identified during the manufacturing process.

API Specification Q2 First Edition June 2016 defines the quality management system requirements for service supply organizations for the petroleum, and natural gas industries. It is intended to apply to the execution of upstream services during exploration, development and production in the oil and gas industry. This document specifies requirements of a quality management system for an organization to demonstrate its ability to consistently provide services that meet customer, legal, and other applicable requirements.

API Standard 18LCM First Edition, 2017, "*Standard for Product Life Cycle Management,*" recently published April 26, 2017, addresses the lifecycle management of equipment used in the petroleum and natural gas industry. 18LCM provides guidance for tracing a piece of equipment's compliance to its original and/or current manufacturing and design requirements, product standards, and industry/product-specific technical and regulatory requirements. If the fasteners were manufactured to API 20E requirements, they may have been able to perform in accordance with their functional requirements during their life cycle.

SUMMARY OF RECOMMENDATIONS

The QC-FIT key concerns raised during the technical evaluation included the following:

- The RCA conducted by the OEM revealed that the BOP BSR fasteners had material hardness values greater than 35 Rockwell Hardness Scale C (HRC) which could lead to hydrogen embrittlement issues.
- The OEM used an older version of ASTM B633 (1998 Edition), *"Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel,"* which specified an inadequate post electroplating heat treatment bake temperature of 190^{o}C (374^{o}F) for a minimum of 3 hours. Zinc electroplated fasteners with material hardness values greater than 32 HRC have increased risk of hydrogen embrittlement failures when subjected to the specified inadequate post electroplating bake heat treatment time of 3 hours or less. The 3 hour post bake heat treatment time is insufficient time for hydrogen molecules to dissipate out of the fastener's surface.
- OEMs should review their bolt design, and evaluate the requirements for bolt hardness and material property values for subsea applications. After reviewing BSEE's QC-FIT Evaluation of Connector and Bolt Failures Summary of Findings Report #2014-01[19] the OEM decided to lower the fasteners' required yield strength from 167 ksi to 130 ksi with material hardness values to less than 35 HRC. The OEM also specified a longer, 8 hour minimum post electroplating bake heat treatment duration for fasteners per ASTM B850[20] 1998 Edition (reapproved 2015), *"Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement,"* to reduce hydrogen embrittlement concerns. BSEE agrees with the OEM's recommendation to replace fasteners with higher hardness values of 37-42 HRC with fasteners with lower hardness values of 31-34 HRC. Fasteners with lower hardness values and longer post electroplating bake duration of 8 hours or more, provides enough time for hydrogen molecules to dissipate out of the steel fastener material surface thereby reducing susceptibility to hydrogen embrittlement. The OEM should review and follow the appropriate sections from the latest version of API Specification 20E[21], ASTM B633[22], ASTM B849[23] and ASTM B850[24] industry standards. This review will aid in specifying appropriate material properties, including the pre and post electroplating bake heat treatment temperature and duration for fasteners used for subsea critical equipment.
- The OEM's finite element analysis (FEA) on the door assembly revealed that the maximum allowable tensile stress exceeded 83% of the bolting material's specified minimum yield strength as referenced in Section 5.4.3 of API Specification 16A Third

[19] QC-FIT Evaluation of Connector and Bolt Failures Summary of Findings Report#2014-01 can be found on the following website: https://www.bsee.gov/sites/bsee.gov/files/ge-bolt-report-final-aug2014.pdf

[20] ASTM B850 1998 Edition and 2015 Edition *"Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement"* is not incorporated into BSEE regulations.

[21] API Specification 20E Second Edition, February 2017, *"Alloy and Carbon Steel Fastening for Use in the Petroleum and Natural Gas Industries"* is not incorporated into BSEE regulations.

[22] ASTM B633, 1998, 2007, 2011, and 2015 Edition, *"Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel" is not incorporated into BSEE regulations.*

[23] ASTM B849, 2002 Edition (reapproved 2013), *"Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement" is not incorporated into BSEE regulations.*

[24] ASTM B850, 1998 Edition (reapproved 2015), *"Standard for Post-Coating Treatments of Steel for Reducing the Risk of HydrogenEmbrittlement" is not incorporated into BSEE regulations.*

Edition[25], reaffirmed in August 2016, "Specification for Drill-Through Equipment. This indicates that the applied stresses were beyond the normal limit of design requirements.
- BSEE contracted NASA as an independent third party test laboratory to conduct additional evaluation of the fastener failures. The NASA's metallographic evaluation of the fasteners identified a crack at the root of the fastener thread. Inadequate heat treatment of high strength materials can potentially cause cracks to form at the root of the fasteners' threads. These cracks may continue to propagate inward towards the center of the fasteners' diameter, resulting in premature failure of the fasteners under normal loading conditions.

As a result of these findings, in the interest of safety and environmental protection on the OCS, BSEE recommends the following:

- Operators and inspectors should understand that the fasteners failures are not limited to BOP BSR fasteners. There have been failures with fasteners with higher hardness values in other BOP locations e.g. shear blades, connectors, lower marine riser package (LMRP) assemblies, etc. Inspections should be performed on these locations during maintenance when the BOP stack is retrieved to the surface.
-
- BSEE should send copies of the QC-FIT report to OEMs to review the impact of system design, material selection, manufacturing, installation, and maintenance on the functional performance of fasteners in critical equipment locations such as the BOP, BSR shear blades, connectors, LMRP assemblies, etc.
- Industry should perform a comprehensive review of manufacturing best practices, environmental service conditions, and relevant industry standards such as API, ASTM, ASME, NACE, NORSOK, ISO, etc. to develop consistent guidance for ideal material property requirements for the manufacture of fasteners used for subsea critical equipment.
- Industry has initiated a repository for fastener failures and should continue to collectively share and review the following information on fasteners: failure data; research; failure testing and analysis; material selection; design; performance; manufacturing processes; industry standards; human factors; and best practices. The collected data and information should be used to assist industry with fastener design for critical subsea equipment.
- Industry has addressed supply sub-tier vendor manufacturing QA/QC concerns in API 20E. Efforts to address manufacturing QA/QC concerns should continue since existing industry practices and BSEE regulations related to QA/QC and quality management systems (QMS) may not be robust enough to ensure that all manufactured components are "fit for service" throughout the supply chain. QA/QC practices should include controls for identifying non-conformities to industry standards and OEM's specifications.
- Industry should evaluate API Specification Q1, Ninth Edition, June 2014 including the addendums, "*Specification of Quality Management Systems Requirements for Manufacturing Organizations for the Petroleum and Gas Industry*" for the following:
    - Consider including oversight and auditing of subcontracted second-tier, third-tier and lower tiered vendors who perform a manufacturing process into API Specification

[25] API Specification 16A Third Edition, June 2004, Reaffirmed August 2010, is incorporated by reference in BSEE regulation §250.730.

Q1. This requirement would ensure that all components manufactured throughout the supply chain are "fit for service."
    - Ensure that the API monogram program provides a sufficient auditing mechanism such that the OEMs are in full compliance with API Specification Q1 Ninth Edition.
    - Consider including bolts for critical equipment in the API monogram program.
- BSEE should review the latest edition of API Specification Q1 for consideration to be incorporated into regulations.
- API has funded a plating subcommittee to develop a matrix of various coatings and hardness levels to evaluate fasteners' susceptibility to hydrogen embrittlement performance. Industry should consider conducting a joint industry research project on fasteners to determine the ideal material and coating properties, design, torque specification based on the lubricant, installation, maintenance, human factors, fatigue loading, fastener thread manufacture, load capacity, cathodic protection, environment, and the impact of the stress load conditions on fastener performance and reliability during subsea service.
- BSEE should closely monitor the industry's adoption of API Specification Q2, First Edition, June 2016, "*Specification for Quality Management System Requirement for Service Supply Organizations for the Petroleum and Gas Industries*" and consider whether this specification should be incorporated into regulations. This specification defines the QMS process, risk based QMS requirements and provides guidance to ensure that a piece of equipment is manufactured per the OEM's requirements.
- BSEE should review API Specification 18LCM (Life Cycle Management), First Edition, April 2017, *"Standard for Product Lifecycle Management for the Petroleum and Natural Gas Industry"* for consideration to be incorporated into regulations. This specification provides guidance for maintaining and demonstrating continued conformance of products to original and/or current product definition requirements from inclusion into a lifecycle management program to the end of its usable life.
- BSEE should consider incorporating API Specification 20E Second Edition, February 2017, "*Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry*" into BSEE regulations. This specification establishes the requirements for the qualification, production, and documentation of alloy and carbon steel bolting used in the petroleum and natural gas industries. API 20E also specifies various bolting specification levels (BSL) and that manufacturers' qualification process shall be based on QMS evaluations in accordance with API Specification Q1 Ninth Edition, June 2014.

ACRONYMS

API	American Petroleum Institute
ASME	American Society for Mechanical Engineers
ASTM	American Society for Testing Materials
BOP	Blowout Preventer
BSEE	Bureau of Safety and Environmental Enforcement
BSL	Bolting Specification Level
BSR	Blind Shear Ram
CP	Cathodic Protection
CRA	Corrosion Resistant Alloy
FEA	Finite Element Analysis
GOM	Gulf of Mexico
HISC	Hydrogen Induced Stress Cracking
HRB	Brinnell Hardness Scale B
HRC	Rockwell Hardness Scale C
ISO	International Organization for Standardization
KSI	Kilo pound per square inch
LCM	Life Cycle Management
LMRP	Lower Marine Riser Package
MC	Mississippi Canyon
MPa	Mega Pascals
NACE	National Association for Corrosion Engineers
NASA	National Aeronautics and Space Administration
NORSOK	Norsk Sokkels Konkuranseposisjon
NOV	National Oilwell Varco
OCS	Outer Continental Shelf
OEM	Original Equipment Manufacturer
QA	Quality Assurance
QC	Quality Control
QC-FIT	Quality Control Failure Incident Team
QMS	Quality Management System
RCA	Root Cause Analysis
SEM	Scanning Electron Microscopy

APPENDIX I

ADDITIONAL MICRO-PHOTOGRAPHS

Figure 13 shows a macroscopic image of the failed fastener on the nut end. Tear lines indicate two primary fracture crack initiation locations, identified by the black and yellow arrows. The black arrow points to the tip of the chevron pattern (primary crack initiation location) indicating a higher stress area which lead to the initiation of the fastener fracture.

Yellow and Black Arrows Point towards Fracture Initiation

FIGURE 13: FRACTURE INITIATION AT NUT END (NASA RCA)

Figure 14 shows the direction of the crack resulting in a fan shape propagation (chevron pattern) as indicated by the yellow arrows. The fractography and chevron patterns indicate that the macro fracture feature is brittle fracture. Once the crack initiates as shown in figure 8, crack propagation will continue under lower load conditions until failure occurs.

Yellow Arrows Point towards Fracture Initiation

FIGURE 14: CRACK PROPAGATION THAT EXTENDED INTO THE THREAD (NASA RCA)

Figure 15 shows a microscopic image of the ductile dimple structure (orange arrow) indicating an overload condition in the fracture next to the thread root surface.

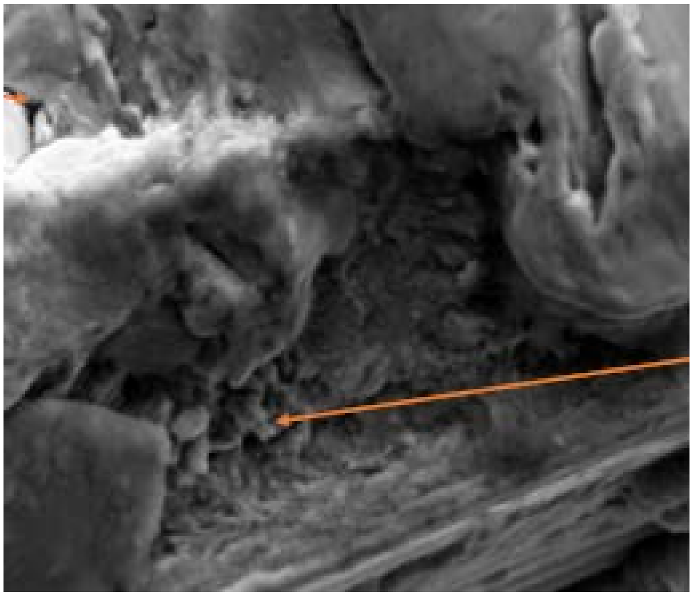

FIGURE 15: SEM IMAGE OF INTERGRANULAR FRACTURE ADJACENT TO THE THREAD ROOT (NASA RCA)

Figure 16 shows intergranular fractures, typical of hydrogen embrittlement. This SEM image indicates that the material is susceptible to hydrogen embrittlement or hydrogen induced stress cracking (HISC) in the presence of hydrogen ions. Hydrogen remains trapped in the material if improper post electroplating bake heat treatment is performed or during service where hydrogen could be generated due to the cathodic protection. When stresses are applied to the fasteners during installation, i.e. fastener torqueing, or the system load condition, this entrapped hydrogen could lead to HISC.

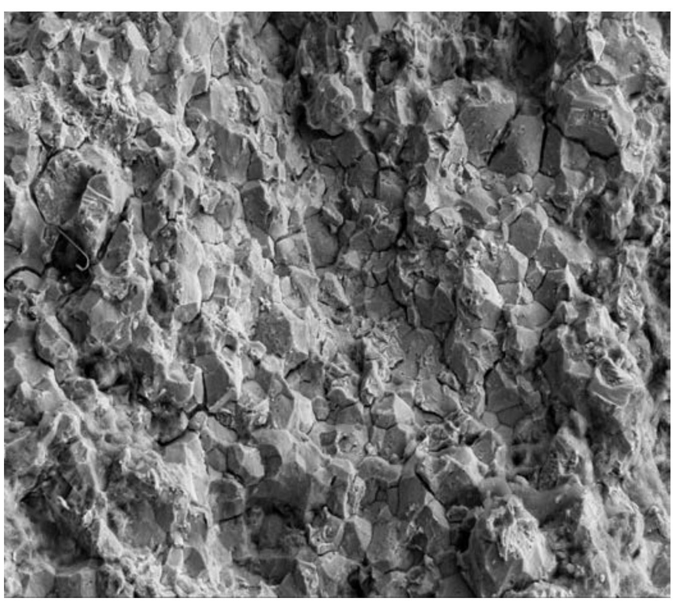

FIGURE 16: SEM CLOSE-UP IMAGE OF THE INTERGRANULAR FRACTURE SURFACE (NASA RCA)

APPENDIX II

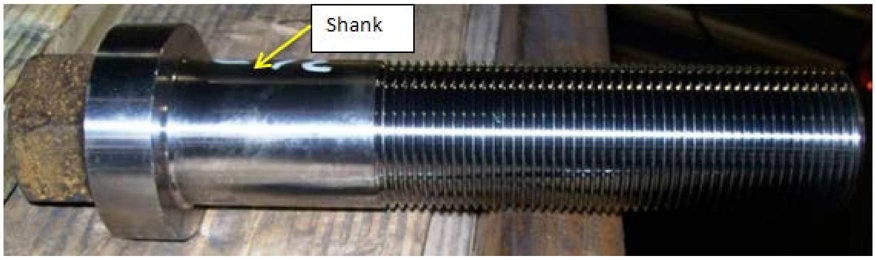

FIGURE 17: PHOTOGRAPH OF NEW FASTENER SHOWING SHANK SECTION

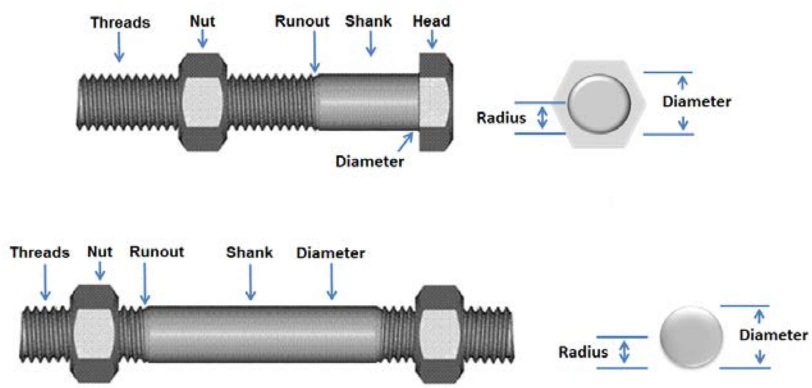

FIGURE 18: SCHEMATIC OF FASTENER (TO) AND STUD (BOTTOM) SHOWING DIFFERENT FEATURES

APPENDIX III

NATIONAL OILWELL VARCO

PRODUCT INFORMATION

Product Bulletin No.: D4516545916-PIB-001

Rev 02

Booster Cylinder Studs

Date: February 24, 2016

Subject: Booster Cylinder Studs

Product: 18 ¾" 15M 14" Poslock X 18" Booster 5K door assemblies;14" Poslock X 16"- Booster door assemblies; 14" Poslock X 14" Booster door assemblies; & 14"- Poslock X 10" Booster door assemblies.

Affected Assemblies: NOV P/N's 20090861, 20091728, 10664626-001, 10664877-001, 10688181-001, 20005584, 10756314-001, 10657238-001, 20090480, 127119, 123272, 123273, 20005559, 125966, 126967, 126901, 20034506, 20010878, 20011873, 20033037, 20005734, 127154, 10607749-001, 20040010, 20014204, 127170, 20093299, 10970453-001, 20014717, 20019693, 125068, 127011, 20091448, 10607687-001, &126775.

Objective: To notify customers of a safety risk posed by broken/degraded Cylinder Studs due to hydrogen embrittlement.

Issue: It has been reported to NOV that when a customer was completing BOP Stack testing, they discovered during operation of the High Pressure Shear function that the Surface Accumulators were unexpectedly bleeding down as they tried to charge the Shear Bottles after the High Pressure Shear function was fired.

The customer reported that subsequently the ROV was used to inspect the BOP and photographs were obtained that indicated that five of the eight Cylinder Head Studs had parted at the Door interface and one of the eight Cylinder Head Studs parted at the Hex Nut (leaving what appeared to be two intact Cylinder Head Studs).

The 18 ¾" 15M 14" Poslocks X 18" Booster 5K Door Assemblies use NOV Part Number 20090870 Cylinder Studs. These Cylinder Studs are manufactured using NOV Specification AX010013 (ASTM A540 B23) material. This material has an HRC range of 35-46 and has been found to be negatively affected by hydrogen embrittlement.

In addition to the aforementioned cylinder stud, the following six cylinder studs were found to be manufactured to material types susceptible to hydrogen embrittlement: NOV P/N 123267, NOV P/N 125887, NOV P/N- 125006, NOV P/N 127014, NOV P/N 20091453, & NOV P/N 20127004.

Solution: NOV recommends replacement of the Cylinder Studs on all affected Door Assemblies with the fasteners shown in Table 1. These Cylinder Studs in Table 1 are made to NOV specifications which have an HRC of 28-35. These materials are resistant to the effects of hydrogen embrittlement.

NOV P/N (Old-To Be Replaced)	NOV P/N (New- To Replace With)	Torque (ft-lbs)
20090870	16543557-001	2,730
123267	16569565-001	2,730
125887	16569606-001	2,730
125006	165004	1,100
127014	16587680-001	2,730
20091453	16587681-001	2,730
20127004	16587682-001	2,730

TABLE 1: REPLACEMENT FASTENER P/N LIST

NOV Part Numbers 20090870, 123267, 125887, 125006, 127014, 20091453, & 20127004 Cylinder Studs should be changed at the next available operational opportunity. The new stud should be torqued to the value shown in Table 1 with a thread lubricant using .067 friction factor. Installation Operation and Maintenance manuals will be corrected to show the new part number and the new torque. Replacement Cylinder Studs will be provided FCA, NOV designated NOV facility (INCOTERMS 2010 Edition) free of charge by NOV for NOV-supplied affected equipment for one year from the date of this revision of this bulletin. Refer to Table 2 to determine which door assemblies contain which cylinder studs.

Stud P/N	Door Assembly P/N	
123267	20005584	125966
	10756314-001	126967
	10657238-001	126901
	20090480	20034506
	127119	20010878
	123272	20011873
	123273	20033037
	20005559	20005734
	127154	
125887	10607749-001	20093299
	20040010	10970453-001
	20014204	20014717
	127170	20019693
125006	125068	
20090870	20090861	10664626-001
	20091728	10664877-001
	10688181-001	
127014	127011	
20091453	20091448	
20127004	10607687-001	126775

TABLE 2: STUD TO CORRESPONDING DOOR ASSEMBLIES LIST

Failure to follow the recommendations and/or guidance in NOV Manuals and Product Bulletins may result in death, bodily injury or property damage.

Customers should also refer to previous NOV Product Information Bulletins and Safety Alerts for any additional information related to this issue and information regarding safe operation, maintenance, and inspection criteria by signing in to your MYNOV account at https://portal.mynov.com and then searching with the Product Bulletin Search available below the heading ‘Application Groups’. For information on registering, please visit https://www.nov.com/Search/register.aspx.

Please contact your local National Oilwell Varco (NOV) Service Center if you have any questions regarding this bulletin.

Revision History:

Rev	Date (mm/dd/yyyy)	Change Description
01	10/30/2015	Initial Release
02	02/24/2016	Added 6 additional fasteners to be replaced & new fastener P/N’s.