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Enforcement

Office of Offshore
Regulatory Programs

QC-FIT EVALUATION OF FASTENER FAILURES- ADDENDUM

QC-FIT Report # 2016-04
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EXECUTIVE SUMMARY

In February of 2014, during pre-deployment testing, a lower marine riser package (LMRP) connector leak was observed and as a result, new connector and fasteners were installed on the blowout preventer (BOP). The fasteners were in service for four months after being replaced during a previous planned maintenance period. On June 30, 2014, while conducting scheduled between well maintenance on a rig's BOP, a subsea engineer discovered a loose fastener¹ on the American Petroleum Institute (API) flange of the hydraulic LMRP connector. Subsequent inspections identified that nine of twenty fasteners were found to have failed on the hydraulic connector flange. The fasteners were adjacent to one another, encompassing nearly half of the hydraulic connector flange connection. Prior to the between well maintenance, the drilling contractor was conducting drilling operations at the Mississippi Canyon (MC) 776 lease block, located in 5,720 feet of sea water. There was no reported injury to personnel or hydrocarbon spill related to the failure of the fasteners.

Following the discovery of the fastener condition on June 30, 2014, BSEE convened the Quality Control Failure Incident Team (QC-FIT) on July 2, 2014 to conduct a technical evaluation of the equipment involved. The team needed to determine if there were global quality assurance/quality control (QA/QC), technology, safety, or environment concerns that required further action by BSEE and/or industry related to the design and use of subsea fastener equipment on the Outer Continental Shelf (OCS). This technical evaluation also compared the June 30, 2014 discovery to a similar fastener failure that occurred on the Transocean Discoverer India at Keathley Canyon (KC) 736 on December 18, 2012. A QC-FIT Evaluation of Connector and Bolt Failures report published in August of 2014 at the following website:

http://www.bsee.gov/uploadedFiles/BSEE/Inspection_and_Enforcement/Accidents_and_Incident_s/QC-FIT_Reports/Bolt%20report%20Final%208-4-14.pdf

The MC 776 incident exhibits similarities to the KC 736 incident evaluation, as well as 2003 fastener failure incidents in which bolts and inserts (nuts) that secured the drilling riser failed and resulted in the riser separating from the assembly. The recurrence of these types of incidents warrants BSEE's continued concern for the risk of future fastener failures on the OCS.

This QC-FIT evaluation consisted of meetings with the operator, contractors, and original equipment manufacturers (OEMs); reviews of reports of similar incidents; and reviews of applicable technical documents and industry standards. These activities provided significant information on the material properties of fasteners used in subsea applications, corrosion fracture behaviors, manufacturing processes and protective coatings for fasteners' in environments similar to those of this application. A comprehensive recommendations list is outlined at the end of this report. These recommendations are applicable to fasteners used for subsea equipment.

¹ Bolts and connectors are referred to as fasteners throughout the report.

Summarized key findings and recommendations are:

- The MC 776 QC-FIT technical evaluation has similarities to the previous KC 736 QC-FIT technical evaluation including: failure of the fasteners, concerns with fastener hardness and coatings, environmentally-assisted-corrosion fastener failures, use of the latest editions of the industry standards related to fasteners, and oversight of second- and third-tier subcontracted vendor nonconformance to the OEM specification.
- Existing industry practices and BSEE regulations related to QA/QC and quality management systems may not be adequate to ensure that components are manufactured as “fit for service” at all levels of the manufacturing supply chain. 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 standards² to ensure that the sections on mechanical integrity and contractor qualification are sufficiently robust.
- 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.
- 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.
- 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 Current safety and environmental regulations are defined in 30 CFR part 250, Subpart S, Regulations for Safety and Environmental Systems (SEMS), October 2010, and standards in API RP75 Third Edition, May 2008, “Recommended Practice for Development of a Safety and Environmental Management Program for Offshore Operations and Facilities.”

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BACKGROUND

In February of 2014, during pre-deployment testing, a lower marine riser package (LMRP) connector leak was observed and as a result, new connector and fasteners were installed on the blowout preventer (BOP). The fasteners were in service for four months after being replaced during a previous planned maintenance period. On June 30, 2014, while conducting scheduled between well maintenance on a rig's BOP, a subsea engineer discovered a loose fastener on the American Petroleum Institute (API) flange of the hydraulic LMRP connector. Subsequent inspections identified that nine of twenty fasteners were found to have failed on the hydraulic connector flange. The fasteners were adjacent to one another, encompassing nearly half of the hydraulic connector flange connection. Prior to the between well maintenance, the drilling contractor was conducting drilling operations at the Mississippi Canyon (MC) 776 lease block, located in 5,720 feet of sea water. There was no reported injury to personnel or hydrocarbon spill related to the failure of the fasteners.

The hydraulic connector (HC), which is located in between the lower marine riser package (LMRP) and lower blowout preventer (LBOP), secures the LMRP to the LBOP (Figure 1). The twenty fasteners on top of the HC (see Figure 2) secure the HC to the bottom of the upper annular in the LMRP, and nine of those the twenty fasteners on the HC failed (Figure 3). Eight of the failed fasteners fractured at the first engaged thread, located below the upper annular flange (see Figure 4). One fastener failed below the nut on the top of the upper annular flange.

The operator, the drilling contractor, the BOP OEM, and an independent third-party laboratory conducted a root cause analysis (RCA) investigation into this failure. The RCA report concluded that an unapproved third-tier subcontracted vendor failed to follow the requirements of the OEM heat treatment and material specification requirements impacting the fasteners' material properties, resulting in fracture due to environmentally-assisted cracking (EAC).³ BSEE agrees in part with the RCA findings; however, the specific damage mechanism for the failure, as hydrogen embrittlement (HE) or hydrogen stress cracking (HSC), was not determined despite the existence of well-established laboratory analysis protocols for studying the brittle fracture of steel. It should be noted that due to the natural dissipation of hydrogen, it is impossible to observe direct evidence of a HE failure. Many potential causes of a brittle fracture of the fasteners were evaluated by the testing laboratory, which identified EAC as the likely failure mode after extensive review of the fracture studs. 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 and which contributed to premature failure of the fasteners under normal loading conditions.

The RCA also determined that the subcontracted vendor's non-compliance to the QA/QC processes led to deviations from the OEMs manufacturing specification.

³ Environmentally-assisted cracking refers to the phenomenon in which a material failure (generally a fracture or crack) occurs due to tensile stress and environmental conditions, such as the presence of liquid and/or corrosive substances.

ASSESSMENT

Following the discovery of the fastener condition on June 30, 2014, BSEE convened the QC-FIT within the Office of Offshore Regulatory Programs to evaluate any technology or safety issues associated with the use of fastening equipment in the OCS. In particular, the QC-FIT was tasked with comparing the condition observed at MC 776 and the KC 736 event, and determining if there were industry-wide issues involving equipment or processes that required further action by BSEE and/or the industry. The summary of this evaluation and recommendations are listed below.

POTENTIAL CONTRIBUTING FACTORS

The three inch diameter fasteners on the HC were made of AISI 4340 steel. A third-party testing laboratory performed a detailed examination of the failed and intact fasteners. The material property analysis included investigation of the steel casting process, chemical composition, hardness values, Charpy impact testing, microstructures, heat treatment procedure, coating processes, and loading simulation. The laboratory evaluated many potential causes of a brittle fracture of the fasteners, and EAC was identified as the likely failure mode after extensive review of the fracture studs. 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 procedure, contributing to premature failure of the bolts in normal loading conditions.

Ultimately the 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. The operator, contractor, OEM, and independent third-party test laboratory indicated that the RCA conducted was adequate to identify the cause of failure. BSEE reviewed the RCA data and found that the RCA was not able to determine the specific damage mechanism, such as HE or HSC.

Due to the inconclusiveness of the RCA, 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, as there are well-established laboratory analysis protocols to study the brittle fracture of steel. It should be noted, however, that due to the natural dissipation of hydrogen, it is impossible to observe direct evidence of a HE failure.

MANUFACTURING

The RCA determined that the approved second-tier contracted vendor did not follow the manufacturer's specification, which called for ingot cast material. The approved second-tier contracted vendor instead used a continuous casting process for the fasteners' raw material. Continuous cast alloy steel can cause "banding" within the raw material microstructure, which can result in areas of localized high hardness and unexpected mechanical properties. This can contribute to the HE susceptibility of the material.

Note on banding: continuous casting does promote banding, but under normal conditions the banding does not result in featureless banding identified in API 20E as deleterious to function.⁴ Due to a heat treatment furnace failure at the approved second-tier contracted vendor, the heat treatment process was subcontracted to a third-tier vendor that was not approved by the OEM. The unapproved subcontracted third-tier vendor did not follow the OEM specification for the heat treatment procedure for fasteners, which resulted in variation in material hardness values above the 35 hardness Rockwell scale C (HRC) specification limits (see table 1), increasing the material's susceptibility to HE. The RCA also found inconsistencies with testing, measuring, and reporting of material data. The quality management systems (QMS) of the OEM overlooked these inconsistencies during the initial acceptance of the fasteners and allowed for deviations from the OEM specifications.

Per the OEM's Global QMS, all the outsourced critical processes are subject to a QMS Technical Audit/Process Validation. This requirement is documented in each purchase order. The approved second-tier contracted vendor subcontracted the heat treatment of the fasteners to a third tier vendor that was not approved by the OEM; despite the note specified in the purchasing order stating "Verify and utilize OEM Approved Vendor for Special processes."

HARDNESS

The OEM's material specification had specified HRC values with a range of 31-35 for these fasteners. Testing showed HRC values ranging from a minimum of 27 to a maximum of 41 (see Table 1). Four of the nine failed fasteners had average hardness values below 35 HRC and five of the nine failed fasteners had average hardness values above 35 HRC. Seven of the eleven intact fasteners had average hardness values below 35 HRC and four of the eleven intact fasteners had average hardness values above 35 HRC. The fastener flange location and correlating hardness values can be seen in Figure 5.

Note: BSEE has concerns with the use of fasteners with hardness values exceeding 34 HRC in subsea applications as it increases their susceptibility to EAC.

COATING

Zinc electroplating with a yellow chromate coating was used to protect the fasteners from corrosion. The third-party testing laboratory examination of the failed fasteners showed no coating present due to corrosion at locations where fractures had occurred. The source of hydrogen was not determined during the industry RCA, as this was outside the scope of testing. It should be noted that the zinc coating helps 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.

INSTALLATION TORQUE

Installation torque values for the fasteners were not adjusted for the lubrication coefficient of friction and may have been a contributing factor in this failure. The coefficient of friction is a major contributing factor in the calculation of fastener torque and stress. This coefficient of

⁴ The deleterious banding is defined per ASTM 1268 A.1.20. The banding displayed in the parts that were analyzed was not of this type, but did show hard spots indicating a problem with the heat treatment/tempering process.

friction can vary significantly based on the type of lubrication used, which can lead to improper torquing of fasteners and overstressing of the material. The OEM's review of the fastener torque pre-stress showed an acceptable safety factor. While installation torque values were not adjusted on the rig during the installation of the connector, the RCA team found that the torque values and lubricant used would have resulted in a preload on the fasteners that fell within an acceptable range provided by the OEM, as described in the RCA report. The torque wrench used on the rig was sent to its OEM to verify its calibration – no issues were identified. The fractography described in the RCA identified that the failure pattern would likely not be due to an under/over torque load failure. As a result, this is not likely to be a contributing factor.

RECOMMENDATIONS:

- Industry should develop improved QA/QC practices to verify manufacturing processes and fastener material properties at each stage of an OEM's supply chain. QA/QC practices should include controls for producing expected products and identifying non-conformities to applicable standards and specifications.
- Industry should develop improved OEM QMS for better oversight of second- and third-tier vendors subcontracted during the fastener manufacturing processes.
- Industry and BSEE should develop a joint research project on fasteners to determine the ideal material and coating properties and related torque values for subsea service.
- Industry should consider further investigation to determine the specific mechanism of the fastener failure, why some of the fasteners with hardness values within the OEM specification failed, and why some with hardness values above the specification did not fail.
- Industry should develop best practices and/or specifications regarding manufacturing and QA/QC processes that may help to prevent similar failures from recurring.

APPLICABLE INDUSTRY STANDARDS

MATERIAL PROPERTIES

The various industry standards with material property requirements (hardness, tensile, yield, elongation, chemistry) for subsea fasteners are not consistent.⁵ If such standards had consistent material property requirements it may have prevented similar fastener failures across the industry. This inconsistency was noted in the August 2014 QC-FIT report on connector failures. BSEE is not aware of any final action that resolves these concerns.

The API Spec 20E First Edition “Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry” was published in August of 2012 with Errata published October 2014. The OEM, operator, contractor, and third-party testing laboratory all agree that API Spec 20E is the

⁵ API, ASTM, NACE, and NORSOK standards (API 6A, API 16A, API 16F, API 17A, ASTM B633, ASTM B849, ASTM B850, ASTM F1941, ASTM F1137, NACE MR0175, and NORSOK-M001) have different material property requirements for the manufacture of fasteners.

appropriate standard to use to address subsea fastener manufacturing concerns. API 20E specifies the requirements for the qualification, production, and documentation of alloy and carbon steel bolting used in oil and gas applications. The OEM and operator indicated that they will incorporate API 20E into their future contracts.

QUALITY ASSURANCE

API Spec Q1, Spec Q2, and Standard 18LCM (currently in development by API) address quality management, equipment tractability 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 overall quality of equipment being used.

API Spec Q1 Eighth Edition – “Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry” provides the framework for a manufacturer’s quality management system used in the oil and gas industry. The purpose of these requirements is to ensure that equipment is manufactured pursuant to a quality management system that will help to ensure conformance to the specified requirements.⁶ A revised ninth edition of Spec Q1 was published in June 2013. The August 2014 QC-FIT report regarding fastener failures in KC 736 recommended that this document be revised to address multiple tiers of subcontractors. A revision to address this concern has been proposed in recent API standards meetings, but no definitive action has been taken as of the date of publication of this report.⁷

API Spec Q2 First Edition - “Specification for Quality Management System Requirements for Service Supply Organizations for the Petroleum and Natural Gas Industry” defines the fundamental QMS requirements and service controls for the service supply organizations. The first edition of Q2 was published in December of 2011, and an API workgroup has been working on implementation and interpretation of this standard in the industry. This standard could apply to the repair and servicing of equipment using subsea fasteners.

API Standard 18LCM First Edition - “Standard for Product Lifecycle Management for the Petroleum and Natural Gas Industry” is currently being drafted by an API subcommittee. This new standard will address the lifecycle management of equipment used in the petroleum and natural gas industry. When complete, this standard will provide guidance for tracking 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,

⁶ Companies that have a quality assurance program in place that meets the requirements of API Spec Q1 and have passed an audit are eligible to use the API Monogram which demonstrates compliance with industry standards.

⁷ BSEE regulations incorporate the API Spec Q1 quality assurance requirements for safety and pollution prevention equipment in 30 CFR 250.806. The proposed BSEE Well Control Rule also requires the use of API Spec Q1 for various well control components. BSEE regulations currently incorporate API Spec Q1 Eighth Edition – “Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry” for production safety equipment. The 9th edition requires that improved quality management system requirements be developed and may be adopted in the future.

throughout its lifecycle. API Standard 18LCM First Edition is planned to be a companion document to API Q2.

QUALITY MANAGEMENT SYSTEMS

Quality Management Systems (QMS) is in reference to API Q1 & API Q2 specifications where these industry standards establish minimum requirements for organizations that manufacture products or provide services or service-related products for use in the petroleum and natural gas industry.

COMPARISON OF MC 776 TO KC 736 INCIDENT (SIMILARITIES AND DIFFERENCES)

The failure of subsea fasteners due to environmentally-assisted corrosion continues to affect offshore safety and environmental protection. The failure observed at MC 776 has similarities to an incident which occurred on KC 736:

1. Failure of the fasteners was mainly due to EAC.
 - a. In the MC 776 failure, the third-party testing laboratory narrowed the EAC failure mechanism down to either HE or HSC.
 - b. In the KC 736 incident, the third-party testing laboratory narrowed the failure down to EAC but the specific failure mechanism could not be determined without further study. Micro-cracks were observed at the root of the threads in some of the samples analyzed, which would be due to an inadequate heat treatment procedure contributing to premature failure of the fasteners under normal loading conditions.
2. Failures of fasteners were in similar locations on the BOP.
 - a. In the MC 776 failure, nine out of twenty fasteners on the API flange fractured as part of the HC between the LMRP and the LBOP.
 - b. In the KC 736 incident, all thirty six fasteners fractured as part of the HC between the LMRP and the LBOP.
3. Zinc electroplating with a yellow chromate coating was applied to the fasteners as a protective coatings for subsea use.
 - a. In the MC 776 failure, the subcontracted coating vendor followed pre- and post-bake procedures which incorporate ASTM B633.
 - b. In the KC 736 incident, the subcontracted coating vendor relied on an outdated ASTM B633 standard, which resulted in foregoing the post-baking step which increased the risk of HE.
4. Material hardness concerns were identified.
 - a. In the MC 776 failure, the hardness of nine out of twenty fasteners was above 35 HRC (36-43HRC). This was outside of the OEM specification (31-35 HRC).
 - b. In the KC 736 incident, the hardness of all the fasteners was between 36-38 HRC. This was within the OEM specifications (34-38 HRC).
 - c. BSEE has concerns with the use of fasteners with hardness values exceeding 34 HRC in subsea applications as it increases their susceptibility to EAC.
5. OEM QA/QC practices led to several unidentified nonconformities to the manufacturing specification.
 - a. In the MC 776 failure, an unapproved subcontracted third-tier vendor conducted improper heat treatment by not following manufacturer specifications.
 - b. In the KC 736 incident, a subcontracted third-tier vendor relied upon an obsolete version of ASTM standard B633 resulting in the fasteners not receiving the ASTM 633-required post-bake electroplating treatment.

The similarities between the MC 776 and KC 736 failures may also be shared by other incidents and/or events, some of which were noted in the QC-FIT report published in August 2014 such as the 2003 BP Thunder Horse failure. The Thunder Horse platform also experienced riser bolt and bolt insert failures resulting from HE. For additional information see the QC-FIT Evaluation of Connector and Bolt Failures report referenced herein.

The KC 736 incident resulted in an environmental release of drilling mud and was reported to the BSEE pursuant to the regulations. The OEM took an active role in ensuring that information related to the incident was provided to the industry. The MC 776 incident could be classified as a “near-miss” and was discovered by BSEE⁸ in July 2014.

⁸ API Q1 Eighth Edition Section A.8 states: “API solicits information on products that are found to be nonconforming with API-specified requirements, as well as field failures (or malfunctions), which are judged to be caused by either specification deficiencies or nonconformities with API-specified requirements. Customers are requested to report to API all problems with API monogrammed products. A nonconformance may be reported using the API Nonconformance Reporting System available at <http://compositelist.api.org/ncr.asp>.” BSEE does not believe that the customers in either incident reported the failure to API despite both OEMs being API Licensees.

SUMMARY OF RECOMMENDATIONS

The following are the combined recommendations of the QC-FIT evaluation team:

1. Due to the inconclusiveness of the RCA, 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 and root cause of the failure. The RCA should be updated when the mechanism of failure and root cause are identified.
2. Industry should develop improved QA/QC practices to verify manufacturing processes and fastener material properties at each stage of an OEM's supply chain. QA/QC practices should include controls for producing expected products and identifying non-conformities to standards and specifications.
3. BSEE and/or industry should consider funding a joint research project on fasteners to determine the ideal material and coating properties, related torque values, and the impact of the stress load conditions at the LMRP on the fastener performance and reliability during subsea service.
4. BSEE and/or industry should consider funding a joint research project on fasteners to evaluate the impact of the stress load conditions at the LMRP on the fasteners' performance and reliability during subsea service. The stress load conditions at the LMRP assembly are critical, as evidenced by the failures that occurred in both the MC 776 and KC 736 incidents.
5. Industry should consider further investigation to determine the specific mechanism of the fastener failure, why some of the fasteners with hardness values within the OEM's specification failed, and why some with hardness values above the specification did not fail.
6. Industry should perform a comprehensive review of industry standards 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.
7. BSEE should evaluate API Spec 20E First Edition "Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industry" for incorporation by reference into regulations for consistency in material property requirements, with the aim to improve offshore safety and environmental protection.
8. BSEE should review the latest edition of API Spec Q1 Ninth Edition "Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry" for consideration to be incorporated into regulations, and closely monitor the industry's adoption of API Spec Q2 First Edition "Specification for Quality Management System Requirements for Service Supply Organizations for the Petroleum and Natural Gas Industry" and consider evaluating whether this specification should be incorporated into regulations.
9. Industry should finalize API Standard 18LCM First Edition "Standard for Product Lifecycle Management for the Petroleum and Natural Gas Industry" and BSEE evaluate whether this specification should be incorporated into regulations if not adopted by industry.

10. As noted in the previous QC-FIT report, industry needs to develop better processes to ensure that failures of components in safety critical equipment are collected, analyzed, and reported to the industry.
11. Industry should develop and improve the API Spec Q1 quality management standard to address the oversight and auditing of subcontracted second- and third-tier vendors who perform a manufacturing process in the manufacturing chain. This would ensure proper manufacturing at the lowest levels. The industry and BSEE should also review API RP75 Third Edition, May 2008 'Recommended Practice for Development of a Safety and Environmental Management Program for Offshore Operations and Facilities' and the BSEE SEMS regulation (Subpart S), October 2010 to ensure that the sections on mechanical integrity and contractor qualification are sufficiently robust.

FIGURES

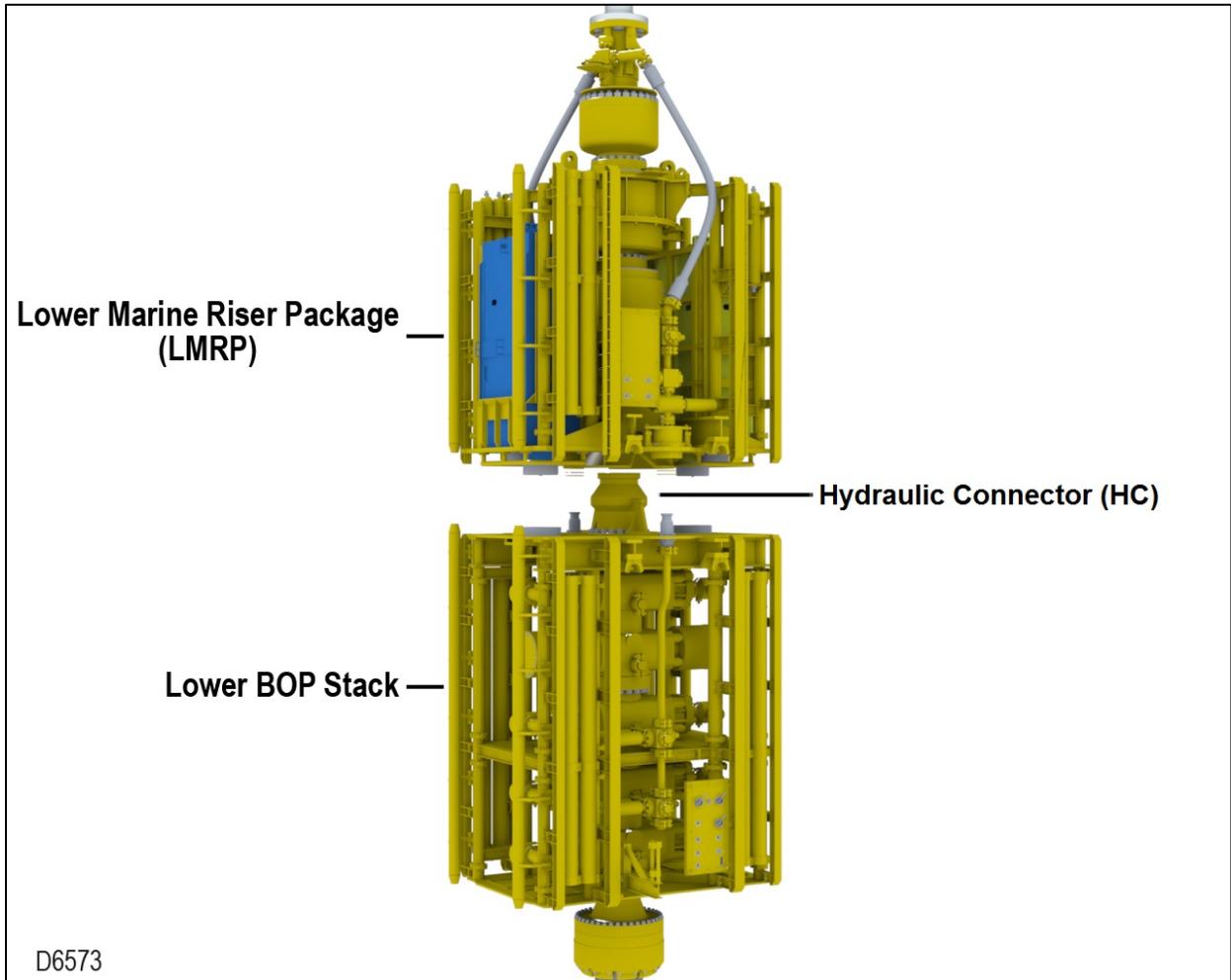


Figure 1: LMRP / HC / lower BOP assembly

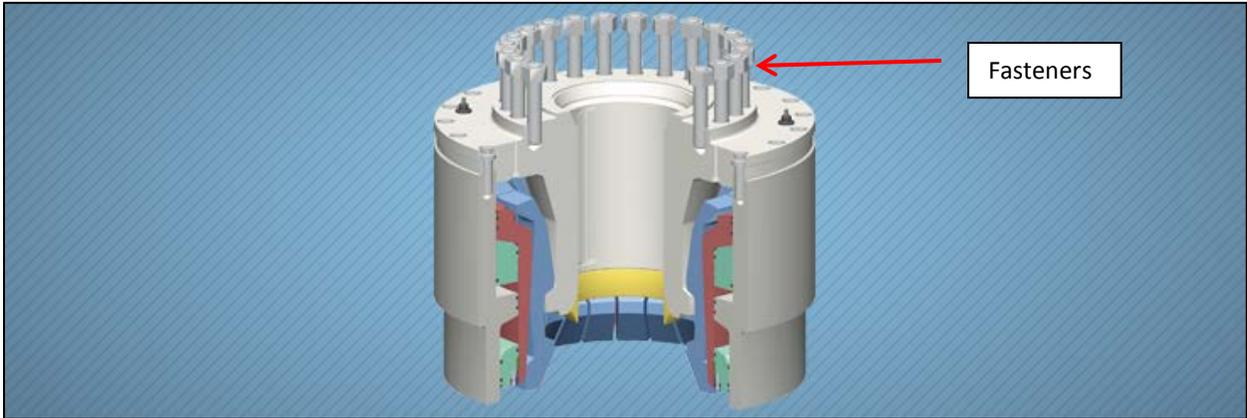


Figure 2: Hydraulic connector showing fasteners (WWW.C-A-M.COM)



Figure 3: Hydraulic connector sheared fastener



Figure 4: Hydraulic connector flange/fasteners showing failures and first engaged threads

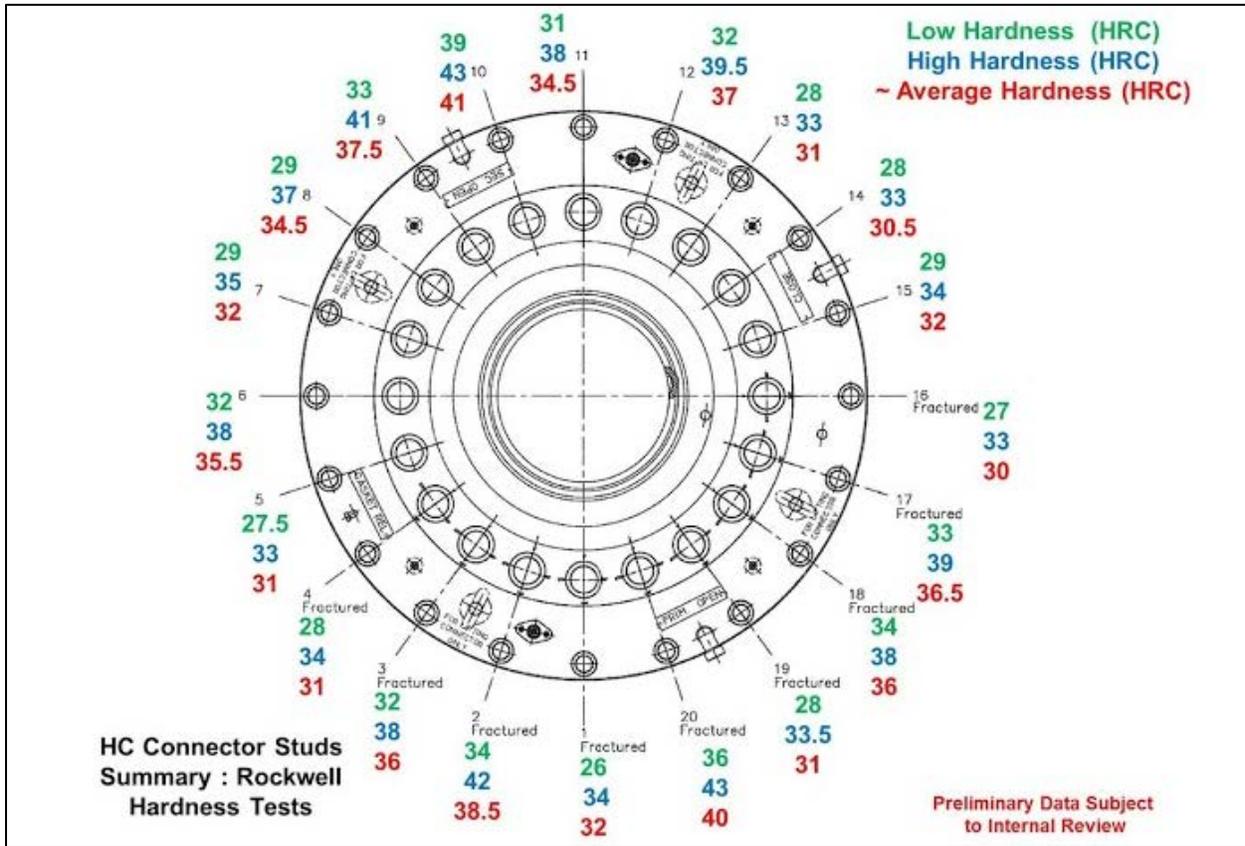


Figure 5: Fracture location and corresponding Rockwell Hardness Values

OEM SPECIFICATION 31-35 HRC				
Fastener	Condition	Rockwell Hardness C (HRC)		
		Minimum	Maximum	Average
1	Failed	26	34	32
2	Failed	34	42	38.5
3	Failed	32	38	36
4	Failed	28	34	31
5	Intact	27.5	33	31
6	Intact	32	38	35.5
7	Intact	29	35	32
8	Intact	29	37	34.5
9	Intact	33	41	37.5
10	Intact	39	43	41
11	Intact	31	38	34.5
12	Intact	32	39.5	37
13	Intact	28	33	31
14	Intact	28	33	30.5
15	Intact	29	34	32
16	Failed	27	33	30
17	Failed	33	39	36.5
18	Failed	34	38	36
19	Failed	28	33.5	31
20	Failed	36	43	40

Table 1: Measured hardness values of fasteners (as recorded by third-party testing laboratory)

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
EAC	Environmentally-Assisted Cracking
HC	Hydraulic Connector
HE	Hydrogen Embrittlement
HRC	Rockwell Hardness Scale C
HSC	Hydrogen Stress Cracking
KC	Keathley Canyon (KC)
LBOP	Lower Blowout Preventer
LCM	Life Cycle Management
LMRP	Lower Marine Riser Package
MC	Mississippi Canyon
NACE	National Association for Corrosion Engineers
NORSOK	Norsk Søkkel Konkuranseposisjon (Norwegian Technology Centre Standard)
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
RP	Recommended Practice
SEMS	Safety and Environmental Management Systems