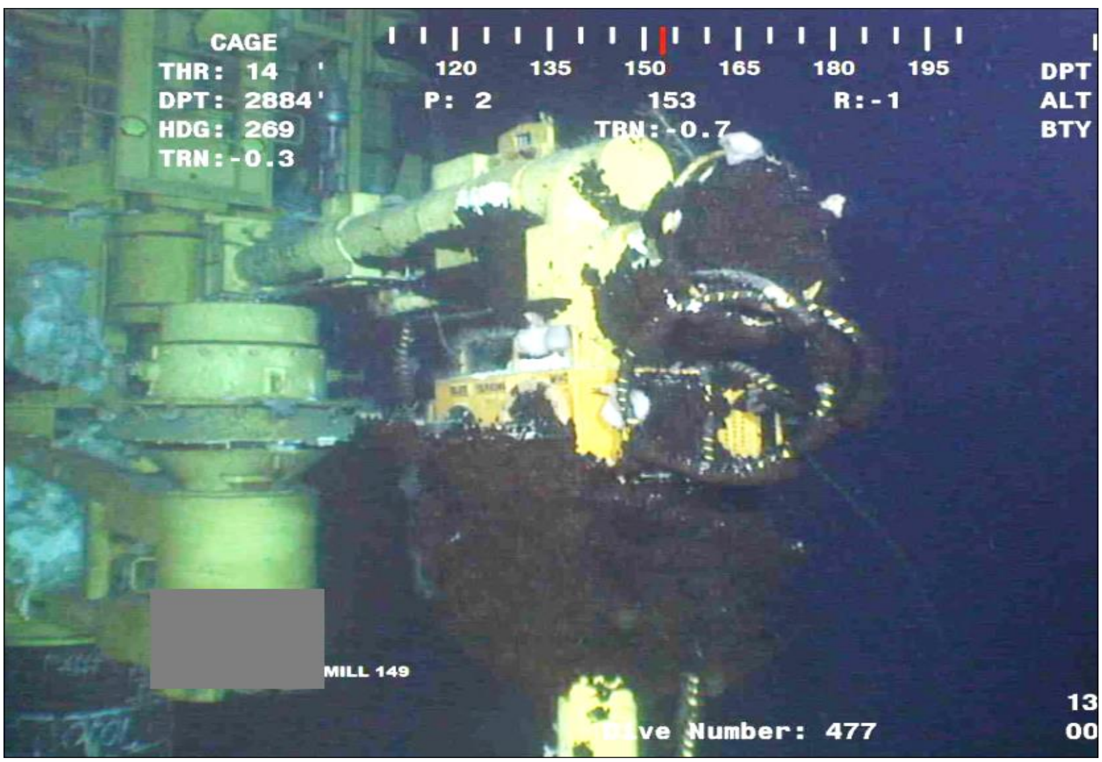
BSEE Panel Report 2018-001

Investigation of May 11, 2016, Shell Glider Subsea Jumper Leak, Lease OCS-G15565, Green Canyon Block 248 Subsea Well #4

Gulf of Mexico Region, Houma District
Off Louisiana Coast

March 9, 2018



U.S. Department of the Interior
Bureau of Safety and Environmental Enforcement

Contents

Abbreviations and Acronyms

- AISI - American Iron and Steel Institute
- ASTM - American Society of Testing Materials
- bbls- Barrels
- bopd- Barrels of Oil per Day
- BSDV- Boarding Shut Down Valve
- BSEE- Bureau of Safety and Environmental Enforcement
- CRO- Control Room Operator
- DVA – Direct Vertical Access
- EDS - Energy Dispersive X-ray Spectroscopy
- F – Fahrenheit temperature scale
- FCV- Flow Control Valve
- FOSC – Federal On Scene Coordinator
- GC- Green Canyon
- GOM – Gulf of Mexico
- LLJ- Load Limiting Joint
- mmcfd – Million Cubic Feet per Day
- MAOP – Maximum Allowable Operating Pressure
- MSCL - Multi-Sensor Core Logger
- MTR - Material Test Record
- MV – Marine Vessel
- OCS- Outer Continental Shelf
- OES - Optical Emission Spectroscopy
- OIM- Offshore Installation Manager
- OSCLA - Outer Continental Shelf Lands Act
- PLET – Pipeline End Termination
- PSL – Pressure Safety Low
- PSN – Pipeline Segment Number
- ROC- Rate of Change Sensor
- ROV- Remotely Operated Vehicle
- SCSSV- Surface Controlled Subsurface Safety Valve
- SEM - Scanning Electron Microscopic
- Shell- Shell Offshore, Inc.
- SS- Subsea
- SSW- Subsea Well
- Stress- Stress Engineering Services, Inc.
- TLP- Tension Leg Platform
- USV- Underwater Safety Valve
- WFMT - Wet Fluorescent Magnetic Particle

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Executive Summary

On May 11, 2016 at 23:11 at the Shell Glider field located in Gulf of Mexico Green Canyon (GC) Block 248 of the Outer Continental Shelf there was a substantial acoustic activity identified via the subsea well's control panel followed by a significant pressure loss of the Glider subsea system. This subsea system is tied back to the Shell Brutus tension leg platform (TLP) located in GC Block 158. The initial thought of the control room operators (CRO) on shift, was of a large gas bubble entering the system known as slugging. CROs on shift at the time began trouble shooting the believed slugging issue. At this time, the CROs did not suspect a subsea leak within the Glider system due to the recent history of slugging issues within the Glider subsea system.

The CROs continued to troubleshoot the suspected slugging issue until approximately 05:00 on May 12, 2016 when the CROs began to suspect the possibility of a mechanical integrity failure within the topside equipment associated with the Glider Field. A deck operator was dispatched to inspect the boarding shut down valve (BSDV) and flow control valve (FCV). The deck operator discovered no abnormal conditions with the topside equipment. At this time the day shift CROs were beginning their shift. Night shift CROs began to discuss the abnormalities with day crew as part of their normal handover procedures.

At 06:23, based on the verification of the mechanical integrity of the topside systems, the CROs began to verify the mechanical integrity of the Glider subsea system. Starting at 06:37 and continuing until 08:52, seven hours after the initial acoustic anomaly and pressure temperature drop in the Glider subsea system, CROs performed a controlled shut in of the Glider subsea field. At approximately 07:30, a crew change helicopter was diverted by the offshore facility management to search for signs of an oil sheen at the surface location of the Glider field.

At 07:46, the CROs suspected mechanical integrity issues subsea since they were unable to bleed the subsea system below hydrostatic pressure. At 07:55, the helicopter confirmed the presence of a surface oil sheen in the vicinity of the Glider field. At 08:52, the CROs secured the Glider subsea field by closing all surface controlled subsurface safety valves (SCSSV). Around 11:00, Shell made the decision to shut in the entire Brutus TLP, which included all direct vertical access (DVA) wells and the GC Block 157 J. Bellis subsea field. By 11:11, all DVA wells and J. Bellis wells were shut in.

On May 12, 2016 at 11:35, Shell notified BSEE of the incident. On the evening of May 12, 2016, Shell enacted their inspection procedure and a remotely operated vehicle (ROV) was called into the field to visually inspect for a leak in the Glider subsea system. Just after midnight on May 13, 2016, a crack was located on the Glider subsea well (SSW) #4 jumper below the mudline (Figure 1). The estimated volume associated with this leak was 1,926 bbls of oil.

Stress Engineering was contracted by Shell to perform evidence preservation and failure analysis of the Glider SSW #4 jumper. Stress concluded and BSEE agreed, the failure was a result of a ductile tensile overload fracture of the load limiting joint (LLJ) on the subsea jumper. After reviewing all available documentation, the BSEE investigation concluded the ductile tensile overload was caused by the burial of the subsea jumper and sled #2. This burial caused additional stress to the Glider # 4 jumper that was not accounted for in the jumpers design (Figure 2). This stress included the sled #2 settling further than anticipated and the partial burial of the Glider #4 jumper. This allowed additional stress impact the LLJ along with the jumper's restrained movement. The failure of the LLJ was most likely triggered by thermal expansion due to bringing the Glider #4 back into service.

The BSEE investigation revealed Shell was aware of the burial of parts of the Glider subsea system as early as February 2014. Shell performed a burial risk assessment; however, they failed to consider the LLJ as a potential risk due to it not being notated on the drawings used in the assessment. The LLJ was shown on structural drawings of the flowline jumper, but not on the piping instrumentation drawings which were used by Shell for their risk assessment. Additionally, Shell opined that even if they had not used the LLJ, the additional settlement and overburden over time, may have eventually failed the jumper at the next weakest point.

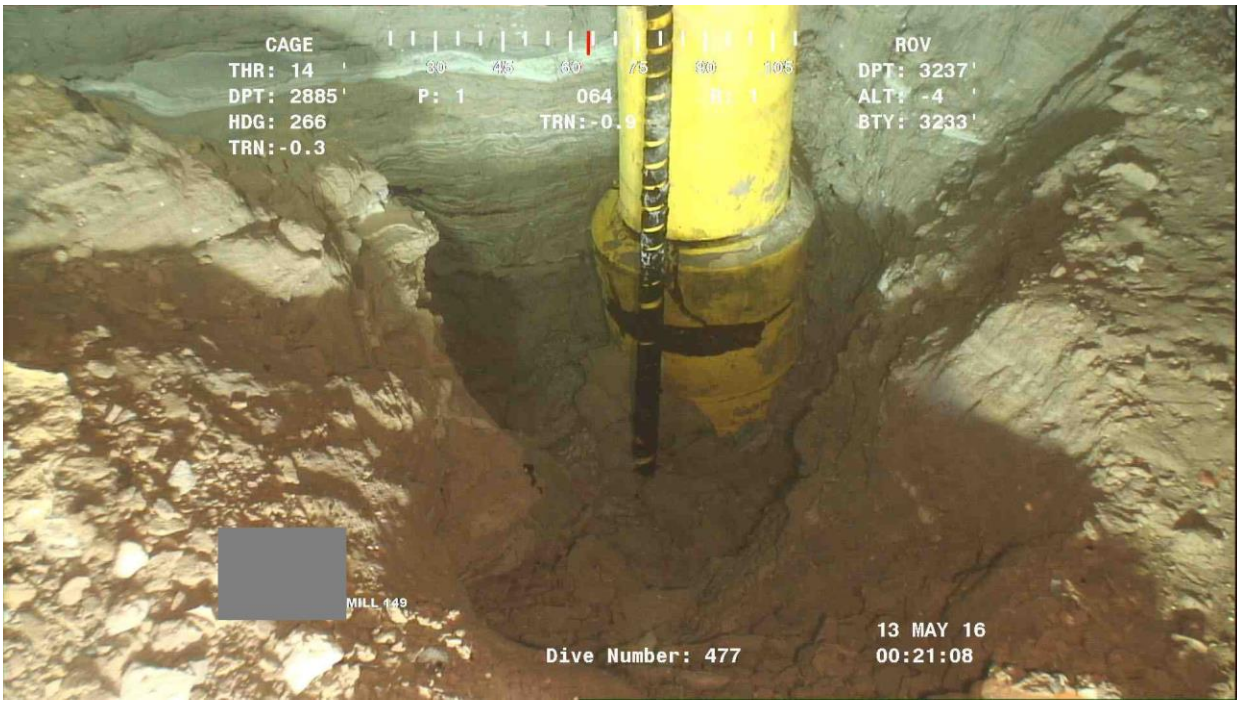

Figure 1 Glider #4 Well Side Jumper and Load Limiting Joint

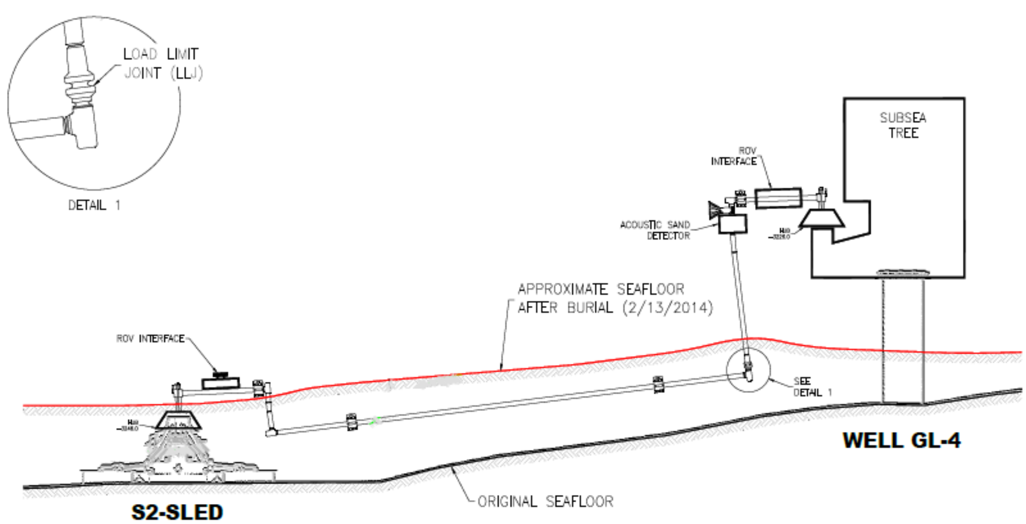

Figure 2 Glider #4 Jumper

Introduction

Pursuant to 43 U.S.C. § 1348(d)(1), (2) and (f) [Outer Continental Shelf Lands Act, as amended] (OCSLA) and United States Department of the Interior regulations 30 CFR Part 250, the Bureau of Safety and Environmental Enforcement (BSEE) is required to investigate and prepare a public report of this incident. BSEE convened a panel investigation that included:

- Stephen Dessauer(Chair), Chief, Production Operations Section, New Orleans District
- Candi Hudson, Chief, Systems Reliability Section, Emerging Technologies Branch, Sterling, VA
- Kelly Bouzigard, Production Operations Supervisory Inspector, Houma District
- Terry Hollier, Accident Investigator, Houma District
- Keith King, Special Investigator, Safety and Incident Investigation Division, Washington DC
- Cemal Ozoral, Petroleum Engineer, Office of Incident Investigation, Gulf of Mexico Region
- Phillip Smith, Petroleum Engineer, Pipeline Section, Gulf of Mexico Region

The purpose of this investigation was to identify the cause or causes of the Glider subsea well (SSW) #4 jumper failure at Green Canyon (GC) Block 248 and issue recommendations to reduce the likelihood of a recurrence or similar incident in the future. The BSEE Panel also makes other findings, conclusions, and recommendations relevant to the leak on May 11, 2016.

Companies Involved

Shell Offshore Inc. - (Shell) operates oil facilities and drilling units, and produces crude oil and natural gas. The company was incorporated in 1981 and is based in New Orleans, Louisiana. Shell Offshore, Inc. operates as a subsidiary of Royal Dutch Shell plc and was the operator of the Brutus tension leg platform (TLP) in Green Canyon 158 and the Glider field located in Green Canyon 248 on May 11, 2016.

Stress Engineering Services, Inc. – (Stress) According to their website, Stress has been providing solutions for companies and industries that require in-depth technical knowledge and proven performance in the fields of engineering design and analysis, thermal and fluid sciences, instrumentation, and testing since 1972.

Stress was contracted by Shell to perform evidence preservation and failure analysis of the Glider subsea well (SSW) #4 jumper.

Oceaneering – According to their website, Oceaneering is a global oilfield provider of engineered services and products primarily to the offshore oil and gas industry, with a focus on deepwater applications, founded in 1964. Their business offerings include remotely operated vehicles (ROVs), built-to-order specialty subsea hardware, deepwater intervention and manned diving services, non-destructive testing and inspection, and engineering and project management.

Oceaneering was contracted by Shell to perform the dredging activities, jumper removal, and soil sample collection via ROV from the marine vessel Norman Flowers. In addition, Oceaneering also provided evidence preservation and geotechnical analysis on the soil cores taken in the Glider field.

NGI – According to their website, since the 1950s Norwegian Geotechnical Institute (NGI) has been offering geotechnical expertise.

NGI was contracted by Oceaneering to ensure quality assurance and quality control of Oceaneering's laboratory destructive testing of the ROV cores and compiling the final report.

Background

Brutus TLP

Brutus TLP located in GC Block 158, was installed in 2001 in the GOM with a first production in September 2001 (Figure 3). The facility has eight direct vertical access wells, and is host to two subsea tieback developments, one of which is Shell's Glider field. The capacity for this facility is 130,000 bopd and 150 mmcfd.

Figure 3 Brutus TLP

Glider Subsea Field Overview

The Glider Field (Figure 4) is a deepwater oil and gas development with a water depth of about 3,000 feet located in GC Block 248 in the GOM, approximately seven miles southeast of the Brutus TLP. The water depth at the TLP is about 3,500 feet. The Glider Field consists of five completed SSWs; production from the Glider Field is through a single flowline and the field utilizes an electro-hydraulic umbilical to supply electrical power, communication, hydraulic power and chemicals to the subsea equipment. Shell was the BSEE designated operator of the Brutus TLP and Glider field at the time of the incident.

Figure 4 Glider Subsea Field

Relevant Equipment:

The Glider Subsea Tree

A Subsea tree is an assembly of valves, spools, and fittings used for hydrocarbon extraction. They are installed at the wellhead to monitor and control production from a well. Glider subsea tree was a dual bore Subsea tree rated for 10,000 psi, 7,500 feet water depth, and designed to operate between a temperature range of 35°F and 250°F.

The Glider #4 Jumper

The Glider #4 six-inch well jumper transports bulk oil from SSW#4 to sled #2 in GC Block 248. The jumper was assigned pipeline segment number (PSN) 14371 and installed and tested on March 30, 2004. The bulk oil then flows from sled #2 to the subsea manifold to and then to the Brutus TLP though the infield flow line Pipeline Segment Number (PSN) 14368.

Load Limiting Joint (LLJ)

The LLJ is located on the vertical portion of the jumper nearest to the well (Figure 5). It is an engineered weak section in the jumper so that the jumper will fail in a known way if overstressed. This section prevents the possibility of transferring unwanted loads to the SSW in an overstress event such as an anchor drag from a mobile offshore drilling unit, also known as a MODU.

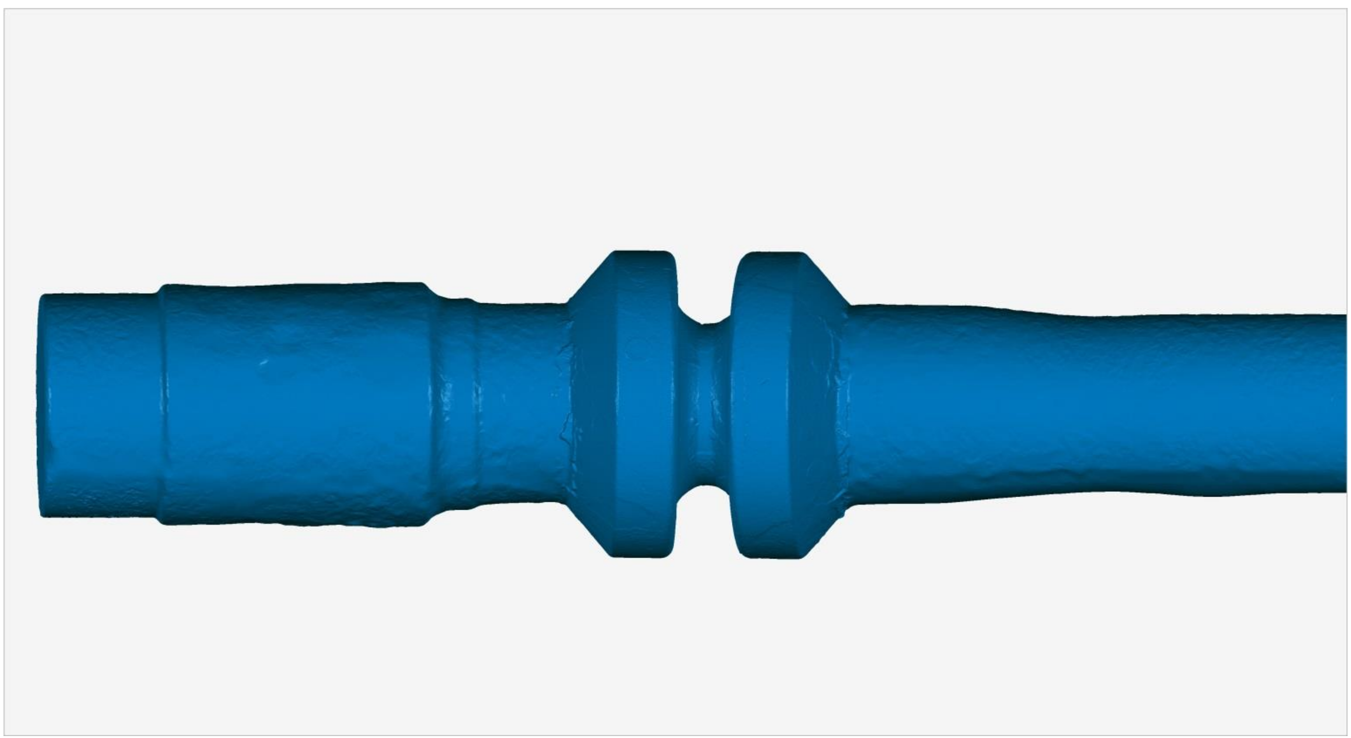

Figure 5 Load Limiting Joint

Timeline

- 5/5-5/8 - Xylene soak for Glider #4
- 5/11 at 18:00, Shift change from day crew to night crew. Day crew informed night crew Control Room Operator (CRO) of continued slugging issues for situational awareness. At this time Glider SSWs #3, #4, #7, and #8 were all producing.
- 5/11 at 20:15, further opening of topside flow control valve (FCV) 56% to 60% (normal operating conditions of SSWs)
- 5/11 at 21:15, further opening of topside FCV 60% to 65% (normal operating conditions of SSWs)
- 5/11 at 23:09, further opening of topside FCV from 65% to 70%. Sled #2 pressure remain stable(normal operating conditions of SSWs)
- 5/11 at 23:11, Multiple Glider subsea pressure sensing devices detected a pressure drop accompanied by a large acoustical anomaly. Multiple system alarms (operator use only) were triggered. CROs were aware of these alarms and pressure drops. The CROs then started trying to trouble shoot the situation. Past experience and hand over notes lead the CROs to believe this incident was caused by gas slugging.
- 5/11 at 23:13, Glider FCV 70% to 35%
- 5/11 at 23:17, Glider well #3 automatically shut in due to a rate of change sensor (ROC) alarm high set point. Please note, the ROC alarm is not designed for subsea leak detection (Glider #3 choke was fully open)
- 5/11 at 23:25, CROs reopen Glider #3. CROs assumed the well shut in due to a gas slug in the flow line dropping the pressure which would allow the Glider #3 well to flow at a higher rate.
- 5/11 from 23:31 to 5/12 at 05:00, CROs continued to manipulate topside and subsea FCVs to troubleshoot the declining pressures.
- 5/12 shortly after 05:00, day crew members came in to the control room and were made aware of situation (Offshore Installation Manager (OIM) and Production Engineer). A deck operator was dispatched to the boarding shut down valve (BSDV) area and FCV area to look for hydrocarbon leaks or malfunction of valves systems.
- 5/12 at 06:41, Glider #3 and #4 shut in by closing subsea FCVs.
- 5/12 at 06:50, Glider #7 shut in.
- 5/12 at 06:59, Glider #8 shut in.
- 5/12 at 07:08, Glider FCV opened to 50% to try and bleed sled #2 pressure below hydrostatic pressure.
- 5/12 at 07:30, A crew change helicopter was diverted to check for possibility of a sheen in the area of the Glider subsea field.
- 5/12 at 07:46, Glider FCV opened to 100% in order to try and bleed sled #2 pressure below hydrostatic pressure. Sled #2 pressure stabilized at hydrostatic pressure and would not bleed below. Subsea leak was suspected and awaiting visual confirmation.
- 5/12 at 07:55, Inbound helicopter observes sheen.
- 5/12 at 08:35, Shell notified BSEE Houma District Office of this incident.
- 5/12 at 08:35, Shell activated its Incident Management Team and stood up a unified command with USCG Morgan City and the Louisiana Oil Spill Coordinator's Office. Shell deployed 5 skimming vessels and requested authorization for the use of aerial dispersants.

- 5/12 at 08:52, All SCSSV’s shut-in (Glider subsea FCV all closed prior). All potential sources were closed. USVs and SCSSVs closed.
- 5/12 at 11:35, Shell notified BSEE of the incident.
- 5/12 at 18:30, the first recovery asset arrived on scene and began recovering oil. While the Federal on Scene Coordinator (FOSC) had the authority to utilize aerial dispersants, Shell was never granted authorization.
- 5/16, No recoverable oil could be found by aerial assets and the decision was made to stand down the Unified Command. Skimming vessels recovered 842 barrels of oil/water emulsion by the end of the response. Shell's response to this incident was in compliance with their Oil Spill Response Plan.

The BSEE Investigation

The BSEE Panel collected and reviewed large volumes of electronic and written material, including but not limited to well data, emails and other records related to Shell's equipment, management systems, supervision of employees and contractors, communications, performance and training of personnel, relevant company policies and practices, and work environment. The BSEE Panel conducted interviews of multiple personnel and was involved in additional fact-finding through inspection, observation, and testing of involved equipment in the GC Block 248 incident.

Evidence Preservation and Testing Protocols:

Throughout the course of this investigation BSEE worked closely with Shell, Stress Engineering Services, and Oceaneering on evidence collection, preservation, and testing protocols. These protocols ensured BSEE and Shell received timely and accurate results which allowed BSEE to formulate our conclusions.

Initial Onsite Investigation:

BSEE investigators arrived at Shell Brutus TLP on the afternoon of May 12, 2016, to conduct their initial onsite investigation. Due to weather restrictions, the initial BSEE investigation was relegated to verifying the size of the sheen only. BSEE investigators returned on May 13, 2016 and conducted additional investigative activities and retrieved documentation. BSEE investigators also verified the shut in and securing (BSDV, USV, and SCSSV closed) of the Glider field. BSEE personnel were onsite at the Shell response center working with Shell on their containment and response to this incident.

Follow Up Onsite Investigation:

On May 15, 2016, a BSEE investigator arrived on the Marine Vessel (MV) Norman Flower to witness the Shell and BSEE approved dredging operations and recovery of the Glider #4 well jumper assembly. The BSEE investigator also witnessed the Shell and BSEE approved soil sample extraction.

Interviews:

BSEE panel members conducted multiple interviews of office and offshore personnel associated with the Glider incident. These interviews were instrumental in developing the Glider incident timeline, as well as the thought process of the individuals associated with the incident, both onshore and offshore. There were two CROs on the night shift with the lead operator having 1.5 years of experience and the secondary operator starting his first period of service also known as a hitch, as a CRO. Both night shift CROs were considered by Shell as being qualified for their respective positions. Based on interviews conducted, Shell typically would include a 3rd CRO to mentor employees. However, the assigned mentor was on vacation and was not replaced by Shell due to it being an optional position.

Offshore Personnel Interviews:

BSEE investigators conducted multiple interviews of offshore personnel at Shell's corporate office located at One Shell Square in New Orleans, Louisiana. The personnel included the acting OIM, CROs for the day and night shift, and a production technician. The testimonies provided by these individuals were consistent and the information gathered is as follows:

On May 11, 2016 at 18:00, the night shift started their shift with a handover briefing from the day shift which explained the slugging issues the Glider subsea field was experiencing. These slugging issues were believed to be a result of the xylene soak which was recently completed. This was the first working day of their rotation. The night shift CROs were continuing to ramp up well production as instructed by the day shift CROs when the pressures of all pipeline end terminations dropped by approximately 500 psi. The normal operating pressure of the sleds was approximately 2,000 psi. This pressure drop was accompanied by several system alarms (a sand detection alarm from the acoustical sensor and various pressures sensors) which prompted the CROs to begin troubleshooting the issues. The Glider SSW#3 was shut in approximately 6 minutes later due to the ROC sensor.

Based on the notes provided in the handover briefing, the initial thought of the night shift CROs was this pressure drop was caused by slugging. The previous day shift had received a gas slug and had reacted by manipulating the topside FCV. The night shift CROs manipulated the topside FCV, just as day shift had. Again, this was due to the belief that a large gas slug was headed to the platform and they did not want to over pressure the Glider separator which would cause a field shut in. Additionally, the Glider SSW#3 was also reopened. When the night shift CROs did not see the response they were expecting from the topside FCV adjustment, the night shift CROs began manipulating the subsea FCV to maintain the well bottom hole pressure. These adjustments continued from approximately 23:30 on May 11, 2016 to 05:00 on May 12, 2016.

After not seeing the expected pressure responses all night, the day and night crew CROs began troubleshooting the topside mechanical equipment for system integrity. A deck operator was dispatched to the Glider BSDV area and FCV area to look for hydrocarbon leaks or malfunction of valves systems. No issues were found topside. The day crew CROs began their shift at this time. They shifted their focus to troubleshooting a possible subsea mechanical integrity issue. The Glider SSW #3 and #4 production were shut in by closing the well FCVs. Around this time, a crew change helicopter was diverted to the surface location of the Glider field to check for an oil sheen. While the helicopter was rerouted to the Glider subsea field, the day shift CROs attempted to bleed the sleds below hydrostatic pressure to verify subsea mechanical integrity. They were unable to bleed below hydrostatic pressure. Around this time, the helicopter observed an oil sheen at the surface location of the Glider field and notified the Brutus TLP. This confirmed the existence of a subsea leak in the Glider subsea system. The CROs then began to secure all Glider SSWs by closing the well USVs and SCSSVs.

Based on testimony provided during the interviews of the night shift CROs, they did not consider a subsea leak to be the cause of the original pressure drops documented at 23:11. As per testimony, subsea leaks were not a scenario they had been trained to recognize either by class room or on the job training. In addition, testimony provided by the CROs opined the robustness of the subsea system was high and therefore the probability of a subsea leak in their minds was extremely low. The Glider subsea system was rated for 10,000 psi maximum allowable operating pressure (MAOP) and the normal operating pressure at the time of the incident was approximately 2,000 psi. Based on testimony and records reviewed the pressure within the Glider system never exceeded the MAOP.

At the time of the incident, Shell did not include any subsea leak detection and recognition as part of their training for CROs.

Onshore Personnel Interviews:

The onshore personnel interviewed at One Shell Square were flow assurance engineers assigned to the Glider field. Based on testimony, Shell's flow assurance engineers were available after hours, but are seldom contacted. By the time the engineers reported to work the morning of May 12, 2016, the Glider field was already shut in and the oil sheen had been confirmed. Their testimony was predominantly about how they assisted in determining the location of the leak and with the estimation of oil released. One of the engineers mentioned that Shell was aware the flow line jumper had been buried, but that it was determined by Shell's risk assessment team not to be an issue at the time.

Evidence Collection and Testing:

BSEE worked with Shell, Stress, and Oceaneering on the collection, preservation, and testing of all evidence associated to this incident. BSEE viewed and approved the testing procedures proposed by Shell and Stress. Metallurgical test conducted on the subsea jumper and the LLJ were approved and witnessed by BSEE Engineers. Testing took place at Stress test facilities located in Houston Texas. Results of the metallurgical testing performed on the jumper and LLJ were summarized in Stress's report dated August 30, 2016. In addition to Stress' report, BSEE conducted an independent analysis of the data. BSEE's findings were in agreement with Stress' results.

Material and Soil Testing and Witnessing:

Metallurgical testing revealed no manufacturing defects or anomalies with the jumper line and LLJ. The LLJ failure was a result of a ductile tensile overload fracture from bending loads imposed on the jumper and LLJ (Figure 6). The source of these bending loads was produced by drill cuttings and excess cement which had covered the jumper line, sled #2, and LLJ. These cuttings and excess cement were deposited by the open hole drilling of Glider #6, #7, and #8 development wells in late 2013 and early 2014.

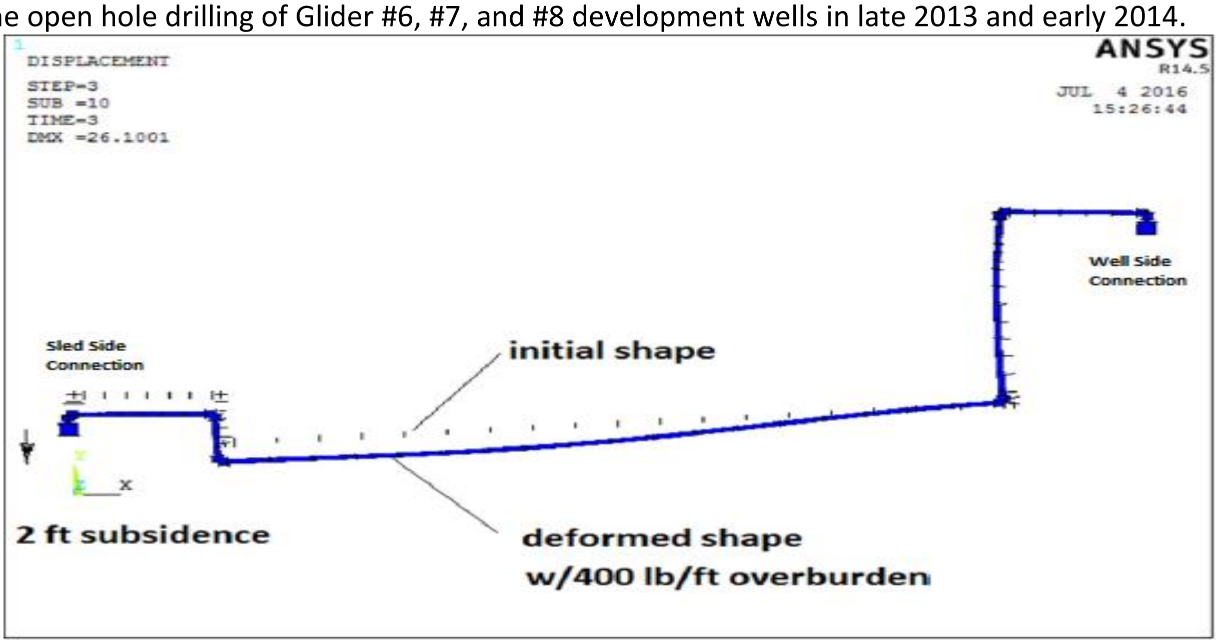

Figure 6 Deformed Shape of the Jumper

Metallurgical Analysis:

Shell submitted the failed Glider GL-4 well field jumper LLJ, piping, tree, and sled connectors to Stress for laboratory metallurgical failure testing and analysis. The equipment was transported to Stress's test facility in Waller, Texas for storage, photographic documentation, initial observation, and sample collection. A storage, initial observation and metallurgical test protocol[1] for the failed LLJ was developed by Stress and Shell with concurrence from BSEE.

Since the only identified cracks were located at the designed "weak-link" U-Groove of the LLJ, the metallurgical failure testing and analysis focused on the LLJ fracture (Figure 7). The following metallurgical tests and analyses were performed on the LLJ:

- Insulation removal
- Borescopic[2] examination of the jumper inner diameter around any leak/fractures
- Cross-sectioning at the fractured U-Groove LLJ for fracture evaluation
- Structured white light scan of the jumper including near leak and fracture location
- Wet fluorescent magnetic particle (WFMT)[3] examination for any observed secondary cracks
- Visual observation and fracture morphology characterization by, stereomicroscope and scanning electron microscopic (SEM) examination[4] with back scattered electron imaging mode[5] and energy dispersive x-ray spectroscopy (EDS)[6] of the fracture surface and any identified deposits/corrosion products
- Metallographic examination[7] of etched surfaces
- Fractography (fractographic)[8] examination of the fractured surface
- Hardness measurements in and surrounding the fractured location
- Charpy impact tests
- Tensile tests; and
- Verification of base metal chemical composition by optical emission spectroscopy (OES)[9] per the LLJ's Material Test Record (MTR)[10].

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[1] Note, the Storage /Initial Observation and Metallurgical Test Protocol proposed Scope of Work (SOW) was developed without knowledge of the existence of any additional leak points or fractures. Any identified additional leak locations/fractures were documented during the initial observation process.

[2] Borescope is an optical tool used to non-destructively visually inspect inaccessible areas that would require destructive methods for observation.

[3] Wet Fluorescent Magnetic Particle (WFMT) Inspection is a non-destructive method for identifying surface and subsurface abnormalities in metals.

[4] Scanning Electron Microscope(y) (SEM) is a high resolution microscope used to view images at high magnifications greater than an optical microscope (resolution greater than 1 nanometer). SEM produces images by scanning the sample's surface with a focused beam of electrons. The electrons interact with sample's atoms resulting in an image with surface structure and composition information.

[5] Back Scattered Electron (BSE) imaging mode (detector) on the scanning electron microscope (SEM) is a feature used to image fractured surface features of a component. BSE is also used to determine a component's elemental composition and analyze any identified corrosion products or dirt.

[6] Energy Dispersive X-ray Spectroscopy (EDS) is a method used to determine the chemical composition for a material. EDS is usually a part of a scanning electron microscope (SEM).

[7] Metallography (Metallographic) Examination is visual observation of a metal's microstructure, grain size by optical microscopy under different lighting to verify that the correct heat treatment was performed. Kaling's etchant was used to reveal the microstructure of the failed LLJ U groove base metal.

[8] Fractography (fractographic) is examination of fractured metals' surfaces at high magnification to determine the fracture type (brittle, ductile) and cause for fracture.

[9] Optical Emission Spectroscopy (OES) is an analytical tool used to determine the elemental/chemical composition (chemical elements) for a metal alloy. OES is a quick analytical test method which can produce results within 1-5 minutes. The OES instrument strikes the sample surface which bounces light that is diffracted into the analyzer to determine the chemical composition.

[10] Material Test (Trace) Record (MTR) is a record of the metal's chemical composition, mechanical properties, heat treatment

Figure 7 Load Limiting Joint Fracture

The etched microstructure for the LLJ base metal was tempered martensite[11], typical microstructure for American Iron and Steel Institute (AISI) 410 stainless steel and per the Material Trace Record (MTR) specification. There were no identified manufacturing microstructural defects or anomalies present in the etched microstructure that may have contributed to the fracture of the LLJ. The chemical composition, hardness, Charpy impact, yield and tensile strengths for the fractured LLJ and identified secondary crack were verified to be within the MTR specification for AISI 410 stainless steel.

Based on visual inspection, optical, SEM examination and metallurgical testing of the LLJ and jumpers, it appears that the fracture in the LLJ responsible for the Glider GL-4 leak was a result of bending tensile loads imposed on the jumper and LLJ system due to the deposited soil, cement, and drill cuttings. Further, BSEE and Stress concluded, the vertical tree-to horizontal jumper and 90-degree connection/elbow was subjected to a bending moment caused by the overload which resulted in an attempt to straighten the elbow (90 degree connection). The bending moment placed the inside of the elbow in tension with the outside of the elbow in compression. As a result of the overload, the tension side of the LLJ fractured in response to the applied moment. The ductile fracture LLJ occurred at the designed “weak link” U-groove joint failure location (weakest joint). The ductile fracture, most likely due to bending loads imposed on the jumper and the LLJ system.

The tension side (inside the 90-degree elbow) of the LLJ U-groove fractured in response to the applied moment due to overload likely from the drill cuttings. While the compression side of the U-groove did

conditions, raw material processing method with conditions, and materials test performed on the component’s base metal. Tests performed on base metal typically are: hardness; tensile; Charpy V-Notch Impact; and chemical composition analysis.

[11] Tempered martensite is the microstructure for iron based steel materials resulting from the tempering heat treatment process. Temperature martensite microstructure looks like small, needle like shaped dense particles. Tempering is a heat treatment process performed to increase iron based alloys toughness by reducing the hardness property.

not fracture. There was an increase in the wall thickness of the U-groove due to the applied moment to the jumpers. Therefore, forensic metallurgical analysis confirmed the fracture morphology was primarily due to ductile tensile overload of the LLJ.

Fractographic and WFMT examination of the compression side of the crack identified that the crack was generated due to cleavage fracture (brittle fracture). The presence of cleavage fracture indicates that the crack generated under different conditions than the primary fracture, i.e., either under lower temperatures or dynamic loading or both conditions. Determining the load history and the environmental effects (Joule-Thomson Cooling Effect[12]) post primary fracture were beyond the scope of the metallurgical investigation.

Soil Analysis:

A ROV collected seven[13] push soil core samples at GC Block 248 Shell Glider field in the GOM. The ROV push core samples were acquired from the MV Norman Flower between May 15, 2016 and May 17, 2016 during operations to dredge and recover the GL4 well jumper. The ROV push core soil samples were collected in 2.5 inch outer diameter (OD) steel core barrels from a depth of 1.58 feet (ft.) to a maximum depth of 4.4 ft., covering an approximate area of 350 square feet (ft^2). Two samples were collected from a dredged line approximately 3 feet below the current sea floor before collection.

The collected core soil samples were sent to Oceaneering for storage, laboratory testing and analysis. A separate storage and test protocol[14] for testing and analysis of the collected core soil samples was developed by Oceaneering and Shell with concurrence from BSEE. Oceaneering subcontracted NGI to ensure quality assurance of the geotechnical laboratory testing, data analysis and interpretation of the soil parameters, soil structure interaction for the partially buried well jumper and LLJ. Several laboratory classification tests and analyses were conducted per American Society of Testing Materials (ASTM) standards on the collected core soil samples to characterize the soil nature and properties. The following non-destructive analyses and classification tests were performed on the core soil samples: X-ray imaging; multi-sensor core logger (MSCL) analysis; water content; unit weight; specific gravity; organic content; calcium carbonate; salinity; plasticity index; grain size, drained and undrained strength tests.

The majority of the recovered cores consisted of recovered silt (80% fines), fine sand with a high specific gravity of approximately 4. There was an exception for one of the cores (Core 4) which consisted of soft clay just below the silt at the bottom of the sample. Grain size measurements included particle sieve analysis for the more coarse sandy material, while hydrometer measurements were conducted on finer sized particles. The maximum particle size for the cores was 1 mm. The cores sediment layer had a total unit weight of approximately 150 lb./ft^3 (pounds per cubic foot, pcf), while for Core 4, the total unit weight of the clay soil was approximately 128 pcf. The submerged unit weight of the fill sediment varied between 86 to 95 pcf. The clay identified at the bottom of Core 4, the submerged unit weight was approximately 64 pcf.

Undrained miniature vane strength tests were conducted prior to classifying the sediment as

[12] Joule-Thomson "Cooling" Effect (also known as the Joule-Kelvin Effect, Joule-Thomson Expansion) is the temperature change of gas (or liquid) when forced through an insulated valve where heat is not exchanged with the environment.
[13] One of the collected push core soil sample tubes was bent, therefore six samples were analyzed.
[14] The soil storage and testing analysis protocol outlined custody transfer, storage procedures, and timeline for testing.

granular/cohesionless. The results were not reported because undrained strength is not recommended to characterize the granular behavior for sediment. There was an exception to this recommendation for Core 4 at depth of 3.93 feet where clay was identified. The measured undisturbed strength at 3.93 feet depth was between 270 psf to 400 psf (1.9 to 2.8 psi), typical values for soft clay. The measured sensitivity for the clay was approximately S_t=2.0.

Due to the granular nature of the most of the core samples, plasticity tests were not possible. There was one exception for the bottom of Core 4 at 3.93 ft. depth where the plasticity index value was approximately 27%.

A comparison of the original Glider field soil properties with collected core soil samples properties was made. The soil at the bottom of Core 4 was harder than the original soil sample. Since the original sample location was a considerable distance from Core 4, therefore, it cannot be confirmed that the soil parameters are the exact same before the fill sediment was deposited. Also, the soil below the silt layer consists of clay at the bottom of Core 4 sample.

Investigative Document Review:

BSEE investigation revealed Shell was aware of the burial of parts of the Glider subsea system as early as February 2014. During the second phase of the Glider field development, Shell's underwater survey identified several subsea components as being buried by the riserless hole drilling of Glider #6, #7, and #8 development wells. Specifically, with regards to this incident the sled #2 and Glider well #4 jumper were identified as buried.

Shell performed a risk assessment to identify hazards associated with the burial of the Glider subsea components. Based on Shell's risk assessment, three phases of dredging were implemented that spanned across 19 months. Dredging was performed to allow for access to all controls and valves, visual inspection of equipment, and monitoring of cathodic protection. At the conclusion of the dredging program, the Glider well #4 jumper to include the LLJ remained partially buried. (Ref figure 8)

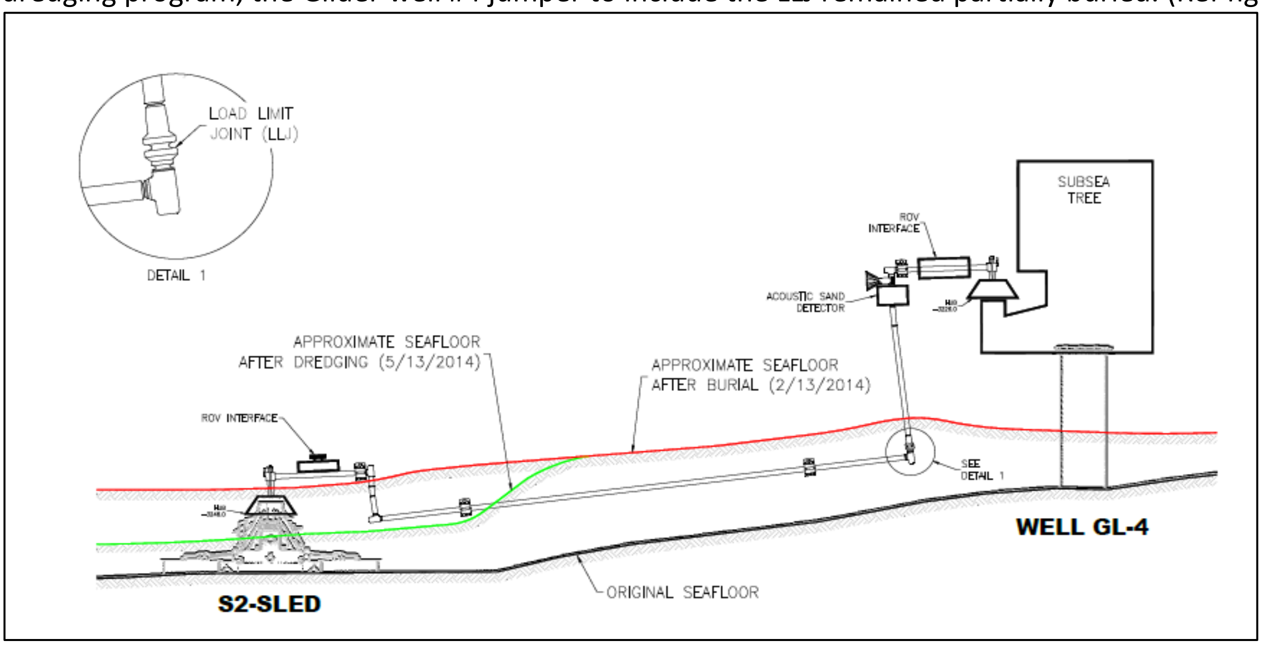

Figure 8 Jumper Line Pre and Post Dredging

BSEE's investigation revealed that the drawings of the Glider #4 jumper used in Shell's risk assessment did not show the LLJ. The LLJ was shown on structural drawings of the Glider #4 jumper, but not the piping instrumentation drawings Shell used for the risk assessment. This risk assessment did not consider structural integrity as a potential risk; therefore, the structural drawings were not reviewed. Post incident analysis shows that even if Shell had not used the LLJ, the additional settlement and overburden over time may have eventually caused the jumper to fail at the next weakest point.

Documents provided by Shell (ref figure 9 and figure 10) show the difference between a slug working its way through the Glider subsea system and the rupture which happened May 11, 2016. In figure 9, it is noticeable when the subsea pressure for sleds #1, #2, and #3 drop between 50 and 100 psi due to a slug. It is also noticeable when the slug leaves the system and return to normal operating pressure occurs. Figure 10 shows a more dramatic pressure drop between 400 and 500 psi for sleds #1, #2, and #3. Additionally, in figure 10 there is almost no return to normal operating ranges as you see happen during a slugging issue in figure 9.

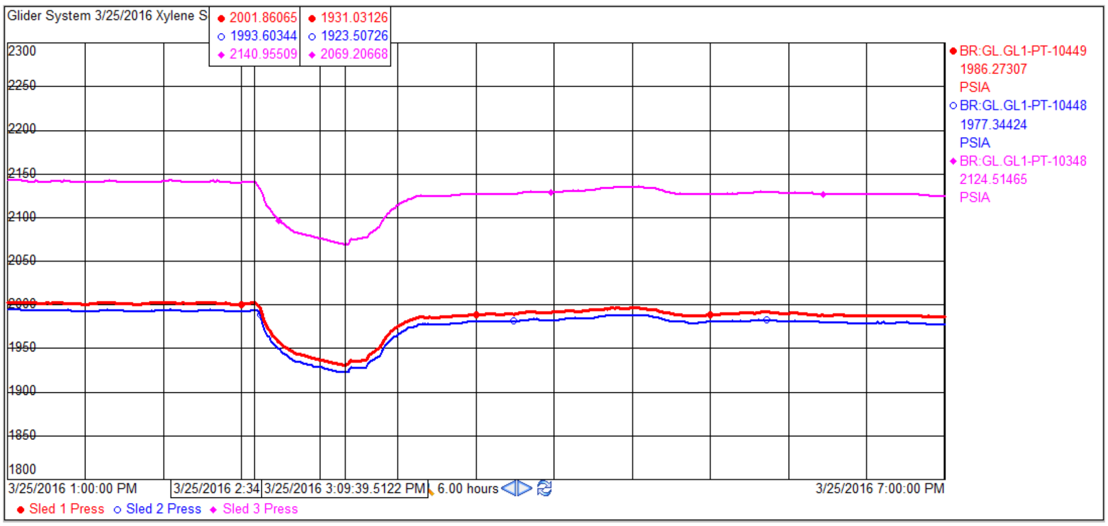

Figure 9 Glider Subsea Systems Processing a Slug

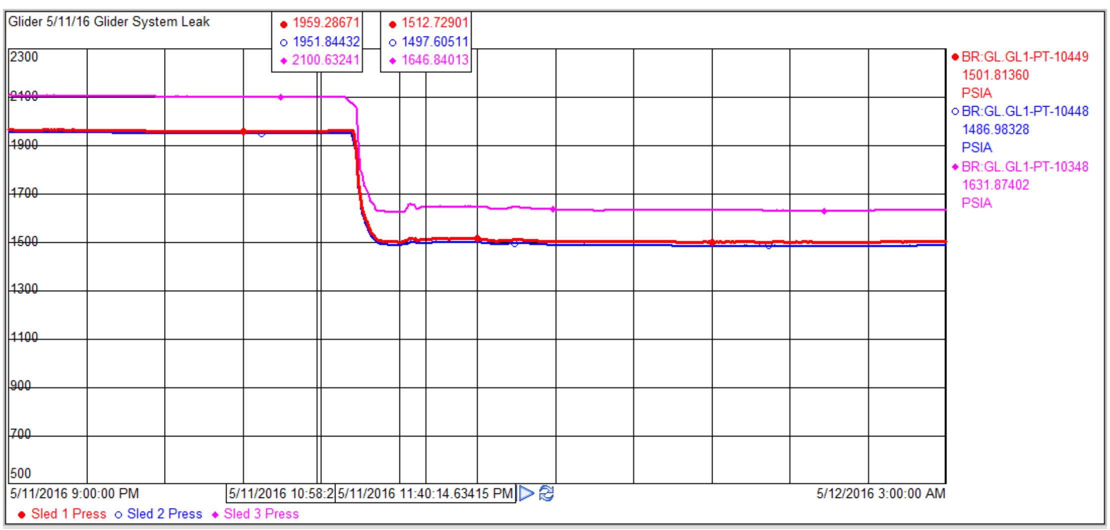

Figure 10 Glider Subsea Systems During Rupture

Documents reviewed by BSEE showed that the Pressure Safety Low (PSL) sensor on the incoming flowline from the Glider Sub Sea Field was set at 169 psi. BSEE inspectors had performed an inspection at the Brutus TLP the week prior to the incident. During that inspection, BSEE Inspectors had reviewed the range chart data establishing the PSL set point for compliance as well as tested the PSL for proper activation. On the day of the incident, CROs were manipulating the Brutus TLP top sides choke while troubleshooting the pressure drop at the subsea pipeline sleds. The CROs manipulation of the topsides choke kept the pressure at the surface above the set pressure of the Glider PSL sensor. In addition, BSEE confirmed that required isolation equipment (BSDV, USVs, and SCSSVs) was operating properly and was tested in accordance with BSEE regulations.

Conclusions

Based on BSEE's investigation and all available data, BSEE concluded that the loss of containment in the Glider subsea system was caused by the ductile tensile overload fracture of the LLJ of the Glider #4 jumper. The ductile tensile overload fracture was caused by the bending loads imposed as a result of the partial burial of the Glider #4 jumper and subsequent subsidence of the subsea sled #2 (ref figure 7).

Based on BSEE's investigation and all available data, BSEE concluded there were no manufacturing defects or anomalies in the components of the Glider #4 jumper, to include the LLJ.

Based on BSEE's investigation and all available data, BSEE concluded Shell had knowledge of the burial and did not recognize and therefore did not fully assess all possible factors for the structural risk associated with the burial of the Glider #4 jumper system.

Based on BSEE's investigation and all available data, BSEE concluded CROs were not cognizant of the possibility of subsea mechanical integrity failure due to the lack of training in subsea leak detection and the perceived robustness of the Glider subsea system. In addition, CROs incorrectly diagnosed the loss of pressure in the subsea system as a slugging event instead of a breach of the system. This directly led to the delay of identifying the subsea leak, which delayed the shutting in and securing of the Glider field. A quicker identification of a subsea leak would have led to a reduced volume of oil released.

Based on BSEE's investigation and all available data, the required Glider leak detection system (Pressure Safety Low sensor) installed on the Brutus TLP was operating properly and was tested in accordance with BSEE regulations. In addition, isolation equipment (BSDV, USVs, and SCSSVs) was operating properly and was tested in accordance with BSEE regulations.

Recommendations

Based on BSEE's investigation and all available data, the Panel recommends when drilling the riserless portion of a subsea well in the vicinity of other subsea infrastructure (i.e. pipelines, sleds, subsea wells, etc.), operators need to ensure the resulting drill cuttings and cement are not adversely affecting or posing additional risks to existing subsea infrastructure.

Based on BSEE's investigation and all available data, the Panel recommends OCS operators should educate CROs that, subsea leaks are possible. Training should include how to identify subsea leaks and how to perform appropriate isolation activities.

Based on BSEE's investigation and all available data, the Panel recommends that when it is discovered by the operator that environmental factors have changed (i.e. equipment has become buried) an engineering assessment should be performed to ensure equipment is operating inside acceptable design parameters. Additionally, notifications should be made to appropriate regulatory authorities.

Based on BSEE's investigation and all available data, the Panel recommends that operators conduct a routine underwater visual survey of their subsea infrastructure to ensure that their subsea system is still operating within the designed parameters.

Based on BSEE's investigation and all available data, the Panel recommends that industry and regulatory authorities seek out the best available and safest available technology for leak detection in complex subsea projects. For subsea installations that include more than a single subsea well tieback, operators should analyze the system for any potential leak events and implement processes to identify/detect parameters that are more indicative of a leak than the required Pressure Safety Low Sensor located upstream of the Boarding Shutdown Valve.