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Use of Pressure-Activated Sealants to Repair Leaking Subsea Horizontal Tree Connectors (Unlatch HXT)

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Abstract

A large, Australian operator was in the process of a subsea abandonment campaign of 12 wells, 9 of which were completed with Horizontal Trees (HXT) installed, when they initially noted hydraulic system failure from multiple HXT H4 connectors during their attempts to hydraulically unlock and remove the trees. Planned contingency unlock methods were employed but proved to be successful for only 2 of the 9 HXT's. As the operator progressed through the campaign, all 9 of the HXT connectors of the same make and design were confirmed to be affected. To proceed with abandonment operations as planned, and avoid the extensive costs associated with a significant scope change, the operator identified the need to restore hydraulic integrity as the only practical means of generating sufficient force to unlock the connectors and remove the HXT's.

The operator made contact with an engineered sealing solutions provider and discussed the issue at hand. Through analysis and discussion with the operator, a repair procedure was developed to utilize a subsea accumulator skid to inject a custom blended sealant via HFL's through a RWOCS plate and into the HXT Tree Connector Unlock System. This sealant would then be injected to completely fill the unlock chamber temporarily restoring integrity of the damaged elastomeric seals and enabling the connector to be unlocked conventionally

Following the development of the necessary approach and sealant blend, the first two HXT connectors were repaired and successfully disconnected using a retrofit RWOCs panel skid with affixed accumulators. Prior to performing the third repair, the operator designed and manufactured a purpose-built accumulator skid with all associated tooling to streamline the operation. The next two HXT connectors were then successfully repaired and disconnected using this enhanced equipment spread and methodology. Currently, operations have proceeded using this methodology with 100% success rate to unlock connectors on all the remaining wells.

Whilst the root cause of the failed seal elements within the connector has not yet been determined, the repair procedure has proven to be successful and has evolved over time to meet the bespoke requirements of each connector, including sealant repair of the Tree Connector Lock chamber, thereby enabling cycling of the connector to break friction and encourage movement of the locking dogs prior to TCU repairs. This

approach, along with modified overpull techniques, has proven successful in enabling the HXT's to be removed.

Introduction

The MODU based Plug & Abandonment "P&A" scope included 12 subsea wells, 9 of which were completed with HXTs. These 9 HXTs all latched onto the wellhead via an H4 Tree Connector that was uniform in design and operated hydraulically by a water-based control fluid. As the operator proceeded through the campaign, it became apparent that none of the HXT's could be unlocked conventionally i.e. hydraulically via the Tree Connector Unlock (TCU) system. Additional issues were noted when injecting via the Tree Connector Lock (TCL) system in some candidates. The issue was severe enough to prohibit any connector stroke or development of effective pressure at varying injection rates.

Statement of Theory and Definitions

The H4 connectors in question were designed with a single annular piston which could be hydraulically stroked downwards via the TCL system to lock the tree in place, or upwards through the TCU system to unlock the tree and allow its removal (See Figure 1). A combination of static and dynamic elastomeric seals arranged on both the annular piston and connector body serve to isolate the lock and unlock chambers to facilitate piston movement according to the desired action. In the lock position, the geometry of the annular piston is such that the locking dogs are engaged against the hub. Conversely, as the connector is unlocked, the piston profile allows the dogs to retract, and due to the interface of the locking dogs on the hub profile, allows the tree to be pulled.

Given the inability to use conventional means to unlock the connector, the operator was left to determine a forward path. The TCU side of the annular piston features an effective surface area of approximately 610 in2 and a typical unlocking operation could involve application of up to 3,000 psi, its maximum working pressure, which would deliver approximately 1,830,000 lb/f. Industry advice, however, suggests the connector design would be expected to commence unlocking in the range of 1,000 psi to 1,200 psi for connector installed subsea over long durations. Some of the HXTs designs featured a override system interface, essentially guide rails, which allowed a jacking system to be placed below the override ring load transfer blocks and apply external force to manually function the piston (See Figure 2 below). This jacking system was composed of three (3) separate cassettes, each featuring three (3) hydraulic jacks, comprising a total effective piston area of 99 in^2. Structural limitations within the system enabled a maximum pressure of 7,100 psi to be applied to the nine (9) jacks to deliver a maximum force of approximately 702,900 lb/f. The force resultant from these jacks is theoretically sufficient to unlock the connector, however, as the operator would observe throughout the campaign, additional factors limited the success in the application of the jacking system. Throughout the development of the campaign, the bespoke jacking system was only utilized successfully in 2 cases, although it was installed on all HXT's featuring override rails, to function as a supporting mechanism for the operator's selected primary approach: restoration of connector hydraulic integrity.

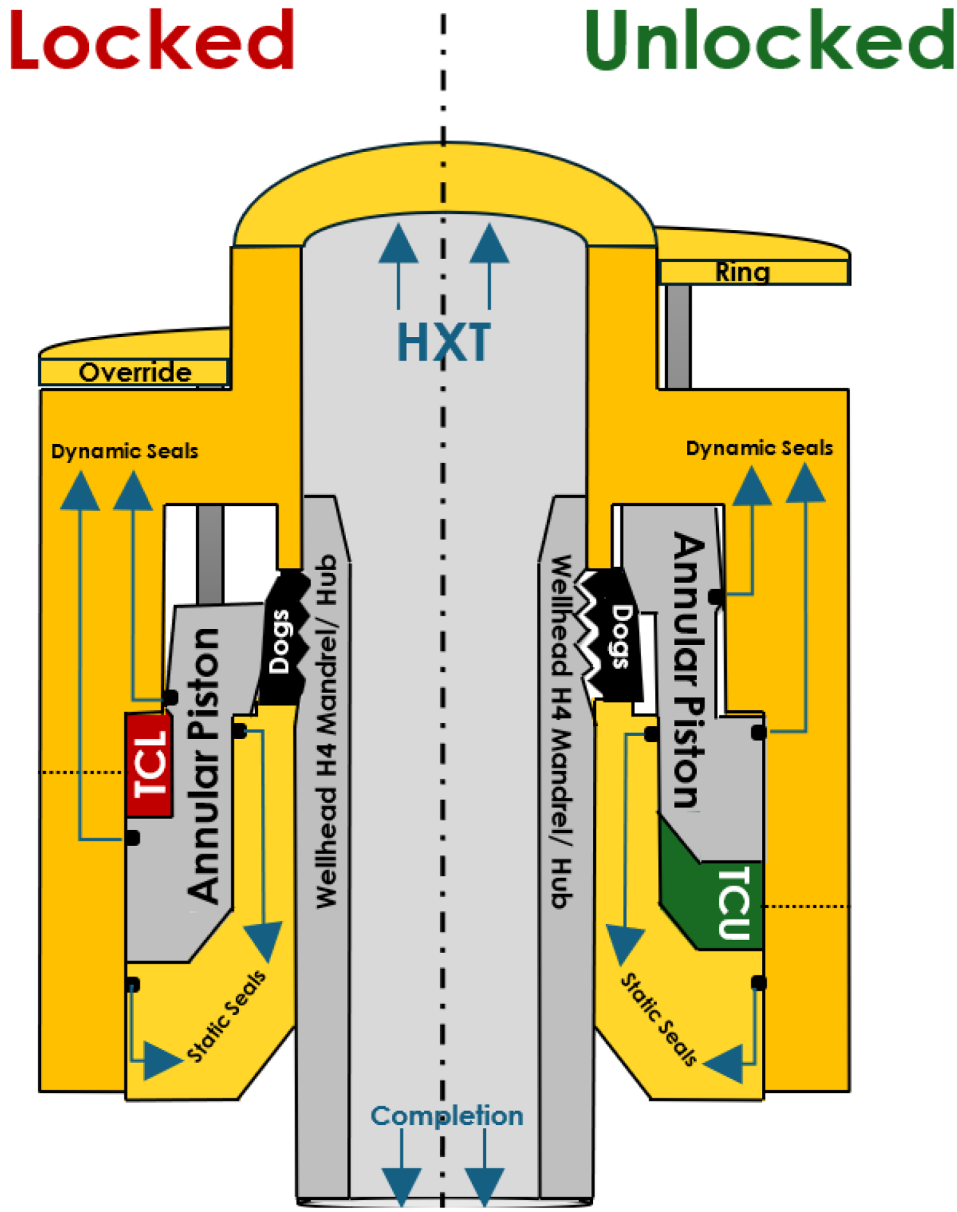

Figure 1—Simplified H4 Connector Visual Representation

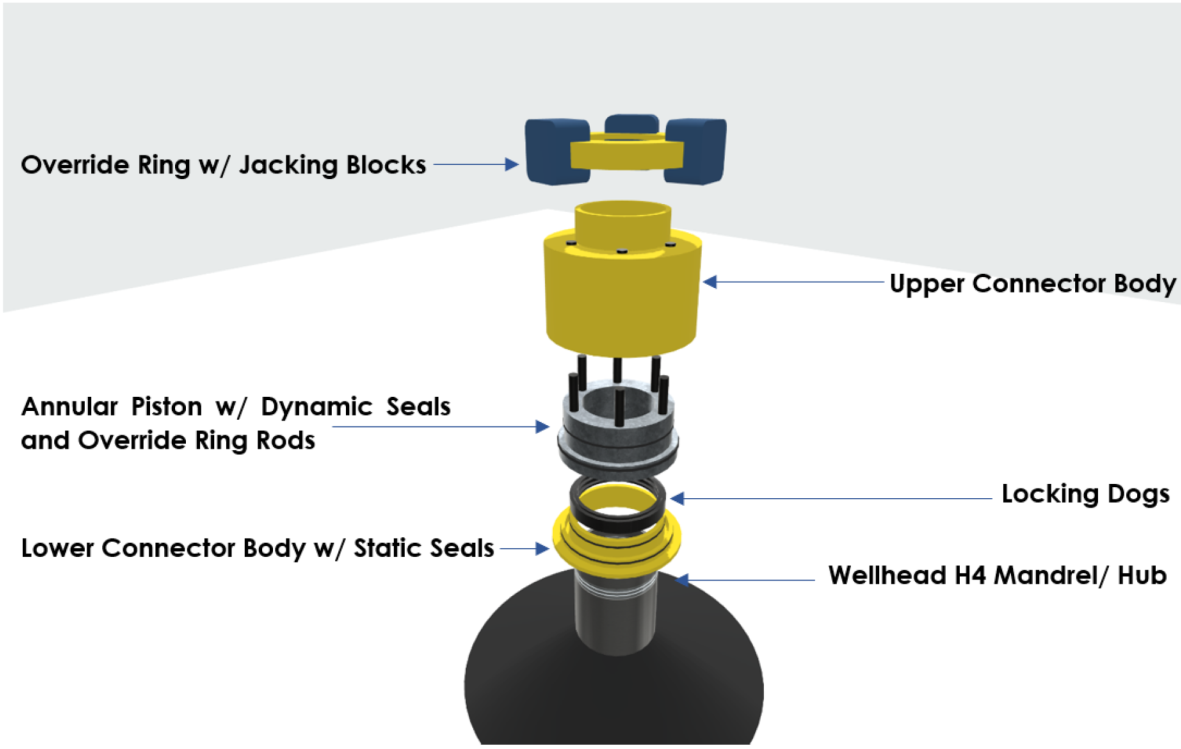

Figure 2—HTH4 Connector Exploded View

The operator contacted an engineered sealing solution provider to assess their current situation and evaluate any remediation techniques possible for them. Following the provider's analysis, pressure-activated sealant was presented as the optimal solution to repair the damaged connector seals, enabling the connector to be hydraulically unlocked. The design principle of the proposed pressure-activated sealant treatment program hinges on differential pressure, such as fluid displacement from a damaged elastomeric seal element. As internal pressure would be applied, the liquid sealant would be squeezed through the effective elastomer(s) undergoing a discrete pressure differential, prompting a chemical reaction referred to as polymerization. During this process, the initially liquid sealant changes to a flexible solid, gradually plating out on the edges of the leak area. Throughout the repair sequence, applied pressure would be gradually increased in steps to further the polymerization process until it would completely fill the affected aperture(s). Short cure periods would be employed at pressure to harden the solidified sealant to the consistency of a standard elastomer. Any sealant not exposed to the differential pressure at the leak site would remain in a liquid state, able to be activated as the connector is stroked to remedy any further seal degradation throughout the unlock. The composition and polymerization mechanisms of the sealant are proprietary but can be modified to suit any given application.

Description and Application of Equipment and Processes

With the proposed pressure-activated sealant approach accepted, the provider and operator worked together to develop the necessary equipment spread to implement the repair procedure. The connector TCU had a roughly 16L fill volume, with an additional 40L stroke volume. As time was critical, a RWOCS panel skid present on the rig was retrofit to attach 2 bladder-style accumulators of 20L and 50L volumes (Pictured in Figure 3). The shell side of the two accumulators would be filled with two distinct blends of pressure-activated sealant, while the bladder would serve as a piston, displacing sealant as it would be filled with water-based control fluid.

Figure 3—Photo of Retrofit RWOCS Panel Bladder-Accumulator Skid

For the 2nd connector, the operator attempted to utilize the jacking system unsuccessfully prior to mobilization of the sealant provider technician. Upon his arrival to location, the accumulators were integrated into the RWOCS panel skid and plumbed, then tested accordingly. Three combinations of sealant blends were ultimately deployed as injection constraints within the hydraulic circuit of the connector dictated.

A very aggressive and highly viscous sealant blend was deployed during the initial treatment, however, during its injection, challenges were encountered. The RWOCS plate mated to the HXT TCU/TCL system with poppeted couplers (See Figure 4a below), were equipped with four 1/8" holes for the injected fluid to flow through. Due to the rheological properties of the sealant, debris within the system was swept into the small ID poppet holes and served to further restrict flow, generating sufficient differential to cause premature sealant polymerization at these connectors. Once no further injectivity was possible, the RWOCS plate was recovered to surface and the connectors were examined as seen in Figure 4b below. The 3 pictured materials are a combination of thread sealant applied during skid make up, particulates within the system, as well as polymerized pressure-activated sealant.

Figure 4—(a) Assembled and Disassembled Poppeted Coupler; (b) Poppet from Blocked Connector with Blockage Material Separated by Type

From this point, all subsequent repairs were performed using the same two sealant blends. The first of which was sent to location in concentrate form and blended with fresh water prior to charging the accumulator. The other was sent out in "neat" form, however, the severity of the observed leaks necessitated the addition of a viscosifying agent to aid in generating differential pressure, thus improving sealant activation. Small changes to the blend ratios and components were made as needed on an individual connector basis.

Following the successful HXT removal on the 2nd and 3rd connectors, the operator designed and manufactured a purpose-built skid to help simplify the subsea operation. This skid featured a smaller footprint, flushing circuit, skid mounted pressure gauges, and isolation valves not present in the RWOCS panel skid. Additionally, the skid comprised of two major components, a base and an accumulator housing. The design was such that the ROV could turn a handle and release the housing from the base. Housing weight and buoyancy was allocated to allow the ROV to then carry the skid to a desired location and work on a connector with the rig engaged on a different well.

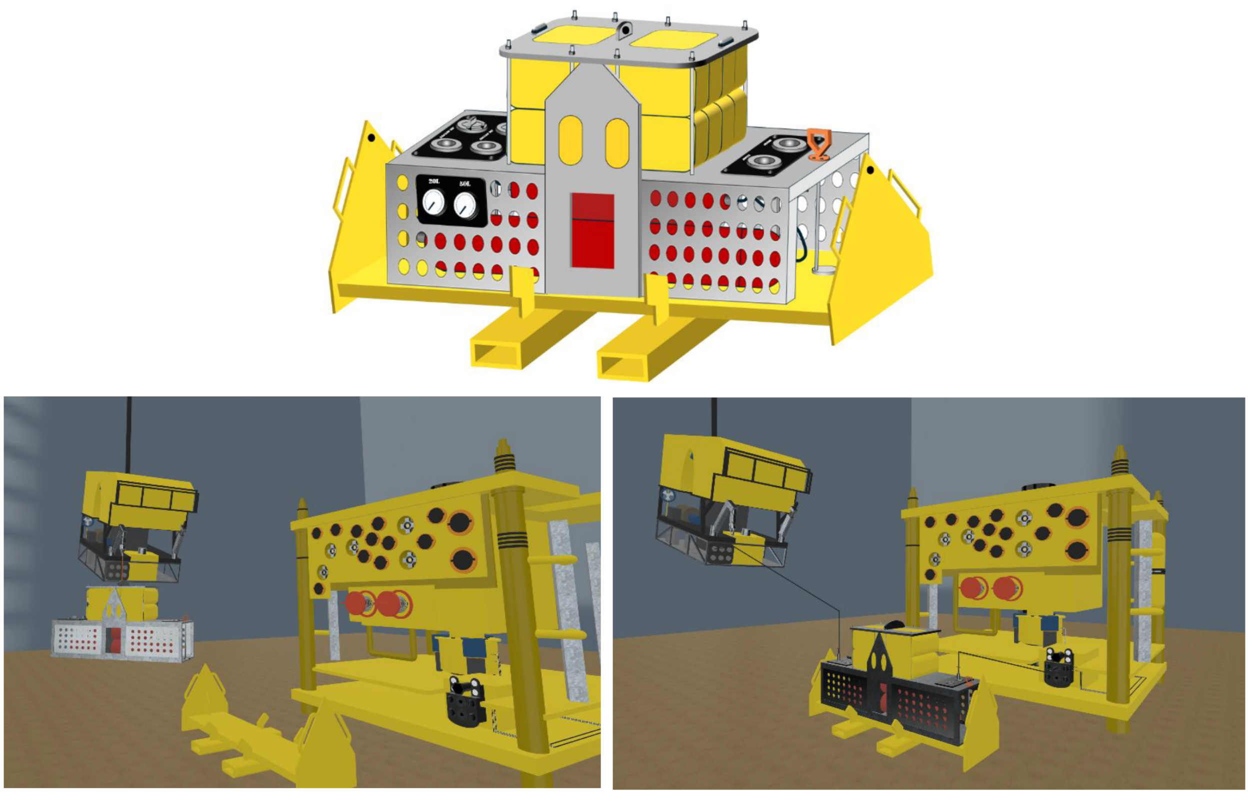

Figure 5—(a) Purpose Built Subsea Sealant Injection Skid Drawing; (b) Rendering of ROV-Skid Maneuverability and Interface

As the campaign progressed, multiple connectors were observed to regain unlock chamber integrity via sealant injection, but initial attempts to lift the HXT clear of the wellhead failed at the specified overpull. This behavior was attributed to a combination of friction and incomplete relaxation of all locking dogs. The operator successfully developed further contingency overpull and pressure assist procedures to further improve the process. In addition to these refinements, initial sealant repair of the lock chamber was pursued to enable connector cycling. The above techniques expanded the toolbox to facilitate HXT removal and were utilized in conjunction as necessary.

Presentation of Data and Results

First Mobilization (Initial Three Wells)

The configuration of the first three connectors/ trees allowed the operator to utilize the override ring jacking system. This system was successful in unlocking the first connector, but unsuccessful for the second and third connectors. Switching gears, as described above, the operator mobilized the sealant technician and moved onto the preliminarily developed pressure-activated repair procedure, with sealant injection via the retrofit RWOCS panel skid for the second well. After flow rate fingerprinting through the damaged seals via the TCU plumbing, the initial rectification attempt was made with a single blend of water-based sealant, mixed on site with fresh water and other additives. As this initial blend was injected, injection rates and total volumes were closely monitored to evaluate consumption of sealant over time. Injection rates were staged up incrementally to generate increasing levels of differential pressure at the leak site(s), when the sealant injection system pressured up. Despite the onboard flowmeter showing less than a quarter of the sealant injected by volume, the RWOCS panel skid gauge showed 0 psi, indicating that the accumulator had been depleted. Moving forward, the actual volumes and rates were roughly estimated proportionally from the flowmeter readings. The injection skid was then lined up to chase the sealant with hydraulic fluid at high rates to generate a seal but ultimately was unable to do so. After this, an ROV survey was performed, which showed sealant exiting the connector from underneath the override ring near one bank of the jacks. The RWOCS panel skid was then recovered to surface and confirmed to be emptied.

As the initial blend of sealant seemed to not be aggressive enough for the severe leakage present, the 20L accumulator was charged with 10L of an extremely viscous and aggressive blend of sealant, while the 50L accumulator was re-charged with a similar to the previous blend of water-based sealant. The RWOCS panel skid was then re-deployed and sealant injection commenced with the new blend. Shortly after beginning the injection, the skid and RWOCS Plate gauges would intermittently register pressure, but little to no flow was achieved. Given this behavior, the hot stab was removed from the RWOCS plate and continuity of flow was confirmed, indicating that the blockage was in or around the RWOCS plate. A variety of methods were employed to attempt to clear the line but were ultimately unsuccessful. The RWOCS panel skid and RWOCS Plate were recovered to surface and through inspection, the blockage and mechanism were identified at the couplers as pictured above in Figure 4. This was rectified and the accumulators were re-charged with a similar blend of sealant as the previous attempts for the 50L accumulator, and a different viscosified blend of water-based sealant for the 20L. Additionally, due to the gauge behavior throughout the above-described events, all relevant gauges had the pulsation dampeners removed to facilitate reliability throughout the sealant injection.

The RWOCS Plate and panel skid were deployed and staged to proceed with further sealant injection. Beginning with the 20L accumulator, TCU pressure began to rise as the sealant polymerization process was underway. Despite TCU pressure being maintained around the reported levels to stroke the annular piston upward, no movement of the connector was observed, and the operator opted to make a further attempt to utilize the jacking system. Once again, the jacks were unable to facilitate unlock. The ROV stabbed into the TCL to confirm integrity of the shared static seal between the TCU and TCL. As pressure remained steady, the leak(s) were hypothesized to be sealed. The operator directed further alternating sequences of hydraulic fluid and sealant injection from the 50L accumulator in steps until maximum TCU pressure was achieved, with the connector appearing visually to be fully unlocked. From this point, the connector was removed in the span of the next few hours.

With the lessons learned from the first connector, the rig kedged directly over to the next well. The RWOCS panel skid was charged with the same two blends of sealant from the previous successful repair and deployed to depth. Injection commenced as above, successfully restoring hydraulic integrity, and the connector was fully stroked to the unlock position. The jacking system was staged to ensure that the connector remained in the fully unlocked position. The HXT was disconnected and subsequently wet parked per the operators program.

Second Mobilization (Fourth Well)

Following the first two successful pressure-activated sealant HXT removals, the operator proceeded with other aspects of the MODU program for a span of three months. In this time, the above-described purpose-built skid was developed, received, tested, and mobilized to the rig for use on the next connector. Upon arrival to location, the sealant technician blended sealants and charged the 20L and 50L accumulators as done previously for the two prior connectors. The new skid was deployed and the sealant repair proceeded as per the refined program. The treatment was successfully executed and the connector was unlocked in a single sequence. Once fully unlocked, the operator utilized the jacking system as it had for the most recent connector, to hold the override ring in the unlocked position as the rig prepared to pull the tree. Once in place, the HXT was removed with no complications.

Third Mobilization (Fifth and Sixth Wells)

After a brief few weeks' intermission, a sealant technician was mobilized to begin treatments for the fifth and sixth wells of the campaign. Upon pressure testing the accumulators that were integrated into the purpose-built skid, the rubber bladder within one of the accumulators ruptured and the skid was redressed. In response, the pre-deployment testing procedure was reworked to minimize stress on this component. The two sealant blends used across the previous applications were prepared, the accumulators were charged accordingly, and the skid was deployed to begin treatment for the fifth well. Injection to the TCU was performed as before, and TCU integrity was restored up to the maximum working pressure of the connector, but no movement was observed. Pressure was trapped within the TCU and the RWOCS plate was lined up to begin hydraulic fluid injection into the TCL to confirm there was no blockage preventing annular piston stroke. Throughout this injection, pressure was able to be developed within the lock chamber, but with fluid returns observed out of the top of the connector. As the configuration of this connector and tree did not allow for use of the jacking system to apply supplemental unlocking force, the operator demobilized the sealant technician to shore for just under a week as they considered modifications to the existing program to enable HXT removal.

When the technician was re-mobilized, the operator elected to kedge the rig over to the sixth well as deliberation continued concerning remedial steps for the fifth well. Sealant and equipment were staged as previously and injections commenced. TCU pressure was gradually increased via sealant injection up to the maximum working pressure of the connector where it remained relatively stable with no apparent movement of the connector. Injection was lined up via the TCL to confirm no hydraulic lock, but no pressure was able to be built. At this point, the operator decided to perform rig overpull cycles as it kedged in a figure 8 pattern, while maintaining TCU pressure. These measures did not seem to yield any significant movement of the connector. The operator then requested sealant treatment of the lock chamber to enable cycling of the connector and break any friction holding the locking dogs in place. The lock chamber was then sealed and the RWOCS plate was lined up to inject hydraulic fluid, followed by sealant in alternating steps to the TCU. During these operations, the connector began to slowly unlock. The rig then pulled upward with neutral tree weight and sealant returns were observed from the lock side vent. At this stage, the connector appeared to be ¼" from full travel. Alternating hydraulic fluid and sealant injections via the TCL were performed to cycle the connector downward and free the locking dogs. Once fully locked, further TCU sealant injections were performed and the connector ultimately stroked to the fully unlocked position. The ROV maintained TCU pressure to keep the connector in the unlocked position as the rig kedged with maximum overpull applied. The tree suddenly began to move and was successfully pulled after two short overpull cycles.

With the sixth well now completed, and the rig remaining above it, operations resumed on the fifth well offline. The skid was recovered to surface, re-loaded with sealant, and deployed. Hydraulic fluid injection began via the TCL to confirm injectivity, and sealant injection followed shortly thereafter. Unlock and lock chamber pressure cycles were then performed in alternating steps to free up the locking dogs for movement. Upon the second cycle for the unlock chamber, the connector began to stroke unlocked and continued until reaching full travel. TCU pressure was maintained for the next 24 hours as the rig kedged over the well and successfully pulled the HXT.

Fourth Mobilization (Seventh and Eighth Wells)

Given the challenges on the previous two wells, the operator and sealant vendor appended the repair program to include the employed mechanisms that seemed to most effectively promote connector travel. The seventh well was configured such that the jacking system was unable to be used. Bearing this in mind, the two blends of sealant used thus far throughout the campaign were to be used again, however, volumes for each of the respective blends were swapped to provide 50L of the "neat" blend of sealant described previously, along with 20L of the concentrate blended formulation. This was done to better leverage the sealing characteristics of these two blends. The accumulators were loaded accordingly and deployed to begin sealant injection into the TCL with the 50L accumulator housed sealant. A seal was obtained and the skid was recovered to surface, refilled, and sent back down. Sealant injection via the TCU commenced, and integrity was restored, however the connector had not stroked to the fully unlocked position. Overpull cycles were attempted, but did not induce any further movement. Further flushing was performed with hydraulic fluid through the TCL by isolating the TCU, attempting to provide cleaning action without degradation of the shared seal between the TCU and TCL. Following this, further sealant injection to the TCU was pursued with intermittent overpull cycles to encourage further connector travel. Despite the performed tertiary recovery methods, the connector remained approximately 1" short of the fully unlocked position. The operator elected to temporarily suspend attempts and proceed onward to the eighth well. In this time, as the eighth connector/tree was equipped to accept the jacking system, the operator deployed this equipment spread and was able to fully unlock and remove the HXT with no sealant injection necessary.

Upon returning to the seventh well, the program was designated to cycle sealant and hydraulic fluid pressure via the TCU and TCL in an alternating fashion to help the annular piston get past whatever restriction it was facing. After several injection cycles, with overpull assistance, the connector ultimately unlatched and the HXT was pulled successfully.

Fifth Mobilization (Ninth and Final Well)

A technician was again mobilized approximately two months after the most recent treatments to commence work on the final connector of the campaign. To further improve the sequence, a new blend of pressure-activated sealant was designated to replace the prior concentrate-based blend. The purpose-built skid was pressure tested, filled, and function tested to demonstrate compatibility with the existing injection pathway. Shortly thereafter, the skid was deployed to begin injection of the new blend into the TCU. As injection continued, TCU pressure began to build until the 20L accumulator had been depleted. Swapping to continue through the 50L accumulator, the connector was observed to stroke to what appeared to be the fully unlocked position just as the accumulator had been nearly emptied. Pressure within the TCU was monitored over the following few hours and increased slightly to compensate for slight losses prior to recovering the skid to surface. As the technician was refilling the skid for a second deployment, the HXT was successfully lifted clear of the wellhead.

Conclusions

The pressure-activated sealant approach employed was able to be effectively implemented across all cases presented. The additional manpower and equipment spread associated with its provision was negligible in comparison to alternative means of remediation and removal.

Despite the campaign being localized to a singular connector design within one operator's assets, each remediation was unique, with each treatment carefully planned and executed on a case-by-case basis. In the implementation of the general concept, pressure-activated sealant provided a means to rectify all deviations from the baseline, without larger implications to the overarching abandonment plans or sequence. As such, in cohort with decades of successful subsea repairs, this 100% successful campaign further reinforces the application of pressure-activated sealant as a potential first-line approach to address well integrity concerns.

Acknowledgements

The authors would like to acknowledge the unbelievable efforts of all parties involved in this globally unprecedented rectification campaign. Throughout the 9-month span of the project, the team addressed every unique challenge presented across the candidates without the need for a change in abandonment philosophy. Kudos to all involved for a 100% successful campaign.