Computed radiography deployed by a subsea remotely operated vehicle

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Arguably, the Remotely Operated Vehicle (ROV) business traditionally understands the word ‘Inspection’ as a general or close visual record of a subsea item using a remote camera and other data-gathering peripherals such as sonar, bathymetric and profilers. Subsea NDT methods with ROVs are generally confined to cathodic potential surveys, single-point wall thickness measurements and flooded member detection. Conventional NDT is usually diver-deployed in hyperbaric habitats more than in the wet, usually to test for welding defects.

In contrast, topsides plant inspection is synonymous with NDT and invariably means components undergo some form of non-destructive examination to provide integrity information. In addition, the last 15 years or so has seen a revolution in NDT systems and inspection companies have gradually introduced ‘Advanced’ NDT systems to their range of services, to meet the ever-increasing demands from Risk Based Inspection (RBI) approaches to managing pressure systems.

The upstream oil and gas industry is now applying the same RBI approach subsea, but with the ever-present HSE restrictions on using divers in addition to deeper water exploration and production, there is a growing requirement for ROV-deployed NDT systems.

1. Introduction

A major Norwegian Subsea Gas Field Development produces gas condensates or Natural Gas Liquids (NGL) and is serviced by a 120 km-long, 120 mm-diameter umbilical pipe bundle, which provides remote process control and communications. These services include Monoethylene Glycol (MEG), which is pumped into the template wellhead to stop freezing and help decrease the viscosity of the product, helping transport in the pipeline back to the onshore plant, where the MEG is separated out and re-used, and the NGL product is compressed to form Liquified Natural Gas. The LNG is exported through a subsea pipeline to northeast England.

The 120 mm-diameter umbilical cross-section is complex, consisting of spirally wound 2 x 22.78 mm and 4 x 24 mm super-duplex welded pipes, 5 x four core copper quad cable bundles, and 2 x fibre-optic cables. The remaining space is packed with various ‘filler’ materials like rope and plastics. It was designed and manufactured by Nexans Norway A/S. See Figure 1. The pipe marked ‘X’ was leaking.

An ROV visual survey recently observed seepage of MEG from a seawater ballast hole in the plastic outer surface, subsequently traced back to a leak in one of the internal duplex pipes due to a reduction in line pressure. The cause of the leak was unknown and the client needed an NDT examination before deciding on a course of action. The umbilical is buried under a clay-type soil on the seabed at 120 m of water.

This paper describes the very busy 12-week period starting December 2006, covering the concept development and approval, design and fabrication, to testing and final execution in February 2007, of a proposed ROV-deployable NDT solution to determine the possible nature of the defect, combining computed radiography, an ROV and a unique subsea so-called ‘X-ray Habitat’.

2. Inspection concept

From an NDT perspective, this is a difficult item to test because the umbilical construction is relatively complex. It involves a wide variety of very closely packed, spirally wound materials, including the duplex pipes, each with their own mechanical, magnetic and electrical properties. See Figure 1; the pipe marked ‘X’ was leaking.

Although there is a wide range of NDT methods, it was concluded that there were no ultrasonic, electrical or electromagnetic-based NDT solutions applicable, but that an ‘X-ray’ image of the umbilical would provide the best integrity information. In addition, the significantly greater ‘exposure latitude’ offered by Computed Radiography (CR) media, ie phosphor imaging plates (IP) in place of conventional radiographic film, would be more suited to this application where there are widely varying material attenuations affecting radiation dose on the plate.

Note that the description ‘X-ray’ is often used to describe the image resulting from work using ‘Gamma’ as well as ‘X’ radiation sources. A radioisotope was always the preferred option in this instance.

3. Concept evaluation

The overall concept evaluation can be split into three initial questions:

1. Will the CR image be good enough quality to see representative defects?
2. Is there an appropriate radiation exposure system?
3. How do we deliver a CR image at 120 m depth?
3.1 Computed radiographic image quality test

3.1.1 Equipment

The test equipment consisted of GEIT Computed Radiography systems, one with CR100 logarithmic scanner and a second with the linear CR50P scanner, high-resolution laptop with RadView and Rhythm software, and IPS 2 type phosphor imaging plate (IP). Given the need to penetrate the liquid-filled duplex through heavy copper cables, the chosen source of radiation was an Iridium 192 rather than Selenium 75.

3.1.2 Radiographic technique

A 200 mm length of sample umbilical was set-up in a radiation exposure facility utilising the ‘stand-off’ technique where the source is placed a distance from the front surface of the specimen and detector in contact with the back surface. This provided the optimum image sharpness and the maximum coverage per exposure. Two exposures at 90° spacing would be required to provide the necessary coverage.

However, the stand-off technique in-situ would present a challenge because ionising radiation is readily absorbed in water and it is not desirable in terms of exposure time nor image quality to expose through a water-filled environment, therefore evacuation of the water in front of the radiation beam had to be overcome to produce the best quality results. In addition, although the initial image was very good with a Source-to-Detector Distance (SDD) of 700 mm, the large size of habitat required to accommodate this stand-off and, therefore, water volume to evacuate at depth, was considered very difficult to achieve. Consequently, a smaller SDD of 350 mm was tested; the images were acceptable and the resulting smaller habitat and water volume evacuation was considered reasonably achievable. See Figure 2 for the test set-up showing the relative positions of image plate, source and umbilical for both exposures.

3.1.3 Sample description and preparation

As briefly mentioned in the introduction, the Nexans umbilical provides MEG through 2 × 24 mm super-duplex welded pipes, hydraulic fluid through 2 × 22.78 mm and 2 × 24 mm super-duplex welded pipes; three pipes are within a 50 mm centre, all 1.5 mm thick. The remaining three pipes are outside this 50 mm central core; although smaller diameter, two are thicker at 1.88 mm. Other services are electrical power from 5 × four core copper quad cable bundles, and digital information through 2 × fibre-optic cables. The remaining space is packed with various ‘filler’ materials including plastics, rope, wrapping tape, wrapping steel, nylon, polypropylene, all surrounded by a 4 mm-thick outer sheath made from yellow High Density Poly-Ethylene (HDPE). See Figure 1. Clearly, a fairly wide mixture of materials.

To reproduce actual subsea operating conditions, hydraulic fluid was poured into all six super duplex pipes after the test-piece had been left in a bucket of water to mirror the effects of seawater ingress. In practice, the seawater soaks into manufactured 10 mm-diameter ballast holes in the HDPE outer sheath to help provide additional ballast sinking the umbilical into the seabed.

In consultation with the client, possible failure scenarios were identified and representative anomalies artificially introduced into the test sample. First, a 1.5 mm drilled hole into the leaking super duplex pipe; second by inserting a steel nail and drill-bit part way into the bundle; and lastly, drilling two off 10 mm-diameter holes 5 mm deep into the HDPE outer sheath. The resultant image showed all the anomalies and these positive results were crucial in the decision to progress to the next stage.

Test image 1 (Figure 3) utilises the CR100 scanner with RadView software analysis and test image 2 (Figure 4) utilises the CR50P with Rhythm software analysis. The CR100 and RadView combination produced a better overall image most likely due to the wider dynamic range typical of logarithmic data capture over linear...
data capture, as distinct from any major differences in the image analysis software packages.

The logarithmic data image displays greater ‘exposure latitude’ and is more ‘forgiving’ to the large variations in radiation attenuation characteristics of the different materials within the umbilical itself. The result is a high-definition image of most of the internal features.

Differing exposure latitudes is well illustrated by comparing the visibility of the internal drilled 1.5 mm hole in duplex pipe #L3, at the same time as viewing the two 10 mm external HDPE holes; the linear image 2 shows neither whilst the logarithmic image 1 shows both anomalies.

3.2 Radiation delivery system

The Sentinel Model 865 Subsea gamma radiography system is pneumatically operated and has a depth rating to 609 m which is more than sufficient for the umbilical water depth of 120 m. However, the depth rating only applies to the container and actuation of the system relies on high pressure rated hoses and connections appropriate to pressure at depth. The project concept relies on actuation of the system under 12 bar pressure (120 m) on the seabed and therefore the challenge of performing local actuation of the system with the ROV had to be overcome. The successful actuation of the container introduced another technical risk.

3.3 Delivery of the image at depth

The client stated the delivery method was by ROV and, therefore, the next challenge was to deliver an acceptable image at 120 m water depth. This involved the design, fabrication and testing of a unique ‘X-ray Habitat’ and interface with a workclass Triton XL37 ROV. There were at least four main hurdles to overcome:

1. How to ensure the umbilical is not damaged in the process
2. How to evacuate the water from the habitat
3. How to actuate the radioisotope container and waterproof the IP
4. How to achieve an adequate seal around the irregular umbilical surface

3.3.1 How to ensure the umbilical is not damaged in the process

A primary requirement of the project was to ensure the NDT process did not damage the umbilical. This involved seabed trenching, cable cleaning plus careful design and fabrication of the X-ray Habitat. This was made up of two separate frames: a lower umbilical support frame and an upper frame housing the radiation source and imaging plate. These are shown in Figure 5. Note the upper frame illustration is transparent for clarity, and shows the source and detector plate positions; the actual habitat is constructed entirely from aluminium overall dimensions 1600 × 1300 × 1032 mm height.

The ROV holding the lower habitat frame would be gradually positioned under the umbilical, sliding slowly up sloping forks into two half-circle shaped ‘cradle supports’. All umbilical-to-frame contact surfaces would be covered in a rubberised compound and the support cradles covered in a special aerated sponge material which is designed to mimic and seal the outer umbilical surface to the frame. The upper X-ray Habitat frame would be lowered into position mating the holes with the stab guides on the lower frame, gently settling on the rubber contact areas, including the upper half of the cradle support contacting the upper half of the umbilical. The positioning process is illustrated in Figures 6-10.

3.3.2 How to evacuate the water from the habitat

As stated in paragraph 3.1.2, radiation is readily absorbed in water and it is not desirable in terms of exposure time nor image quality to expose through a water-filled environment. Consequently, the principal design challenge is the evacuation of the water so the radiation beam passes through a gas or air-filled environment. Given the 350 mm SDD, the total volume of water in the habitat top half could be evacuated by continually delivering air from the vessel deck, given the need for 12 bar plus 2 bar actuator pressure to expose the source inside the habitat. Pressure calculations dictated that a high powered compressor would be required on deck to deliver the necessary pressure at 120 m depth.

The habitat was built with a 1” diameter hole positioned on the top surface of the upper frame, to accept an air supply delivered through a 1” diameter ‘stab-in’ to push the water out from the open bottom of the habitat, but also to blow the air across the surface of the imaging plate to remove water droplets as the water level dropped.

As the air pressure is applied, the water level would be visually monitored by CCTV mounted on the ROV, through a clear Plexiglass window and a cylindrical level float indicator. The correct pressure would be indicated by a consistent stream of bubbles from the bottom of the level indicator tube. See Figure 11.

3.3.3 How to actuate the radioisotope container and waterproof the IP

The actuation of the Sentinel 865 subsea container only requires 2 bar pressure, however the container has a source rod which projects out of the actuator into the atmosphere indicating ‘source open’ position. The source rod will therefore ‘see’ 12 bar of pressure and has to push against this to open properly.

The solution was to supply local air pressure using a small compressed air cylinder, built onto the side of the upper frame with pressure rated hoses connected to a four-way valve and special switch marked ‘O’ (open) and ‘C’ (close) which could be operated by the ROV manipulator. In this way, 14 bar pressure is delivered to the container actuator and the source rod position could be visually monitored by the ROV CCTV through the clear Plexiglass window.

In addition, the imaging plate opposite the source of radiation would also be wet and under 12 bar pressure. To best represent this, a trial was conducted using a rigid, light-proof cassette, hermetically sealed and vacuum packed in a foil waterproof envelope. The package was exposed to radiation through the umbilical sample, and placed into a pressure chamber to 20 bar for 10 minutes and subsequently retrieved and scanned. Although the image was acceptable, the cassette was crushed and there was some water ingress affecting image quality, including water marks. It was difficult to assess the effect on quality, if any, from the crushing of the plate.

Timescales did not allow further trials at representative pressure using different IP cassette packaging combinations and
the solution, if there was one, remained a source of worry for the offshore work.

3.3.4 How to achieve an adequate seal around the irregular umbilical surface

The only contact areas between the outer sheath of the umbilical and the X-ray Habitat, is at the joint between the lower support cradle to the upper frame, making a circular seal. The umbilical is an irregular 120 mm pipe, with an uneven surface making up the pseudo-circular shape. This makes it very difficult to seal and a special aerated sponge material was sourced which would be soft enough to mould around the small changes in shape of the umbilical, whilst robust enough to withstand the pressures, and expand enough after each lift to reshape for the next positioning of the upper frame.

The seal pressure is established by integrating a series of five circular bucket compartments into the upper frame; one on each corner and one central on the roof. These compartments were made to house five separate lead counterweights, each 85 kg (77 kg in water).

Illustrations of the X-ray Habitat in its final condition ready to expose the isotope is shown in Figures 5(c) and 10. The process involves two exposures and, therefore, two separate dives with the upper half of the habitat being brought back to the surface to change the imaging plate. The exposure direction is changed by swivelling the upper half of the habitat through 180° then placing it back on top of the lower half subsea.
4. Wet trials

A prototype X-ray Habitat was fabricated and the various practical solutions, including those associated with the radiographic challenges, were put to the test. It was accepted from the outset that there remained a degree of technical risk and, therefore, chances of failure to deliver an acceptable image at depth, particularly from the uncertainty of the reaction to the radiation of the IP cassette assembly. Pressure on the various layers including the phosphor coating, could compress the cross-section and affect the absorption characteristics of the IP. However, wet trials on a 5 m length of umbilical were introduced to at least reduce some technical risk by testing the combination of radiographic exposure system and the assembly method underwater.

All the practical solutions proposed in Section 3.0 were incorporated into the prototype design and the wet trials could be summarised under the following general headings:

1. Positioning the isotope container inside the habitat
2. Marinising the imaging plate
3. Actuating the source
4. Remote visual confirmation of source position and water level
5. Radiation Safety and Emergency Contingency Plan

4.1 Positioning the isotope container inside the habitat

The Sentinel 865 isotope container weighs 26.8 kg and is very heavy considering the overall size 31.1 cm long × 12.7 cm diameter. Even with the habitat laying on its side, there was restricted access to position the container and safe manual handling was difficult to achieve. Fortunately, there are four mounting holes on the container foot, and an additional bracket was fabricated and attached to the foot, such that the container weight could be supported by temporarily placing the new bracket on the habitat bracket. This provided adequate conditions to allow the four off attachment wing-nut bolts to be screwed into place without undue manual handling stress on the operators. The new habitat bracket arrangement altered the distance from isotope emission point to image plate (SDD) to 400 mm, and an ODD of 50 mm ie not in direct contact with the imaging plate.

This operation was done quickly to minimise the radiation dose (approximately 200 μSv/h) from the external surface of the container to the operator’s hands and practice with a ‘dummy’ 865 container reduced this time to approximately four minutes. Figure 12 shows the Sentinel 865 radioisotope container.

4.2 Marinising the imaging plate

Success in marinising the IP to withstand 12 bar pressure remained the area of most concern and presented the greatest technical risk of failure. It was not possible to expose the IP at under 12 bar pressure during the wet trials, however various combinations of cassette assembly were prepared and tested in the tank. The plan would be to place the best (driest) cassette assembly combination (determined by the wet trials) on the ROV offshore during non-NDT related dives. Although the cassette would not be exposed to any radiation under pressure, the IP would be recovered and examined on the vessel for signs of water ingress giving at least some assurance of its protection against the conditions on the seabed.

The best combination was to place the IP between two lead screens (for physical protection) and insert into two separate waterproof hermitically sealed vacuum bags. The double sealed IP was placed behind a clear plastic plate which holds it flat against an aluminium back inside the habitat, and screwed tight. This arrangement also allowed placement of an Image Quality Indicator onto the plastic plate to enable comparisons of topside trial image quality to that obtainable under pressure. Note that a special Vacuum Machine had to be obtained so resealing the IPs could be done as required offshore using a supply of spare bags.

4.3 Actuating the source

It was important to connect the two hoses to the correct ports on the container; one exposes the source and the other stores the source. The hoses were colour-coded to minimise error. The actuation switch had to be on the ‘C’ closed position before opening the lock on the container. The safety valve was opened on the air supply bottle and a check was made on supply pressure at around 100 bar. The habitat was then ready to be submerged. Once barriers were erected around the tank, the source was opened manually using the ROV switch. Figure 13 shows the air supply safety valve and gauge.

4.4 Remote visual confirmation of source position and water level

A CCTV underwater camera was positioned opposite the clear Plexi-glass window giving a view of the source rod position,
internal water level and float position in the cylindrical level indicator. The source rod extends some 75 mm from the back of the container when in the exposed position and can be clearly seen in this position in the wet trial. See Figure 11.

4.5 Radiation Safety and Emergency Contingency Plan

During the wet trial, radiation readings were taken around the 2 m high × 3 m square water tank and the maximum reading obtained on the tank surface was 10 μSv/h. The radiation controlled area was set-up and the maximum reading obtained was 2.5 μSv/h, which is one third of the maximum allowable reading at the barriers. In short, the water in the tank was very effective in absorbing the radiation dose from the 30 Curie Iridium 192 radioisotope.

Performing the wet trial step by step provided essential information for forming an Emergency Contingency Plan that would be used offshore in the event the source were to stick in the open position subsea and had to be made safe at the surface.

5. Offshore application

Having successfully completed the inspection concept evaluation, fabrication of the prototype X-ray Habitat and testing in the Oceaneering underwater tank facility in Stavanger, the system was ready for the workscope offshore. This involved three preparatory actions prior to the NDT operations. First, a function and quality test of the system on the deck of the dive vessel on a section of the umbilical; second, a job safety analysis and development of dive procedure; lastly, identifying the leak point using a ROV deployed leak detection Gammatrak radiation sensors to find Scandium 46 platelets introduced downstream into the leaking line. See Figure 14 showing one of the detectors.

The NDT operation involved lifting an open steel basket, with the upper and lower skid secured inside with rope on positioning pins. In addition, a separate basket was lifted and lowered onto the seabed containing lead holding down weights. Sea swell had to be 2.5 m or less and even in these calm conditions, the upper half of the habitat with the radiation source container and IP inside was forced upwards by the trapped air in the void space as it submerged through the surface, then settled back down once the water had forced through the ‘stab-in’ hole on the top. This operation introduced a risk of ‘jarring’ the source container on its brackets and moving the IP from behind the plastic plate. From this early stage onwards, there was no means of checking whether the submerge operation had physically altered the set-up within the upper frame until the IP was scanned on the vessel following the operation.

Figure 15 shows the upper habitat inside the basket and Figure 16 shows the basket submerging.

5.1 Seabed operations

Following the crane landing the basket on the seabed, the first part of the operations involved positioning the wire lifting strops away from the basket, cutting the securing ropes and lifting the lower habitat skid frame from the basket, subsea transit to dredged area, then sliding it under the umbilical. See Figures 6, 7 and 8.

Also, Figure 17 shows the manipulator arm moving the strops. A special circular spirit level incorporated into the lower skid frame indicated that levelling of the skid with sand bags was not required. It was also vital to ensure adequate dredging at the umbilical site to allow room for the skid to slide underneath.

The second part of the seabed operation involved cutting the ropes, lifting the upper habitat frame from the positioning pins, subsea transit to the umbilical position and placement on the lower skid frame positioning pins. Mating the ‘holes’ in the upper and ‘pins’ in the lower habitat frames (and in the basket) proved extremely difficult.

Once the upper and lower halves were mated, inserting the lead weights (see Figures 9, 10 and 18), inserting the air supply ‘stab-in’, and pressurising the chamber using the compressor on the surface went according to plan, although these operations took a significant amount of time, particularly supplying the air hose as this meant involving the crane which was not ‘heave compensated’; in retrospect, a seabed positioned bank of pressurised air cylinders would improve this latter operation. The float and bubble stream
indicated sufficient pressurisation and seal around the umbilical, and, therefore, free air space for the radiation beam.

ROV manipulator actuation of the source, 45 s exposure time, de-pressurisation from the surface, removing the stab-in hose connection, removing the lead weights to the basket, and returning the upper habitat to the basket then to the surface, all went according to plan. The source container was locked immediately upon deck arrival, the imaging plate cassette assembly removed and replaced with a new one, source unlocked and the operation repeated for the second exposure.

6. Image analysis

Figures 19 and 20 were obtained on the seabed. On first impression, it looks impossible to identify each feature, made worse because of the double spirally wound nature of the fabrication process. However, it is possible to identify each individual pipe by careful, step-by-step analysis (see below); superimposition of two central pipes between the fibre-optic cables was the key. Once all the pipes were identified, the leaking duplex pipe was closely examined for anomalies.

1. Identify the possible exposure directions where two central pipes superimpose between the two fibre-optic cables. See Figure 21.
2. Make a ‘trace’ overlay of the umbilical cross-section. See Figures 22 and 23.
3. Trace the profiles of the three internal pipes.
4. Overlay the cross-section trace on the image and revolve the trace to line the pipes up.
5. Identify pipe #L4, inside 50 mm-diameter three pipes, and other two outside pipes.

This exercise relied on carefully mapping the outside diameter of each of the pipes inside the 50 mm central core of the umbilical, along their length on the image. #L1 outlined in red; #L2 outlined in black; the leaking #L3 outlined in yellow. Note also the two fibre-optic cables filled in yellow and black. See Figure 20.

In addition, the images of both fibre-optic cables were difficult to see but discernable enough to place the superimposition of two of the core duplex pipes between them. From this initial analysis, the rest of the pipes can be revolved into place and identified. It should be noted that the manufacturing process involves the central core pipes being spirally wound as a separate operation to the outer pipes and electrical cables. This means that the pipes and fibre-optic cables in the core remain in the same positions relative to each other, as do the outer features, however each group revolves around each other making it a complicated assembly to interpret. The IQI wire 10 was viewable on the image taken subsea as well as the image taken on the vessel deck function and quality test.

7. Summary and conclusion

The task to find the leak site using the ROV-deployed radiation detectors proved more onerous than anticipated, but the dive team eventually narrowed it down to an approximate 1 km stretch of buried umbilical. However, the decision was made to abandon further dredging operations because of an anticipated over-run in the project planned timescale. The work would be postponed to a later date.

Fortunately, and to the credit of an inspired and forward-thinking client, they insisted a complete diving ‘dress rehearsal’ on an exposed part of the umbilical should be carried out because it may highlight design or operational problems with the proposed system and procedure that could be corrected prior to carrying out the later test on the actual leak site. This exercise could subsequently reduce the technical risk of project success. This rehearsal went ahead
and the entire operation from lift and submerge, to delivery and interpretation of the image on the vessel, took 24 hours to complete; the radiation exposure duration was only 45 s.

The simple conclusions from this operation are:
- It is entirely possible to deliver high quality, computed radiographic images, utilising the stand-off technique with a gamma ray emitting Iridium 192 isotope, of a multi-service control umbilical, at 120 m water depth in a controlled and safe manner utilising an ROV.
- It is possible to identify individual features within a complex, multi-service control umbilical on a computed radiographic image.
- It is possible to detect radioactive platelets within a duplex MEG-carrying pipe within a multi-service control umbilical.