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Necessity and Suitability of In-Line Inspections for Corrosion Resistant Alloy (CRA) Clad Pipelines

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Abstract

This paper outlines the necessity and suitability of subsea in-line inspections through an incident occurred to a corrosion resistant alloy (CRA) clad pipeline. In this incident, an ultrasonic pig tool was impacted and damaged the pipeline's CRA clad layer. Pressure surges were effective in dislodging the intelligent pigging tool, but they caused the pigs in the pigging train to collide with one another. Th analysis of metal swarf recovered from the pig receiver revealed that the damage was limited to the CRA layer. The investigations revealed that the intelligent pig tool received a bypass after coming to a stop at 181m due to a combination of low pump rate and intelligent pig tool friction. As a result, the sealing pigs became entangled, damaging the sensor carrier of the intelligent pig tool and causing it to become stuck at the end of the pipeline.

Keywords: Corrosion Resistant Alloy, CRA Clad Pipelines; In-Line inspections; Intelligent Pigging; Subsea Pipelines; Stuck Pig.

1. Introduction

Subsea pipelines play an important role in the production and transmission of the oil and gas industry (Reda et al. 2022a; Reda et al. 2022b). The DNV-STD-F101 Standard (DNV 2021) Clause 3.4.1.2 does not require an intelligently pigged pipeline system if it is made of a corrosion-resistant alloy (CRA). The requirement for inspection pigging is clearly stated in DNV-STD-F101 (DNV 2021), Section 3.4.1.3, for carbon-manganese steel conveying corrosive fluids of categories B, D and E. In the same standard, Section 11.4.3.15 of DNV-STD-F101 (DNV 2021), it is stressed that in-situ wall thickness measurements for the pipeline should be performed using in-line inspections. In addition, Section 11.4.3.16 of DNV-STD-F101 (DNV 2021) states that an inspection pig is used to inspect the pipeline's internal and external surfaces. To confirm the pipeline's fitness for the intended service, either in-situ wall thickness measurements or an inspection pig must be used. In light of this, it is clear that the DNV-ST-F101 (DNV 2021) is silent on the requirement to inspect CRA clad pipeline using intelligent pigging. Furthermore, the ISO 13623 Standard - Section 6.13 (ISO 13623 2017) states that pipelines should be designed to allow for the passage of the internal inspection tools. In this regard, ISO 13623 (ISO 13623 2017) does not specify the type of pipeline material, whether duplex, super duplex, carbon steel, CRA clad or CRA mechanically lined pipe. Clad/lined pipe is an alternative method of providing CRA materials at a

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lower cost than solid CRA when carbon steel is not suitable for the corrosive conditions. Clad pipe or CRA lined is less expensive than solid CRA material because it has a thin layer of CRA materials (typically 3 mm) and a carbon steel outer layer for pressure containment.

When it comes to the integrity management plan of CRA clad or lined pipelines, this paper poses a question to the oil and gas industry: Is it necessary to inspect CRA-clad/lined pipelines? The answer will be through an incident occurred during a baseline survey on a 20-inch metallurgically-bonded clad pipeline with a length of approximately 2.7 km, as detailed in (Reda et al. 2022a). The pipeline was made of carbon steel with an internal Alloy 625 CRA cladding layer of 3 mm cladding thickness. Wet gas was being transported from a wellhead jacket to a production complex via the pipeline. After two pressure surges were applied near the end of the inspection, the intelligent pig stuck inside the CRA clad pipeline and crashed into the receiver, rendering the baseline survey ineffective. As shown in Figure 1, the intelligent pig was discovered damaged in the pig receiver, and the sealing pigs were discovered directly behind the intelligent pig. Metal swarf of various sizes, as shown in Figure 2, was discovered in the sensor carrier and on the first sealing pig, with a maximum thickness of 0.4 mm. As a result of the incident, the inspection tool travelled inside the pipeline, with the sharp edges of the intelligent pig trail contacting the CRA layer and leaving gouges in the pipeline. However, an electro-dispersive X-ray of the scrapings revealed that the damage was limited to the CRA layer, with no traces of carbon steel. A detailed fitness-for-purpose analysis of the underlying failure is presented and explained in (Reda et al. 2022b).

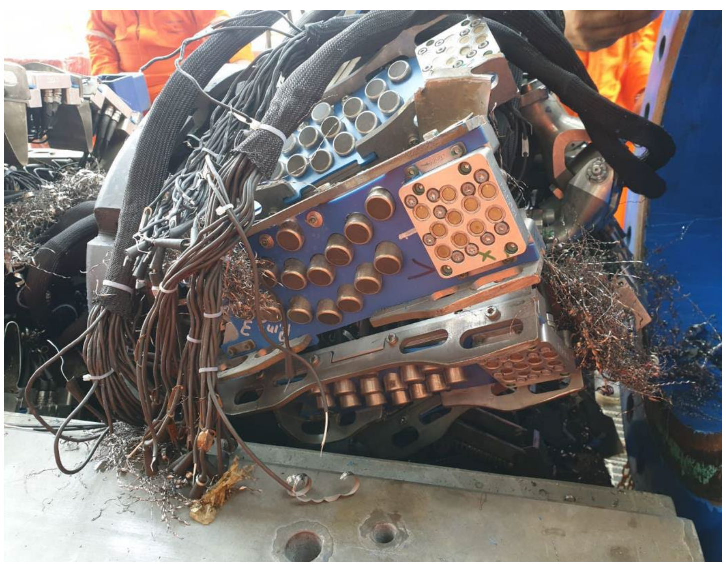

Figure 1: Damaged ILI pig tool.

Figure 2: Metal swarf from pipeline.

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2. FAILURE ANALYSIS

This section discusses some of the aspects investigated during the failure analysis to understand the factors that contributed to the incident and caused damage to the CRA clad layer.

2.1 PIGGABILITY STUDY

Before the failed ILI run for the new pipeline, a detailed piggability study was conducted in which all available pipeline data and configurations were collected and evaluated. Gooseneck bend assembly was given special attention to ensure that the UT(ultrasonic) pig tool could traverse the entire pipeline system, including all risers and spools. The Gooseneck bend assembly was located between the expansion spool and the riser. The pipeline was made up of two assemblies of Gooseneck bends, with approximately 106 m between the Gooseneck bend assembly and the pig launcher. The sensor data revealed that the UT intelligent pig passed the first 181 metres, including all bends and pipeline components, without incident and at the expected speed. The data recovered from the damaged tool showed that the UT pig passed smoothly through the first Gooseneck bend assembly. For the second Gooseneck bend, the UT and other auxiliary data, such as pressure, were unavailable.

2.2 INSPECTIONS WITH 20-INCH INTELLIGENT PIG

The intelligent pig carrier used in the inspections has the bend combinations given in Table 1 and was field-proven.

Table 1:Field-proven inspections and bend combinations.

Project	Bend combinations	Pipeline length
P1 (Carbon Steel)	5D	740 km
P2 (Carbon Steel)	5D	255 km
P3 (Carbon Steel)	5D	172 km

2.3 PUMP TEST IN A STRAIGHT PIPE SEGMENT

Following the construction of the 20-inch intelligent pig carrier, it was pumped through a straight pipe to test its functionality in longitudinal and axial offsets, as well as the data quality of the 20-inch test pipeline. These tests were conducted to validate the measurement performance, and the test run was deemed successful.

2.4 INVESTIGATION OF THE BYPASS POST INCIDENT

The failed run was caused by the bypass on the ILI tool and the sealing pigs catching up to the UT pig, and all other incidents were a result of this. As a result, the circumstances surrounding the bypass had be investigated

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further. Two possible scenarios for such a high bypass were identified. The cup design and setup on the tow module were tested in a 451 mm internal diameter (ID) test pipe. It should be noted that the two modules were tested during the tool's qualification programme, according to the ILI's manufacturer. The internal diameter of the test pipe was the same as the incident pipe's internal diameter. Because a piece of pipe with an ID of 451 mm and sufficient length was not available, a test setup with all 7 modules of the ILI tool was not possible. Figure 3 depicts the layout that was used to define this blow-over test. The primary goal of the test was to define and confirm the UT intelligent pig's bypass and sealing. The battery (tow) module was chained to the inside of the pipe flange. A pump was then used to fill the test pipe with water. To control and monitor the flow and pressure behind and in front of the tow module, flowmeters and pressure gauges were installed. On the launching side, the test pipe was sealed with a lid. At the start of pumping water through the kicker line, the chain that was holding back the towing module was not tense. As a result, the pressure required to move the tow module and the flip overpressure could be calculated. The pipe on the receiving side was left open. Any bypass and the occurrence of a flip over could be observed directly. The pump's pressure and flow were gradually increased. The sealing disc was checked and monitored for sealing until it "flipped over." The pressure values were calculated using only the first two modules. Pressure values across the ILI tool may behave differently. However, the effects of the entire ILI tool on pressure values are difficult to predict without performing a physical test. The pull test was performed to investigate this scenario because severe sagging of the UT intelligent pig can cause a gap to form between the pipeline and the sealing cups in the upper area. Figure 4 shows that the receiver side of the towing module is sitting tight in the pipeline, with no signs of sagging, rotation, or severe sagging. More than 100 kg applied in the radial direction would not move the module away from the centre. As a result, this scenario was rated as extremely unlikely. As shown in Figure 4, applying more than 100 kg in the radial direction has no effect on moving the module out of centre. As a result, this scenario was rated as extremely unlikely.

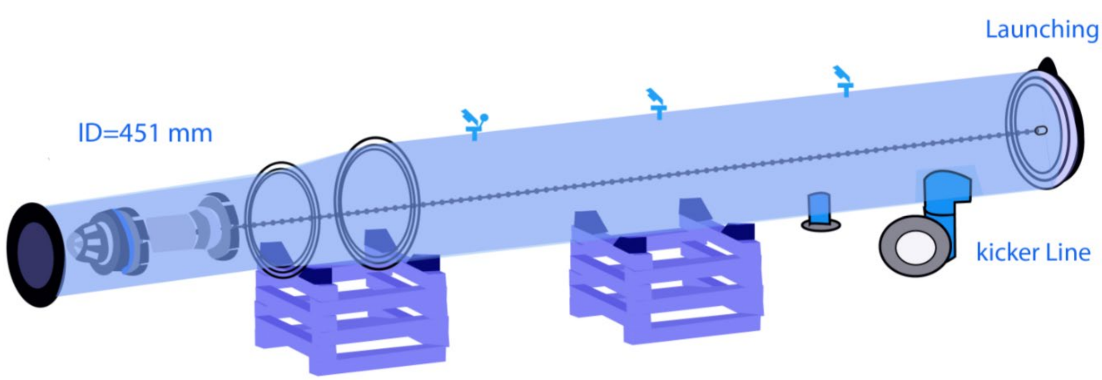

Figure 3: Layout of the blow-over test (showing the chain).

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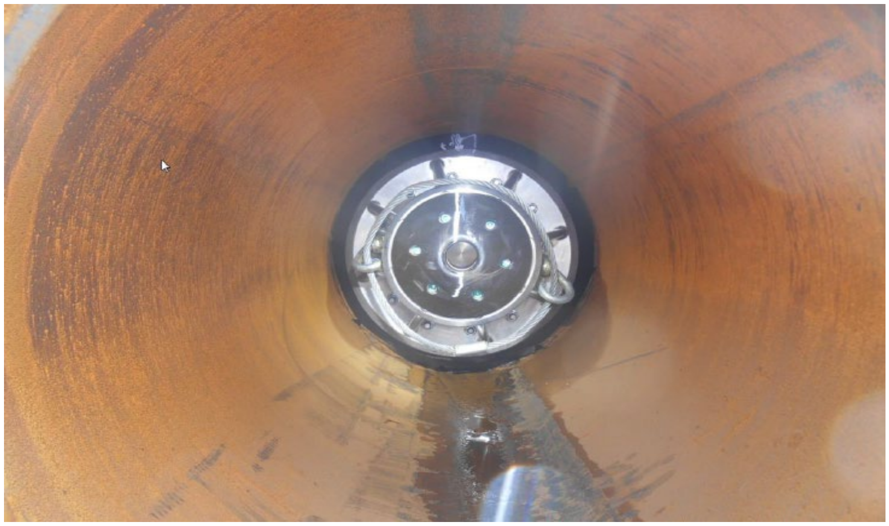

Figure 4: Towing module inside the pipeline.

Figure 5 depicts the sealing mechanism. The sealing cup is made of polyurethane, and the sealing is accomplished by the sealing cup directly followed by a polyurethane sealing disc. When a certain amount of pressure is applied from behind, the cup cannot withstand the applied force and will flip over. When the cup is flipped over, the sealing becomes limited, resulting in a blow over of water from behind. The towing module was bypassed, but the flip overpressure was greater than the pressure required to move the ILI tool.

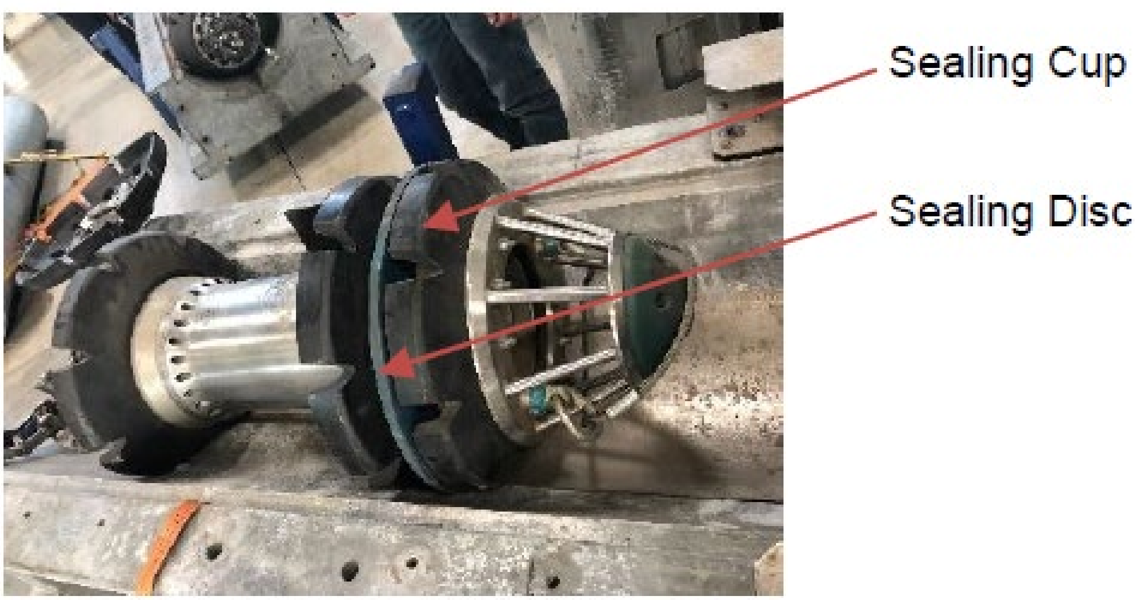

Figure 5: Towing module with sealing cup and sealing disc.

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The result of a series of blow-over tests revealed that the blow-over pressure is dependent on the tow module's alignment with the pipe's centre. At a pressure of 5 bar, the cup did not flip over due to good alignment. The pressure was not increased further because the breaking load of the chain was about 6 bar. The lowest flip overpressure during the tests was 3.6 bar. The results can be summarized as follows:

- There was no leakage at all in advance of the blow over.
- The tow module started moving at about 0.5 bar.
- The sealing cup flipped over at a pressure of at least 3.6 bar.
- Pumping 60 m^3/h through the bypass of the flipped-over sealing cup caused a differential pressure of 1.7 bar. Pumping 60 m3/h through the bypass of the flipped-over sealing cup caused a differential pressure of 1.7 bar.

The first conclusion that can be derived from the tests is that because the pressure required to move the tow module was 0.5 bar, the required differential pressure to move the entire ILI tool must be greater than 0.5 bar. Given the number of cups and the sensor carrier, the required pressure is likely to be greater than 2 bar. Figure 6 depicts a realistic scenario of flipping over. The second conclusion is that it is possible to pump 60 m^3/h across the flipped-over towing module, resulting in a differential pressure less than what is required to move the entire ILI tool.

Figure 6: Blown over the cup.

2.5 MATERIALS ON ILI TOOL VS. INCONEL 625 CLADDING

Table 2 lists the materials of the ILI tool that could have come into contact with the pipe cladding. Thermal spraying was used to apply tungsten carbide wear protection to the skids with a thickness of 0.3-0.4 mm.

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Tungsten carbide is known for its high brittleness and excellent wear resistance. When the front edge of the protection layer is chipped, it peels off in an exponential fashion. When the layer is removed (for whatever reason), the skid only drives on the base material. To produce swarf like the one shown above, a geometrically defined and hardened cutting edge is required, as well as constant cutting forces throughout the process (e.g., machining metal in a turning machine); it is likely that a portion of the damaged ILI tool produced swarf like this one.

Table 2: Materials on the ILI tool.

Part description	Material	Rockwell hardness
Pipeline cladding	Alloy 625	30 HRC
Joint on sensor carrier	Stainless steel 1.4305	20 HRC
Joint on sensor carrier	Stainless steel 1.7131	<20 HRC
castle nut, self-locking nut, washer (on the joint bolt)	Galvanized steel	<20 HRC
Flange on sensor carrier (in front of the cup)	Stainless steel 1.4301	<20 HRC
V-springs on the sensor carrier	Stainless steel 1.4310	20 HRC
Skid base material	Stainless steel 1.4301	20 HRC
Wear protection layer on skids	Tungsten carbide	72 HRC

2.6 THE SEQUENCE OF EVENTS AND OPERATIONAL CIRCUMSTANCES

This section is based on the pressure diagram from the launcher side, log sheets and intelligent pig data. It should be noted that the pipeline was successfully cleaned and gauged prior to the unsuccessful ILI run, as shown in Figure 7, which shows the BiDi (Bi-directional) pig with the gauge plates used prior to the unsuccessful ILI run. As can be seen, there are no signs of damage.

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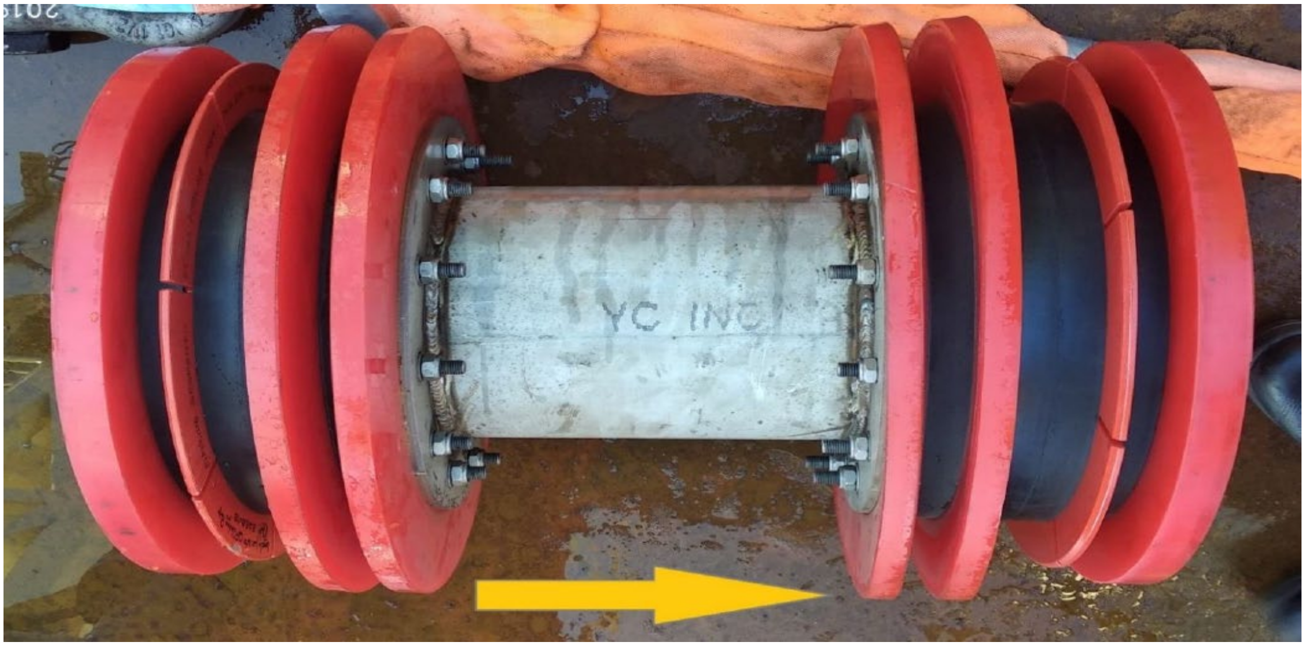

Figure 7: Setup picture for gauge run before unsuccessful ILI run.

2.6.1 Start of pig operation until pump stop for 1st sealing pig

Timeframe: 12:40 - UT intelligent pig launched and 13:30 - pump stopped to insert 1st sealing pig: The UT intelligent pig was launched at 12:40 and travelled with a relatively constant speed of 0.35 m/s. The pig passed through all bends from the topside piping to the riser, including the gooseneck and expansion spools without stopping. The distance of 181 m was reached at 12:49. This distance indicates that the pig passed all installations from topside to riser to gooseneck and expansion loop without any stops. The distance of 181 m was measured from the pig launcher to a position along a straight length of pipe on the seabed. The UT intelligent pig travelled the first 181 m without any issues. At 12:48, the revolutions per minute (rpm) of the pump was slowed down to maintain the break tank level. The following data were valid for this stage:

Pumped volume at 12:49 = 30 m^3 within 9 minutes
Calculated pipeline distance: 187.5 m
Actual position of UT intelligent pig based on UT data: 181 m
Calculated by-pass on this section: 3.6% (expected value)

Suspicious stop after pump back online: The rpm on the pump was increased at 12:54, and the operational conditions on the intelligent pig were not comprehensible. Based on the analysed data, the intelligent pig had no movement between 12:49 and 13:21 (32 min). So even when the rpm was increased at 12:54, the intelligent pig did not move. The data collected indicated that the intelligent pig started to move only at 13:21. When the pump rpm was increased at 12:54, the calculations undertaken demonstrated that the bypass on the intelligent pig significantly increased up to a value of 59.6%. This calculated value does not match the results obtained earlier during the bypass/blow-over test. This level of bypass reveals a possible failure of the sealing elements. The events reported in this section are summarized in Table 3.

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Table 3: Timeline of events from start until pump stop for 1st sealing pig.

Event	Time	Pumped volume (relative value) [m³]	Calculated flow [m³/h]	Distance pipe volume (absolute value)	Actual intelligent pig position	Calculated by-pass
UT intelligent pig launched	12:40	0		0m		
Unplanned pump stop (tank level)	12:48	30	200	187.5 m	181 m	3.6%
Pump rpm increased	12:54	–	–	–	–	–
Pump stopped to insert 1st sealing pig	13:30	38	57	425 m	277 m	59.6%

2.6.2 The 1st sealing pig launched until pump stop for insertion of 2nd sealing pig

Timeframe: 15:30 - 1st sealing pig launched and 15:42 - pump stopped for insertion of 2nd sealing pig: The 1st sealing pig was launched at 15:30 and the intelligent pig started to move at 15:32 with an average speed of 0.23 m/s. The intelligent pig stopped at 15:38 although the pumps were switched off at 15:42. The events reported in this section are summarized in Table 4.

Table 4: Timeline of events from 1st sealing pig launch until pump stop for insertion of 2nd sealing pig.

Event	Time	Pumped volume (relative value) [m³]	Calculated flow [m³/h]	Distance pipe volume (absolute value)	Actual Intelligent pig position	Calculated by-pass
1st sealing pig launched	15:30	–	–	–	–	–
Intelligent Pig starts movement	15:32	–	–	–	–	–
Intelligent Pig stops movement	15:38	26	130	587. 5 m	342	60%

2.6.3 The 2nd sealing pig launched until the ILI tool stopped recording

Timeframe: 19:00 - 2nd sealing pig launched and 21:47 - UT intelligent pig stops recording: After the 2nd sealing pig was launched, the UT intelligent pig moved extremely slowly with an average speed of 0.005 m/s. Starting from 19:18 the average speed was only about 0.04 m/s.

Impact of 1st sealing pig and data loss: At 19:45 and position 400.61 m down the pipeline, an abrupt increase of data loss was observed alongside the visible stand-off changes in the data. At the same time, the UT intelligent pig experienced a small speed peak. It was assumed that the 1st sealing pig hit the back of the sensor carrier of the UT intelligent pig at this location. Furthermore, at this time, the intelligent pig also stopped

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recording AUX data such as pressure, distance and temperature. It was likely that the mechanical impact between the 1st sealing pig and the sensor carrier of the intelligent pig influenced the electronic parts of the pig and resulted in a malfunction. After this position, it was not possible to determine what happened to the UT intelligent pig as no further data were recorded by the intelligent pig.

Sensor carrier starts to see nitrogen: From 20:13 at a position of 558.15 m down the pipeline, the sensor carrier detected the presence of nitrogen above the sensor carrier. The data quality decreased as the nitrogen above the sensor carrier increased. From 21:04, the ILI tool experienced extreme speed peaks and decelerations. It was assumed that nitrogen passed the ILI tool and nitrogen bubbles-built pressure above and below the sensor carrier. At 21:47 (1355 m), the sensor carrier was fully surrounded by nitrogen. At the same time, the ILI tool stopped recording UT data. It was assumed that the mechanical impact of the 2nd sealing pig also led to an electronic malfunction. After this position, it was not possible to determine what happened to the ILI tool as no further data were recorded.

2.6.4 Visualization of Position 181 m at Time 12:48

Figure 8 shows the position of the intelligent pig when stopped at 12:48 in a straight section of the pipeline resting on a flat seabed without contact with flanges or girth welds. The tow module of the intelligent pig stopped at 181 m, which was measured relative to the pig launcher. The last sensor carrier of the intelligent pig was 175.4 m away from the pig launcher. The pig launcher was 171.2 m away from the end of the pipeline flange and the on-mating flange on the tie-In spool.

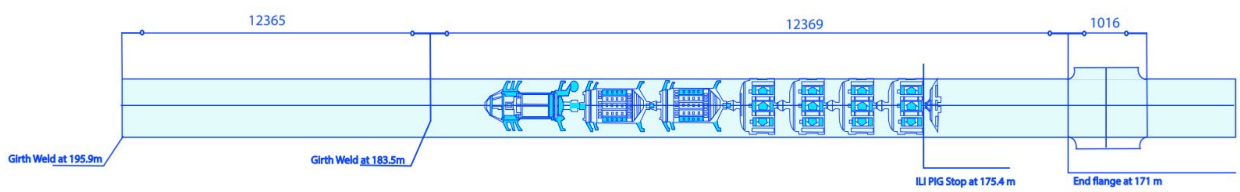

Figure 8: Position of the intelligent pig at 181 m.

2.6.5 Speed UT intelligent pig vs. 1st sealing pig

Figure 9 shows the distance between the UT intelligent pig (solid black) and the 1st sealing pig (dotted black line) in relation to time. The graph for the 1st sealing pig was created from the flow data and readings from the pump log sheets. The dotted black line shows the distance of the 1st sealing pig assuming the absence of the bypass. The 1st sealing pig was launched at 15:30, and at the time of launch, the distance between the 1st sealing and the UT intelligent pig was 277 m. It is indicated that the 1st sealing pig caught up to the ILI tool at 19:56, followed by an acceleration (as shown on the retrieved data from the log events for sensors). It should be noted that the speed of the 1st sealing pig was based on theoretical calculations. In the actual situation, the sealing pig may have experienced some bypass. Hence, the theoretical calculations may have some variation. The theoretical calculations of the 1st sealing correlate to the previous assumption that the 1st sealing pig hit the intelligent pig at 19:45 (400.61 m). The 60% level of bypass should not normally be possible and does not reflect earlier test results. This level of the bypass would only be possible due to a failure in the sealing elements or position, and any conclusion on this can only be determined from the planned sealing tests.

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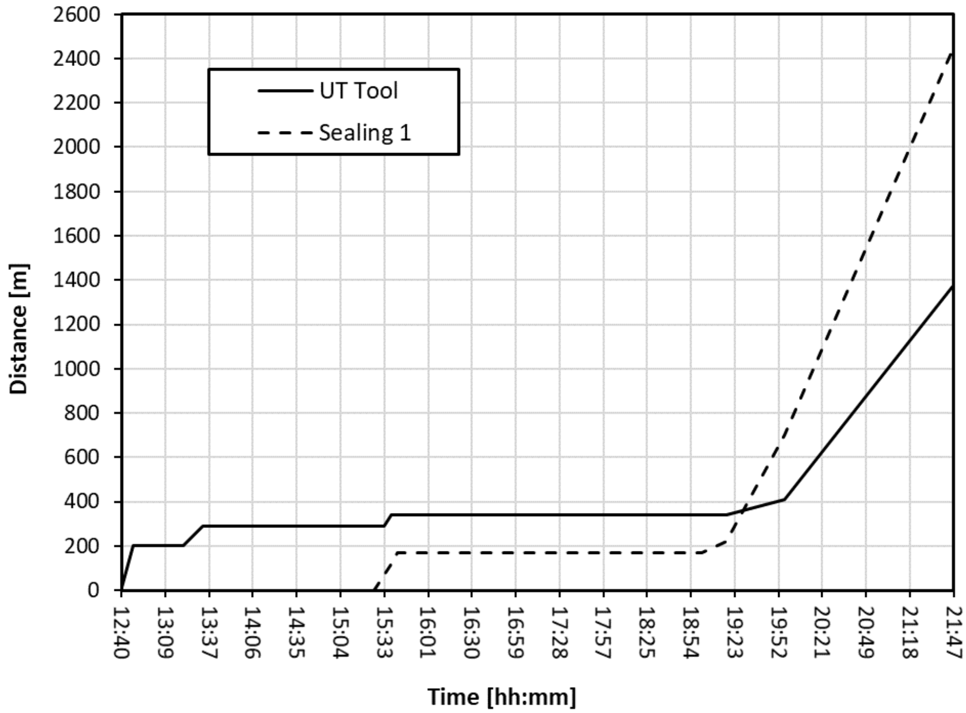

Figure 9: Path-time diagram of intelligent pig and 1st sealing pig.

2.6.6 Speed based on pumped volume

Based on the time and flow readings from the receiver log sheet, the pumped speed versus time was calculated and visualized in Figure 10. It starts with the launch of the ILI tool at 12:40 and ends when 100% of pipeline volume is completed. It can be seen that the flow during the first 181 m is at the required 0.30-0.35 m/s. From the time of the unplanned pump stop to the beginning of nitrogen injection, the flow rate was too low, thus preventing the ILI tool from moving. At 19:00, the injection of nitrogen began and the flow rate was increased at 19:47 and was at the required value of 0.3 m/s.

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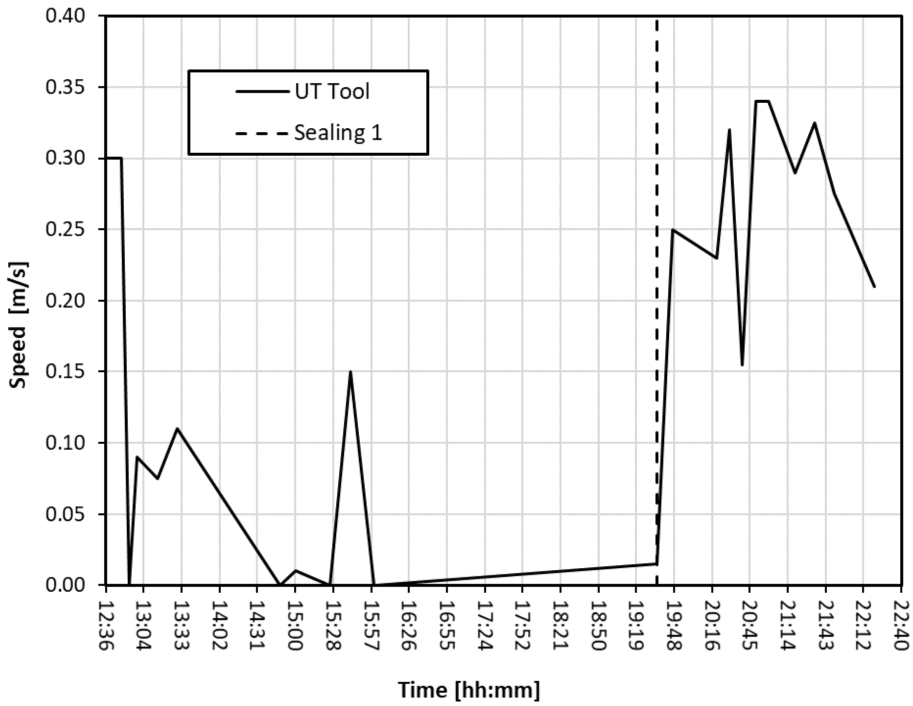

Figure 1: Speed chart based on pumped volume.

2.7 RUNS AFTER THE UNSUCCESSFUL ILI RUNS

Following the failure of the ILI run, a cleaning train was launched. The setup was as follows: 50m³ water/foam (Pig #1), 30 m³ water/BiDi with brushes (Pig #2), 30m³ water/BiDi with brushes (Pig #3), 30m³ water/BiDi with gauge plates (437 + 424 mm) (Pig #4)/N2. The gauge plates attached to Pig #4, as shown in Figure 11, had scratches and were damaged, with one segment deformed. Impaction at pipe bends caused by rapid depressurization (i.e., uncontrolled pressure release and opening and closing of discharge valves) was the cause of the damage. The nitrogen/water mix was received in front of Pig #3, and the pressure suddenly increased to 8 bar during receiving of Pig #3. The same jerk/impact is expected to have occurred with Pig #3, and as a result of the impact, the magnet securing screws became separated from the magnet covers. In front of Pig #4, all magnet retaining screws were counted. A close examination revealed that one of the magnet covers was damaged. The results of the cleaning runs were taken into account for a possible future ILI re-run. Because all lost parts (i.e., magnets) were collected, as well as a minor amount of swarf and FBE coating, it was assumed that the pipeline had been cleaned of any debris and other residue.

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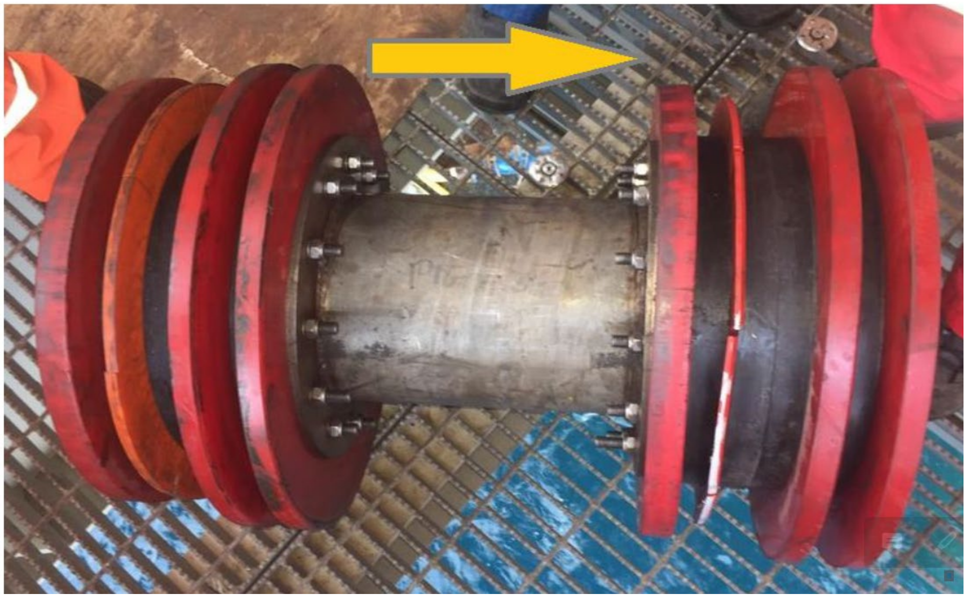

Figure 2: Picture after gauge run (after ILI run).

3. DISCUSSION

ARE IN-LINE INSPECTIONS INCLUDING BASELINE SURVEYS OF CRA CLAD/LINED PIPELINES NECESSARY?

A baseline survey is typically run immediately after the pipeline installation for the following reasons:

- To identify problems associated with the installation of the pipeline.
- To serve as a reference point for comparison with later surveys to enable a projection of pipeline degeneration with time as a result of corrosion or other factors.
- To meet the requirements of the regulator; many regulators grant conditional licenses upon a baseline survey being carried out within the first 5 years of operation and others after 6 months of operation.

The baseline surveys conducted within 6 months or 5 years of start-up impose a considerable cost involving MSV (Multi-Service Vessel) mobilization and demobilization combined with the operational complexity of running a cleaning and calliper pig and an inspection tool. A more cost-effective option, with no operational impact, is to run the baseline survey during the pre-commissioning when the MSV is already present. Arguments against a baseline survey are normally based on the premise that it adds little value to the data already accumulated during the pipeline procurement and installation, which include the following items:

- Controlled manufacturing processes and comprehensive wall thickness and geometry measurements at the mill.
- Weld and NDE (Non-Destructive Examination) records during pipelay.
- Pipeline geometry verification by EGP (Electronic Geometry Pig) after installation.

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- Data entered into electronic pipe tracking software enabling comprehensive reference data of individual joints at any location within the pipeline alignment.
- The detection sensitivity of MFL tools is limited. It is unlikely that these tools will be able to detect corrosion metal loss in a brand-new pipe.
- Correlation of initial and future runs after (say) a 10-year lapse becomes difficult since both software and hardware (sensor sensitivity, resolution and accuracy) develop and improve with time and two different tools may be used from two different suppliers. Although the reporting software may be compatible with data going back many years, re-processing the old data may result in a loss of functionality.

While all of the above apply to carbon steel pipes, they do not apply to CRA-clad or lined pipelines. This is because, for the carbon-manganese (C-Mn) pipeline, it is expected that internal corrosion will take place due to the corrosivity of the good fluids (Reda et al. 2022a; Reda et al. 2022b). Hence, the baseline survey and pigging inspections are required throughout the design life and this is to confirm the inhabitation effectiveness. Carbon steel pipelines, on the other hand, are susceptible to a variety of potential internal and external corrosion risks. In many scenarios, it is acceptable to have corrosion taking place as long as the rate of corrosion/attack is within manageable limits and there are means of checking the type of corrosion damage and extent (i.e., In-Line Inspection, ILI, using pigs). External corrosion is generally not an issue in the corrosion management of carbon steel pipelines because the external issues can all be solved relatively easily by the application of the proper coating and adequate cathodic protection (though there are special considerations in the design and operation of high-temperature lines). Inspections using intelligent pigs are an important part of the corrosion management philosophy for all carbon steel pipelines. During the design life of a carbon steel pipeline, inspection of pipelines using instrumented ("intelligent" or "smart") pigs may be required for the following reasons:

- Determine their continuing fitness for purpose.
- Determine their overall condition.
- Validate the corrosion rate predictions.
- Validate corrosion monitoring results.

Carbon steel pipelines typically must be inspected by the means of intelligent pigs; the frequency of which depends on the corrosivity of the fluids, the remaining corrosion allowance, the required pipeline life and the risk assessment of the pipeline. Intelligent pigging costs include the cost of pre-inspection cleaning, the intelligent pigging operation itself, the costs of any deferred production and the costs associated with analysing the data.

Magnetic flux leakage (MFL) pigs are commonly used; the most advanced of these tools have a sensitivity of approximately 10% for wall thickness. Ultrasonic pigs are used in thick-walled pipes (as they can inspect thicker walls than MFL pigs), and where higher sensitivity is required (5% is achievable). The limitation of the ultrasonic (UT) pigs is that they must be run in liquid-filled lines (or in a liquid slug), which increases costs and degree of difficulty in nitrogen lines and some multiphase lines. The initial inspection frequency should be based on the following items:

- Sensitivity of the selected pig (how much wall thickness must be lost before it can be detected).

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- Assessment of worst-case corrosion rate. This may consider the lowest likely inhibitor system availability and an assessment of how accurate the predicted inhibited corrosion rates are.

The abovementioned considerations are only applicable to carbon-manganese (carbon steel) pipelines, where corrosion takes place as highlighted in (DNV 2021; ISO 13623 2017). The CRA layer ensures that minimal corrosion will take place for the duration of the design life as long as the correct CRA has been selected. Pipeline design typically performed for CRA-lined pipelines make zero allowance for corrosion. Any damage or corrosion to the CRA layer implies that the backing carbon steel will come in direct contact with the transporting fluid and then the pipeline. If the CRA-clad pipeline does experience some corrosion during its design life, then corrosion allowance must be considered in the pipeline design. Additionally, a risk assessment should be carried out to investigate the effect of CRA layer damage on pipeline integrity. It is important to perform fitness testing on the pipeline under the anticipated loading conditions to investigate damage to the CRA layer during the in-line inspection. This is more necessary if the pipeline design relied on the strength of the CRA layer for integrity.

Concerning the manufacturing defects which can be detected during the baseline or in-line inspections, it is not expected that these are aggravated under ordinary operating conditions. Additionally, there are very stringent quality control measures in place during the manufacturing of the CRA layer as per API-5L (API 5L 2018) and API-5LD (API 2015), including ultrasonic checks of the CRA plate, and cladding thickness, and cladding adherence. The thickness of the cladding layer is normally between 2.5 mm to 4 mm. For the subject pipeline, the CRA 625 nominal clad layer thickness was 3 mm with a general tolerance of +/- 0.12 mm. Thus, the minimum thickness would be 2.88 mm.

Concerning the welding on the installation barges, the welding of a CRA-clad or lined pipeline requires scrutiny. It is important to ensure that the field welding operation follows the DNVGL-ST-F101 Standard (DNV 2021). Before the welding process, extra consideration should be paid to the following items:

- Pipe end preparation.
- Cut-out and cut-back.
- Weld alignment and Hi-Lo.
- Matching ID circumference of all components.
- Stringent end ID tolerances +/-0.25mm are optimal for CRA clad or lined pipes.

The alignment of the abutting ends should be made to minimize the radial offset and any misalignment should be reduced to a minimum via the rotation of the pipes to obtain the best fit. During the girth welding process and upon completion of the girth weld on the installation barge, non-destructive testing (NDT) should be performed following the DNVGL-ST-F101 Standard (DNV 2021). In addition to NDT, the root pass of the girth weld for CRA clad/lined pipes is typically visually examined by an internal camera system after the hot pass has been deposited. The camera system is usually equipped with measuring capabilities to accurately determine the extent of root pass defects.

Critical engineering assessment is also usually used to determine the acceptance criteria for the weld body (DNV 2021); however, this is only required if AUT (Automatic Ultrasound) is used. The ECA based acceptance criteria are not applicable to root or hot passes. The girth weld of CRA clad/lined pipes should go through

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stringent quality control processes to ensure the integrity of the girth weld. Inspection of the CRA pipeline is not likely to be required but provisions should be made to allow for inspections if required in the future.

4. Conclusions

Due to differences in acoustic properties and metallurgical structure, the presence of cladding or lining, as well as more "exotic" weld deposits, represents an ultrasonic barrier (grain size, orientation). Thus, the presence of spurious (non-relevant) signals such as high levels of noise and possible mode conversion signals, which can be difficult/impossible to interpret at times, creates difficulties for UT.

It should be noted that following the first unsuccessful ILI, a second ILI was successfully conducted, with corrective actions taken for a rerun of the baseline survey. These corrective actions are listed below and should be included in any future ILI for clad pipelines to avoid damaging the CRA layer and thus jeopardising the pipeline's integrity. The details of the second ILI and the pipelines' fitness for purpose are presented in detail in (Reda et al. 2022b).

Major Findings on Failure Baseline Survey	**Remedial Actions Taken for Re-Run of Baseline Survey (Ump & Uc)**
UT tool designed with hard material for sensor carriers causing internal scouring and mechanical damage.	UT tool was split into two sections, i.e., metal loss and axial crack inspection and transited the flow line independently. Both UMp and UC tools were designed such that they were suitable for CRA pipelines to eliminate mechanical damage.
UT Tool design compatibility with Inconel 625 material.	UT Tool sensor carriers were installed with polyurethane material to prevent damage to the Internal cladding of Inconel 625 material.
Flow rate requirement and differential pressure to be specified by the vendor considering the bypass rate for the UT tool.	A minimum flow rate of 180m^3/hr with a back pressure of 5 bar was maintained and proved successful.
Sufficient water arrangement is necessary for the UT tool to run to maintain continuous operation without stopping.	Due to the non-availability of sufficient potable water, treated seawater was used to propel the baseline survey tool and maintain the required flow rate. This proved highly successful.
UT tool run will be a stand-alone operation without any other batching pigs.	New baseline survey tools were run independently.

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Major Findings on Failure Baseline Survey	**Remedial Actions Taken for Re-Run of Baseline Survey (Ump & Uc)**
Propelling medium should be water to avoid air pockets and uncontrolled velocities during the run.	Treated seawater was used as a propelling medium.
Nitrogen is not a suitable medium to propel the UT Tools.	Nitrogen is no longer envisaged for future UT inspection

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