The Effectiveness of Polymer Lined Pipelines for Subsea Water Injection Service

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Abstract

After 13 years service in the North Sea, a Spool piece including a section of PE80 lined steel pipeline from a reeled water injection line was retrieved for examination when the operator was modifying the subsea production system. This was a unique opportunity for a full condition assessment of a lined section enabling evaluation of the fitness for purpose of the methods and processes used to build and install this PE lined pipeline. Tests and investigations were conducted on the PE80 liner, the end termination assembly, the parent and field joint coatings and corrosion of the carbon steel. Comparison with the original PE80 material grade demonstrated that the liner had retained its original mechanical properties. It was shown that locked-in residual strain continued to provide a tight interference fit of the liner in the host pipe after reeling, installation and 13 years service. A pull out test conducted on the liner from the end termination assembly confirmed joint integrity, as the PE liner remained secure in the joint up to the yield point of the polymer. Only superficial corrosion of the carbon steel was observed on both the internal and external surfaces of the carbon steel pipe thus demonstrating that both the internal PE80 liner and external parent and field joint coatings have provided effective corrosion control. This work presents confirmation of the suitability of polymer lined pipelines for long term subsea water injection service.
1 Introduction and Scope of Work

Polyethylene lined carbon steel pipelines have been used for sub-sea water injection service in the North Sea for more than 15 years. In 2008 a PE lined spool was recovered from the seabed while a water injection system originally installed in 1995 was being modified. The spool provided the first opportunity to retrieve and examine a PE lined section of a reeled water injection pipeline after 13 years service.

![Spool recovered from North Sea after 13 years water injection service](image)

The recovered 2m long spool included both a lined section and WeldLink® joint was the end termination of the 12km x 10” pipeline. The PE80 liner used for this pipeline was a 250mm SDR25 with a wall thickness of 10mm. Stalks of 472m in length had been installed by the Swagelining™ technique, which on reversion provided a tight fitting liner against the host bore size of 242mm.

A condition assessment project commissioned by the pipeline operator was undertaken and managed by Subsea7 Pipeline Production Group with support from specialist contractors engaged to perform testing and measurement of the various constituent components of the recovered spool. This work led to a report[1] that contained all the relevant information to enable objective assessment of the various processes and technologies used in the construction of the reeled water injection pipeline system in 1995. It also produced further evidence to assist in the determination of the suitability of polymer lined pipelines for long term subsea water injection service.

The following constituent components of the recovered spool were investigated and further tests were made as considered necessary during the investigation both after the initial inspection/measurements were made and following re-assessment at various stages of dissection of the spool:

- The PE80 liner
- The WeldLink® Connector and compression ring end termination assembly
- The parent coating and field joint coating
- The girth welds
- Corrosion of the carbon steel

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As this Conference is focused on Polymers this paper focuses on those elements of the project that relate to the condition and integrity of the PE80 liner and jointing system and how the internal liner and external coating has performed in respect of providing corrosion protection for the carbon steel.

2 The Lining Technique and Connector System

Swagelining™ technology has been used globally in a wide range of applications transporting products such as potable water, brine, gas, hydrocarbons and mining slurries since its introduction over 20 years ago after development by British Gas and North West Water (now United Utilities) during the 1980s. The technique can be used for rehabilitation of ageing pipes of any material in order to extend life of the asset, or new pipelines such as high pressure subsea water injection pipelines where installation has previously been carried out by reel lay, j-lay or bundle methods.

For the subject pipeline examined herein, the installation was by reelship. On a spoolbase, the PE pipes are usually supplied as 12 or 18m sticks and then butt fusion welded together into a long string of up to 1km in length before insertion into a carbon steel pipe stalk. A welded carbon steel stalk is prepared of appropriate length, usually only limited by available space on the Spoolbase, and a WeldLink® connector is welded to each end of the stalk. The principle of the technique is to reduce the size of a PE pipe by drawing through a reduction die as shown in figure 2 and maintaining the tension under load during installation through the host pipe.

![Figure 2: Swagelining™ of a PE pipe](image)

The PE liner pipe is originally larger than the internal bore of the host pipe. A wire rope or cable is attached to a towing head mechanically and connected to one end of the PE liner pipe which pulls the liner into the host carbon steel pipe from a winch positioned at the far end of the host pipeline. Once the liner has been pulled through the host pipe with some additional length to allow for axial reversion, the load is removed.

The liner is then allowed to revert naturally by stress relaxation for 24 hours until a tight radial fit has been achieved on the host pipe bore. In effect the natural spring-like property of the polymer is utilized.
The ends of the liner are then trimmed back allowing the insertion of an Inconel compression ring that locks the liner in place between the ring and the WeldLink® castellations. Finally trimming of the liner to optimise flow in the system leaves only CRA or PE exposed to the fluid constituents throughout the length of the completed pipeline. The WeldLink® connectors at the end of each stalk are then welded together to produce a long string suitable for reeling, shown as a cut-out in Figure 3.

3 Evaluation of the Condition of PE Liner Pipe and its Constituent Material

The following tests were conducted on the liner pipe and PE material:

- Reversion of the liner
- Tensile performance of the material
- Flexural modulus
- Environmental Stress Crack Resistance (ESCR)
- Chemical stability

The assessment of the liner material was conducted by a laboratory[2] led by members of the team that developed the original PE80 pipe grade used for this water injection line enabling them to source the actual material for comparison. Tests were therefore performed on samples taken from the recovered spool using the actual material as a control wherever possible.

3.1 Liner reversion

A ring section machined out of the spool was measured and the steel pipe carefully removed from the liner. The external diameter of the liner was then measured periodically over the following four weeks. The strain relaxation could then be determined shown in Figure 4.
This expansion on release from the host pipe shows that the liner still had significant locked-in recoverable hoop strain after 13 years in service thus enabling maintenance of a tight fit against the wall of the host carbon steel pipe with no annular gap throughout the life of the pipeline.

### 3.2 Tensile testing

Duplicate tensile tests according to ISO 527-3\(^3\) were undertaken on samples taken from the 12, 6, 9 and 3 o’clock positions (as received), designated as North, East, South and West with one sample from each position having had volatile constituents removed in a vacuum oven at 90°C (desorbed). It was considered that the liner would have been likely to absorb low quantities of small molecules during its service life and therefore desorption was undertaken to extract these and determine what effect they had on the mechanical properties of the liner. Although some material was desorbed, the quantities were too small to identify the individual molecular species present. Measurements of yield strength, elongation at yield, break strength and elongation at break taken at each of four locations in the axial direction are presented in Figures 5–8, on the following pages:

Figure 5 shows that the average yield strength of the actual pipe material produced from pellets was 20.27MPa. It can be seen that the as received samples tested with an average of 18.59MPa were slightly lower than this though still close to the manufacturer’s specification of 18MPa. Once volatile constituents had been desorbed, the yield strength increased to an average of 19.96MPa, very close to that of the actual material.
Figure 5: Yield strength of PE80 liner compared with actual material and specification

Figure 6 shows that the average yield strain of the actual pipe material produced from pellets was 18.51%. It can be seen that the as received samples tested gave slightly lower values with an average of 17.84%, however once volatile constituents had been desorbed, the yield strain increased to an average of 19.37%, slightly above that of the actual material.

Figure 6: Yield strain of PE80 liner compared with actual material
Figure 7 shows that the break strength of the actual pipe material produced from pellets was 19.61MPa. It can be seen that the as received samples tested with an average of 16.60MPa were lower than this. Once volatile constituents had been desorbed, the break strength decreased further to an average of 13.76MPa.

Figure 7: Break strength of PE80 liner compared with actual material

Figure 8: Elongation at break of PE80 liner compared with actual material
Figure 8 shows that the average elongation at break of the actual pipe material produced from pellets was 757%. The untreated samples tested with an average of 804% were all above the value for the original material which is perhaps surprising after 13 years in service. However much lower breaking strains with an average of 345% were observed for the desorbed samples, which is below the manufacturer’s specification of 500%.

From all the tensile tests it can be seen that the strength and ductility of the PE80 liner has generally retained levels very close to that of the actual material even after 13 years service. Differences between the as received and desorbed samples are seen in each case, this being consistent with a plasticizing effect caused by small quantities of volatile species absorbed by the liner in service. This effect is most clearly seen in the elongation at break and the break strength, though the yield strength and yield strain are more relevant mechanical properties in this application.

3.3 Flexural modulus

Short-term flexural modulus values were determined for as received liner samples taken from each of the four positions in Figure 9 and compared with a sample produced from reference pellets.

The results in Figure 10 show that there has only been a modest reduction in flexural modulus compared with the actual liner material. This effect could be attributable to plasticisation, though this could not be confirmed as these tests were only conducted on as received samples, since no desorbed samples were available. With all the PE80 liner samples giving values of >85% of the value of the actual material it demonstrates that the flexural modulus is still maintained at a high level after 13 years service.
3.4 Environmental stress crack resistance

The stress crack resistance of the untreated and desorbed liner material was assessed using full-notch creep tests (FNCT) according to ISO 16770[^4], at a range of stress levels from 4 to 7 MPa in a 2% Arkopal detergent solution at 80°C. The results shown in Figure 11 are somewhat surprising, as samples from the liner after 13 years service performed much better in these tests than samples produced from reference pellets.

[^4]: ISO 16770

Figure 11: Environmental stress crack resistance of liner after 13 years service compared with reference
However with extractable species desorbed, the environmental stress crack performance was much closer to that expected from the original sample. This difference between the as received and desorbed samples, as with the tensile test results, can be explained by a plasticising effect caused by the small quantities of volatile species absorbed by the liner in service. For stress crack resistance this absorption of small molecules can be seen to be especially beneficial, giving significantly enhanced performance for this property. FNCT is an accelerated test method, whereas the more representative geometry for a plastic pipe is the notched pipe test ISO 13479\[5\] which takes much longer to obtain test results on the same material with failure times in the order of at least a decade longer. The notched pipe test itself is still too severe a geometry for a liner as the test is performed on an unconstrained pipe, which is allowed to expand in response to applied pressure unlike a fully constrained liner in a carbon steel host pipe. Nevertheless stress crack resistance (ESCR) is such an important possible failure mode for a polymer that it must be considered. It is possible to estimate the lifetime of the PE80 liner in this application due to environmental stress cracking by converting the FNCT results obtained here to their equivalent notched pipe test result and then using an extrapolation factor derived for all PE pipe materials\[6\] to obtain a lifetime\[7\] estimate at a maximum operating temperature of 28°C. Using these assumptions a minimum lifetime of 54 years was calculated for the reference pellets, 97 years for the desorbed liner and 177 years for the untreated liner. This trend shows that ESCR is an unlikely failure mode in this application and further suggests that the likelihood diminishes the longer the pipeline remains in service under these conditions.

### 3.5 Chemical stability

Tests were undertaken to determine whether there had been any degradation of the PE80 liner material. In order to measure the residual stabilisation package in the material, oxidation induction time (OIT) tests according to EN 728\[8\] were performed on the desorbed liner, so that the results were not contaminated by absorbed species, and presented in Table 1:

<table>
<thead>
<tr>
<th>Sample</th>
<th>OIT (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desorbed liner (inner wall)</td>
<td>22</td>
</tr>
<tr>
<td>Desorbed liner (outer wall)</td>
<td>28</td>
</tr>
<tr>
<td>Reference pellet</td>
<td>52</td>
</tr>
<tr>
<td>Reference pipe</td>
<td>46</td>
</tr>
</tbody>
</table>

**Table 1: Oxidation induction time**

The data show that although there has been some reduction in stabilisation the level is still above the requirement of 20 minutes for a new gas or water pipe and therefore protection is still available. Pipes exhumed after many years of service often exhibit much lower OIT levels than this without any measurable loss in integrity. Such performance indicates that the remaining chemical life of this liner is beyond the original 20 year design life and likely to be in excess of 100 years.

Fourier Transform Infra-Red (FTIR) analysis also showed that there had been some oxidative degradation in line with the OIT measurements. In further support of these findings melt flow rate measurements showed no difference between the desorbed liner and reference samples confirming that no chemical degradation had occurred.
4 Liner Pull Out Test on WeldLink®

The principle of this test was to pull the PE80 liner with a winch until half the yield strength of the liner was attained. The load was then removed and the liner allowed to relax for 2 hours. After this time had elapsed the liner was to be pulled either until it parted from the WeldLink® connector or to destruction as the liner reached its yield strength.

Once circumferential steel rings had been removed from the spool for tests on the liner and coating, the PE80 liner was exposed 500mm from the WeldLink® so that a towing head could be attached for connection to a winch cable. This enabled pulling of the liner with only the WeldLink® castellations and compression ring anchoring the liner in place.

The PE80 grade used was specified as having a yield strength of 18MPa, which is equivalent to 12 tonnes force on a liner pipe of this diameter. Therefore the liner was initially pulled to 6tₑ at a rate of 0.5tₑ per minute before being allowed to relax for 2 hours.

After 2 hours with the load removed, the load was again imposed and steadily increased by ~0.5tₑ per minute. On this second pull the load continued to be applied increasingly up to the yield point of the liner. As 13tₑ was reached the liner could visibly be seen to stretch, signalling the onset of permanent deformation as the yield point was approached. At 14tₑ the liner yielded in a gross ductile manner from the towing head. Separation occurred at the reduced section where stress concentrations were created due to the position of bolt holes used to secure the liner to the towing head. The strain elongation due to yielding was 34% which is beyond the point of permanent strain deformation. It was observed that the liner remained firmly held in position by the WeldLink® even when the yield strength of the liner was reached. A short film of the pull-out test was made, which will be presented at the conference to demonstrate the integrity of the connection system.

Yielding at 14tₑ equates to a yield stress of 21.16MPa for the PE80 pipe, which is well above the original nominal yield strength of 18MPa, average of 18.59MPa for the as received samples and the average of 20.27MPa for the actual material in the tensile tests. This indicates that the PE80 liner is as strong as when the pipeline was installed in 1995. The slightly higher result may be best explained by the difference in pulling rate and geometry between the pipe and the tensile tests.

The pull-out test showed that the WeldLink® connector system provides a restraint on the liner that is stronger than the liner itself. The risk of service failure is contained to ensuring correct fitment of the connectors during production as insufficient strain can be imposed on the installed liner for the yield point to be even approached after the compression fitting is completed. The strength of the PE80 liner was beyond expectation indicating that the material has retained its properties through insertion into the pipeline and thereafter through installation by reeling and throughout 13 years of service.

5 Tests on the Parent and Field Joint Coatings

An extensive suite of all the applicable tests from the original specifications were performed by a specialist subcontractor[8]. Because these tests were too exhaustive to describe in detail in this paper, a summary of the most pertinent findings is given in the following paragraphs.
5.1 Parent Coating – 3 Layer PP Coating

The visual appearance of the 3 layer PP coating was considered satisfactory in view of the extensive handling that would have occurred during transport, production, spooling, installation and extended service life before being recovered from the seabed, shown in Figure 12.

In support of its satisfactory appearance, test results shown in Table 2 were generally positive:

<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water soak</td>
<td>Tap water at 80°C</td>
<td>7 &amp; 28 days fail, 24 hour pass</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>ISO 527-2 Type 5A</td>
<td>Acceptable (some low results)</td>
</tr>
<tr>
<td>Oxidation induction time</td>
<td>BS ISO 11357</td>
<td>Low but acceptable</td>
</tr>
<tr>
<td>Cathodic disbondment</td>
<td>-1.5 volt at 60°C</td>
<td>Pass after 2 and 28 days</td>
</tr>
<tr>
<td>Optical microscopy</td>
<td>x40 magnification</td>
<td>No signs of damage</td>
</tr>
<tr>
<td>Peel adhesion</td>
<td>BS EN 12068 Annex K</td>
<td>Pass</td>
</tr>
<tr>
<td>Indentation</td>
<td>DIN 30 678 Paragraph 5.3.5</td>
<td>Pass</td>
</tr>
<tr>
<td>Impact</td>
<td>DIN 30 678 Paragraph 5.3.4</td>
<td>Pass</td>
</tr>
<tr>
<td>Flexibility</td>
<td>T/SP/CW/6 Part 1 Appendix D</td>
<td>Pass</td>
</tr>
<tr>
<td>Metrology (thickness)</td>
<td>BS EN ISO 2808</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Macroscopy</td>
<td>Visual inspection</td>
<td>No signs of cracking</td>
</tr>
<tr>
<td>Air entrapment</td>
<td>x40 magnification</td>
<td>No signs of air or voids</td>
</tr>
<tr>
<td>Holiday detection</td>
<td>Outer surfaces at 12.5kV</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Table 2: Tests performed on 3LPP coating

The only significant failure related to the 7 day and 28 day hot water soak test at 80°C. However the 24 hour soak test did pass. Disbondment between the coating and substrate occurred in both 7 and 28 days cases of failure. However at the comparatively low operating temperatures that existed in the pipeline service environment the parent 3LPP coating would be expected to have many more years of satisfactory service before disbondment became a concern.
The original specification for tensile strength was >25MPa and the results obtained were between 21.9MPa and 28.9MPa. These results are what might have been in the range expected for the original material at the time of procurement. It is understood that the lower results around 21.9MPa may have been caused by minor external defects and scratches on the outer surface.

Although the OIT gave a very low value suggesting that antioxidant protection had been lost from the PP, this is not surprising for a polymer exposed to a pressurised aqueous environment where diffusion from the surrounding media is likely to be continually occurring. However it is possible this diffusion may have resulted in a beneficial plasticising effect. If this has occurred, it suggests an explanation of the good performance in critical material properties seen in the test results.

The cathodic disbondment results were within specification for both 48 hour and 28 day tests at 65°C. Optical microscopy showed no signs of cracking, voids, air entrapment or disbondment between the interface surfaces with only minor external surface damage such as abrasion marks that may have been caused by the recovery procedure, subsequent cutting operations and transportation. The peel strength was satisfactory in that the actual bond strength could not be determined since it was greater than the strength of the PP itself. All other tests such as indentation and impact were well within acceptance criteria.

Overall the 3LPP parent coating exhibited material properties consistent with the original properties of the material at the time of installation and it can be concluded that is in very good condition with extended continued satisfactory service predicted in the operating conditions experienced.

5.2 PE Field Joint Coating

The section used for the field joint coating tests is shown in Figure 13.

Tests performed on the field joint coating are shown in Table 3 overleaf, with failures highlighted in red:
<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water soak</td>
<td>7 days in tap water at 80°C</td>
<td>Failure due to disbondment</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>BS ISO 37</td>
<td>Acceptable (some low results)</td>
</tr>
<tr>
<td>Cathodic disbondment</td>
<td>-1.5 volt at 65°C</td>
<td>Failure (28mm radius)</td>
</tr>
<tr>
<td>Peel adhesion</td>
<td>BS EN 12068 Annex C</td>
<td>Failure due to disbondment</td>
</tr>
<tr>
<td>Hardness</td>
<td>BS EN ISO 868</td>
<td>Pass</td>
</tr>
<tr>
<td>Impact</td>
<td>BS EN 12068 Annex H</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Metrology (thickness)</td>
<td>BS EN ISO 2808</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Macroscopy</td>
<td>Visual inspection</td>
<td>Disbondment</td>
</tr>
</tbody>
</table>

Table 3: Tests performed on HTLP60PE field joint coating

The Heat Shrink Sleeve had disbonded from both the surface of the parent coating and the substrate. Cathodic disbondment of this nature is a notable failure as the sleeve easily disbonded from all surfaces and substrates to which it was attached. Although the field joint coating had lost its integrity due to inadequate bonding between the PE layer and the parent coating and substrate, no significant external corrosion of the carbon steel had occurred.

5.3 Flange Protection Coating

It was also noted that the coating material that was intended to provide corrosion protection from the end of the field joint coating had been badly damaged and was largely missing. It is suspected that this is glass flaked epoxy applied offshore but this was not confirmed. Despite the damage and extensive areas of missing material, the flange had remained in reasonable condition with few visible signs of corrosion.

6 Corrosion of the Carbon Steel

Figure 14: Internal surface of the carbon steel pipe exhibiting only superficial corrosion

Figure 15: External surface of the carbon steel pipe exhibiting only superficial corrosion
Figures 14 and 15 on the previous page show the internal and external surfaces of a sample taken from the carbon steel pipe and sent to a specialist sub-contractor for examination. Digital optical microscopy could only detect superficial corrosion on both internal and external surfaces.

![Image](image1.png)

**Figure 16: Area of worst case corrosion on internal surface of the carbon steel pipe x20**

The maximum depth of metal loss was approximately 280㎛ in the area of worst case shown in Figure 16. This area was sectioned and metallographically prepared to a 1㎛ diamond finish shown below in Figure 17.

![Image](image2.png)

**Figure 17: Section through worst case corrosion on internal surface of the carbon steel pipe x50**

Overall corrosion at the internal surface of the pipe was in patches and was essentially superficial. The maximum depth of metal loss observed in the sections prepared through what appeared visually as a location of worst case corrosion was 280㎛ or 1.6% of the nominal wall thickness of 17mm. The major part of the internal surface was not corroded and was covered in cracked mill scale. This corrosion level was so low that no meaningful estimate of remaining service lifetime could be derived. It was concluded that the carbon steel pipe had been adequately prevented from internal corrosion by the PE80 liner and from external corrosion by the parent and field joint coatings.
7 Summary and Conclusions

As far as the authors are aware, this is the first time a PE lined spool from a water injection pipeline has been available for condition assessment after a reasonable period in service and this provided a unique opportunity to conduct an investigation. The testing plan was discussed at length with the pipeline operator and expert contractors before the actual testing work scope was finalised. Testing was focused on gathering relevant information that would enable accurate evaluation of suitability or fitness for purpose of the methods and processes that were used collectively to build and install this PE lined pipeline. From the test data it was considered possible to derive the following conclusions:

- Overall, the corrosion controls put in place to protect the pipeline have been successful. The spool shows only superficial corrosion internally and externally and is considered to be in good condition considering its age and history
- The PE liner has remained tight fitting after reeling, installation and 13 years in service and exhibited residual strain during inspection / testing
- With no deterioration in condition compared to its original sample material, the PE liner material has performed satisfactorily in the service application
- As demonstrated by the pull out test, the WeldLink® connector and compression ring assembly retaining the Swagelined liner has remained fully intact and secure
- The linepipe and field joint coatings remain in good condition and have provided satisfactory corrosion control despite poor adhesion of the field joint coating to the linepipe coating and adhesive substrate

Since the first PE lined water injection pipeline was installed in 1994, none of the PE lined carbon steel pipelines operating in the North Sea are known to have failed to date whereas there is a body of evidence suggesting a lifetime expectancy of less than 7 years for unlined pipelines operating under similar service conditions[11]. The advantages of a polymer lined-pipeline are improved flow, reduced energy consumption, lower weight, better thermal insulation and increased lifetime at a lower overall cost than the alternatives of a corrosion allowance or use of a CRA pipe material. Although the use of polymer lining technology in the offshore industry has largely been limited to relatively low temperature water injection service until now, recent developments in polymer materials, venting and various new methods of connection mean that there is now the opportunity to widen the scope of application to much higher operating temperatures and hydrocarbon service, especially for projects where the cost of clad CRA pipe is prohibitive. New connector systems will enable this technology to be competitive for S-lay applications in the near future.
References


