Shell Global Solutions

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Technical assessment of spoolable fibre reinforced plastic pipe systems for SPDC

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by

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Summary

At the request of Shell Petroleum Development Company (SPDC), Shell Global Solutions International B.V. evaluated several commercially available spoolable fibre-reinforced plastic pipe systems for compliance with Shell DEP 31.40.10.20-Gen. The requirement was for 3” to 6” diameter spoolable pipe, to be used in the swamp areas of the SPDC Western Division, and for the transport of crude oil / water mixture, which contains associated (methane) gas mixtures.

From the technical evaluation it has been concluded that the number of Manufacturers of spoolable pipe that have designed and qualified their products in compliance with DEP 31.40.10.20-Gen, has increased from only one in 2007 to four in 2008, i.e. Fiberspar, Pipelife, Aerosun, and Polyflow, therefore allowing competitive bidding. In addition, the other Manufacturers showed willingness to comply with DEP 31.40.10.20-Gen requirements for future Shell projects.

None of the evaluated Manufacturers have demonstrated by tests that the hydrocarbon emissions for their spoolable pipe system can meet the requirement of maximum allowable emission level of 190 gr./km/year, as specified for the SPDC envisaged application.

Before the DEP qualified spoolable pipe systems can be accepted for the SPDC envisaged application, further measures will be required, e.g. application of an impermeable outer sheath, or adequate venting systems. The Manufacturer must demonstrate by tests that the hydrocarbon emission for their spoolable pipe system, including a permeation barrier, or venting system, can meet the hydrocarbon emission limit requirement.

Two evaluated spoolable pipe systems, i.e. from Pipelife, and Wellstream, are based on steel reinforcement, and therefore may suffer from corrosion due to permeation of corrosive fluids through the polymer material, and consequently pose the potential threat for strength degradation of the load bearing steel. None of these Manufacturers have demonstrated by tests that corrosion attack of the steel reinforcement material is within acceptable limits, i.e. safe and reliable operation of the spoolable pipe within 20 years service life at the SPDC envisaged operating conditions.

Only DEP qualified spoolable pipe systems, including application of a qualified hydrocarbon permeation barrier system, are acceptable for the SPDC envisaged application.

Amsterdam, July 2008

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1. Introduction

At the request of Shell Petroleum Development Company (SPDC), Shell Global Solutions International B.V. has evaluated several commercially available spoolable fibre-reinforced plastic pipe systems for compliance with Shell DEP 31.40.10.20-Gen.

The requirement is for 3" to 6" diameter spoolable pipe, to be used in the swamp areas of the SPDC Western Division, for the transport of crude oil / water mixture, which contains associated (methane) gas mixtures.

From an earlier study it was concluded that fibre-reinforced thermoplastic material, as typically used for spoolable pipe, results in unacceptable high emission of hydrocarbons, and therefore the spoolable pipe system require additional measures to reduce hydrocarbon emission to acceptable limits, e.g. application of an impermeable external sheath, or adequate venting system. This will be further discussed in the report.

2. Scope of work

The scope of work included the following:

- Compile concise specification for the envisaged application.
- Contact at least 6 suppliers of spoolable fibre-reinforced plastic pipe systems and determine interest and potential in providing their pipe system for the envisaged service.
- Request technical data from those suppliers who responded positively to be able to asses their product against compliance with Shell DEP 31.40.10.20-Gen.
- Perform preliminary assessment of the obtained data, and selection of maximum three spoolable pipe systems / vendors with highest potential to fulfil the requirements. Evaluation will include, respond time to request, provision of data, cooperation, and track record within Shell.
- Perform detailed assessment against Shell DEP 31.40.10.20-Gen.

3. Design conditions

The design conditions specified for the SPDC spoolable pipe application are the following:

- Crude oil / water mixture, which contains associated (methane) gas, with a partial pressure in the range 5 bar to 38 bar;
- Design pressure ranges, (i) < 25 bar, (ii) 25 bar to 65 bar, and (iii) > 65 bar;
- Maximum design temperature: 65 °C;
- Inside diameter: 4 inch;
- Hydrocarbon emission: maximum 190 grams/km/year.

4. Specifications

Application of spoolable fibre-reinforced plastic pipe must comply with DEP 31.40.10.20-Gen, which includes requirements for design, qualification, and quality control. For the SPDC envisaged application, the spoolable pipe must also meet the HSE requirement of hydrocarbon emission to be less than 190 grams/km/year.

5. Technical evaluation of the manufacturers

Nine potential manufacturers of spoolable pipe have been requested to (i) offer pipe systems, capable to meet the service conditions, as specified by SPDC, (ii) perform qualification tests, in compliance with Shell DEP 31.40.10.20-Gen, and (iii) show track records with Shell. The outcome of the technical evaluation of manufacturers is summarized in Table 1.

Table 1 *Summary of the technical evaluation of manufacturers of spoolable pipe*

Manufacturer	**Product identification**	**Compliance with DEP 31.40.10.20**	**Track records within Shell**
Aerosun - RTP China	Pipe size 4.5 inch Rating: 100 bar/ 65 °C HDPE / Aramide	MDS (*) - provided Test data (DNV) Willingness to comply with DEP	No
Airborne - RTP The Netherlands	Development stage Pipe size: 2 inch Rating: 80 bar / 65 °C Glass / PP (Plytron)	MDS - not provided Test data (internal) Willingness to comply with DEP	No
Egeplast - RTP Germany	Pipe size: 4 inch Rating: 20 bar / 65 °C HDPE / HDPE-tape	MDS - not provided Test data (internal) Willingness to comply with DEP	No
Fiberspar - GRE USA	Pipe size: 4.5 inch Rating: 100 bar/ 65 °C HDPE / GRE	MDS - provided Qualified (DEP)	PDO - field trial - Shell-US, Texas
FPI - GRE USA	Pipe size: 4.5 inch Rating: 100 bar/ 65 °C HDPE / GRE	MDS - not provided No test data Willingness to comply with DEP	No
Pipelife - RTP **Type M480** The Netherlands	Pipe size: 4 inch Rating: 90 bar / 65 °C HDPE / Aramide	MDS - provided Test data (DNV) Willingness to comply with DEP	PDO - 4” diameter - water / oil: 20 bar - effluent : 40 bar
Pipelife - sRTP **Type H415** The Netherlands	Pipe size: 4 inch Rating: 150 bar/ 65 °C HDPE / steel cord (corrosion issue)	MDS - not provided Test data (DNV) Willingness to comply with DEP	No
Polyflow – RTP Un-bonded layers USA	Pipe size: 4.5 inch Rating: 26 bar / 65 °C PPS / Aramide-PP	MDS - not provided Test data (DNV) Willingness to comply with DEP	No
Technip – RTP **Type Coflexlite** Un-bonded layers France	Pipe size: 4 inch Rating: 100 bar/ 65 °C HDPE / Aramide	MDS - not provided No test data Willingness to comply with DEP	No
Wellstream – RTP USA	Pipe size: 4 inch Rating: 100 bar/ 60 °C HDPE / steel strip (corrosion issue)	MDS - not provided Test data (DNV) Willingness to comply with DEP	No

(*) MDS: Material Data Sheet

6. Qualification

6.1 Requirements

6.1.1 General

To qualify, the Manufacturer must demonstrate by performing tests that the spoolable pipe is fit-for-purpose, i.e. capable of meeting the minimum design requirements. The qualification programme consists of standard methods for quantifying performance with respect to internal pressure, temperature, and axial tensile load, in compliance with DEP 31.40.10.20-Gen.

The Manufacturers qualification tests must be carried out, or witnessed and certified by an independent third party authority, e.g. Lloyds, DNV, etc.

6.1.2 Short-term burst test

The short-term burst strength (STHP) in bar must be determined by testing five replicate pipe (+joint) samples, with minimum test length of 5 times pipe diameter and unrestrained ends, in accordance with ASTM D 1599. The STHP must be taken as the lower deviated (two standard deviations) value of the five replicate samples. Testing is performed at SLT (Standard Laboratory Temperature), i.e. 23 ºC +/- 2 ºC.

6.1.3 1000 hr qualification test

To demonstrate long-term pressure strength capability, i.e. minimum design life of 20 years, two replicate samples (pipe+joint) must be 1000 hr tested, in accordance with ASTM D 1598, at 65 °C, at a test pressure of 2.2 times the design pressure. Fresh water is used for the test fluid.

6.1.4 Tensile strength test

The ultimate tensile strength (TS) must be determined by testing five replicate pipe samples in accordance with ASTM D 2105. The tensile strength (TS) must be taken as the lower deviated (two standard deviations) value of the five replicate samples. Testing is performed at SLT (Standard Laboratory Temperature), i.e. 23 ºC +/- 2 ºC.

6.1.5 Hydrocarbon emission

From an earlier study, see Appendix A, it was concluded that fibre-reinforced thermoplastic material, as typically used for spoolable pipe, results in unacceptable high emission of hydrocarbons, and therefore require further measures to reduce hydrocarbon emission, see Appendix B. In consultation with the Shell HSE department it was decided to limit the maximum allowable hydrocarbon emission to maximum 190 grams/km/year.

To qualify, the manufacturer must demonstrate, by tests, that emission of hydrocarbons for their spoolable pipe system does not exceed the specified maximum allowable emission level of 190 grams/km/year.

6.2 Results

The following summarises present status of the qualification tests performed for the different spoolable pipe systems, which may be used for the SPDC envisaged application.

6.2.1 Aerosun spoolable pipe

Aerosun, manufacturer of spoolable pipe is located in China. The spoolable pipe system consists of the following layers: (i) polyethylene (PE) liner, (ii) structural layer of helical wound aramide-fibre reinforced PE tape, and (iii) external PE sheath.

6.2.1.1 Product identification

For the SPDC envisaged application, the manufacturer has proposed the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4.5 inch;
  - Type: CR100/110;
  - Joint: mechanical.
- Dimensions:
  - Internal diameter: 111 mm;
  - Outer diameter: 141 mm;
  - Thickness liner: 6.5 mm;
  - Thickness reinforced wall: 4.2 mm;
  - Thickness external layer: 4.3 mm.
- Material:
  - Liner: PE 100;
  - Reinforced wall: Aramid Fibre (Twaron 2300) reinforced PE 80;
  - External: UV resistant PE 100 sheath.
- Technical specification:
  - Design pressure / temperature: 100 bar / 65 ºC;
  - Design tensile load: 17 kN;
  - Vacuum resistance: full vacuum.

6.2.1.2 Short-term burst tests

Aerosun has performed short-term burst tests in-house, witnessed by DNV. To verify the Manufacturers burst test results, Shell Global Solutions International BV has performed confirmation tests for 4.5” diameter spoolable pipe (+joint) samples. For safety reasons, the pipe samples used for the burst test have been placed in a metal housing see Figure 1.
A photograph showing the “virgin” Aerosun pipe samples, is presented in Figure 2. Following summarises the test results:

- Aerosun burst test results: 260 bar, 370 bar, 371 bar, 323 bar, 336 bar, and 328 bar, i.e. average burst pressure of 331 bar, and standard deviation 40 bar. The lower deviated burst strength STHP (mean value minus two standard deviations) is calculated at 251 bar. Based on a minimum safety factor of 3.75 on STHP, as specified in DEP 31.40.10.20-Gen, the maximum design pressure is calculated at 67 bar;
- Confirmation burst tests: 260 bar, 279 bar, and 303 bar, and these are within the same range as the Aerosun burst pressure test results. A photograph showing the Aerosun pipe after burst failure is presented in Figure 3, and detail of the fracture is presented in Figure 4.

6.2.1.3 1000 hr qualification test

Aerosun has performed in-house 1000 hr tests, witnessed by DNV. To verify the Manufacturers test results, Shell Global Solutions International BV has performed 1000 hr confirmation tests for 4.5” diameter spoolable pipe (+joint) samples. Following summarises the results:

- Aerosun test results: Two 4.5” spoolable pipe samples have been 1000 hr tested at 140 bar and 65 ºC. Based on DEP 31.40.10.20-Gen, the maximum design pressure is calculated at 64 bar (140 bar / 2.2), i.e. lower, when compared to the maximum design pressure of 67 bar based on STHP / 3.75;

- To qualify for the initial Aerosun specified design pressure of 70 bar, Shell Global Solutions has performed 1000 hr confirmation tests for two pipe+joint samples at 155 bar, and 65 ºC. However, one sample failed after 312 hrs, and the other sample failed after 550 hrs. Consequently the 4.5” spoolable pipe does not qualify for a design pressure of 70 bar.

Based on the results from both the burst and 1000 hr tests, it is concluded that the 4.5” diameter, Aerosun spoolable pipe is qualified for a maximum design pressure of 64 bar.

6.2.1.4 Tensile strength tests

Aerosun has performed in-house tensile strength tests, witnessed by DNV. To verify the Manufacturers test results, Shell Global Solutions has performed confirmation tensile tests for two 4.5” Aerosun spoolable pipe (+joint) samples. Following summarises the test results:

- Aerosun tensile test results: 160 kN, 220 kN, 223 kN, 230 kN, and 254 kN, i.e. average tensile strength of 217 kN, and standard deviation 35 kN. The lower deviated tensile strength (mean value minus two standard deviations) is calculated at 147 kN. Based on a safety factor of at-least 3, as specified in DEP 31.40.10.20-Gen, the maximum tensile design load is calculated at 49 kN.
- Confirmation tensile test results:
  - Test sample 1, maximum load: 103 kN;
  - Test sample 2, maximum load: 104 kN;
  - Testing speed: 10 mm / minute;
  - Effective length (L_0) for pipe sample: 850 mm.

For both samples used for the confirmation test, the maximum applied tensile load values are lower when compared with the Manufacturers in-house performed tests. A photograph showing the tensile test set-up for the Aerosun pipe sample is presented in Figure 5.

From the “load-displacement” curve, as shown in Figure 6, onset of non-linear behaviour for the Aerosun sample occurs at approximately 50 kN. Based on a safety factor of 3 on the elastic limit strength, the maximum tensile design load is calculated at 17 kN, in agreement with the Manufacturers specified value.

It is concluded that the 4.5” diameter, Aerosun spoolable pipe is qualified for a maximum tensile design load of 17kN.

6.2.1.5 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Aerosun has not performed these tests, and therefore Aerosun spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.1.6 Conclusion

Following summarises present qualification status of the 4.5” Aerosun spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: 64 bar / 65 ºC;
- Maximum tensile design load: 17 kN;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.2 Airborne spoolable pipe

Airborne Composites B.V. is located in The Netherlands, and specialised in development and manufacture of novel composite products, including spoolable pipe. The spoolable pipe consists of “electro-fused” (welded) layers of (i) polypropylene (PP) liner and (ii) structural layer of helical wound glass-fibre reinforced PP tape (type Plytron).

6.2.2.1 Product identification

Airborne has only designed and manufactured a 2” diameter prototype version of a spoolable pipe. Airborne has to develop and manufacture a 4” spoolable pipe version for the SPDC envisaged application, and therefore details on wall thickness, design pressure, design tensile load, etc, are presently not available for a 4” spoolable pipe, to be used for the SPDC envisaged application.

6.2.2.2 Technical specification

- Pipe size 4”: presently not available;
- Design pressure / temperature: not defined;
- Design tensile load: not defined;
- Vacuum resistance: not defined.

6.2.2.3 Short-term burst tests

Airborne has performed a limited number of in-house short-term burst tests at both room temperature and 60 ºC for 2” diameter prototype spoolable pipe samples.

The short-term burst strength values for the 2” diameter pipe samples, measured at room temperature are: 435 bar, 420 bar and 410 bar. Burst strength values measured at 60 ºC are: 370 bar, 386 bar, and 393 bar. However, for the SPDC envisaged application, short-term burst tests for 4” spoolable pipe (+joint) samples are required.

To qualify for the SPDC envisaged application, a minimum of five short-term burst tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform burst confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.2.4 1000 hr qualification test

Airborne has performed in-house a 1000 hr test for only one 2” spoolable pipe sample at a pressure of 200 bar, and 65 ºC. However, to qualify for the SPDC envisaged application, 1000 hr tests are required for two replicate 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform 1000 hr confirmation tests for two 4” diameter spoolable pipe (+joint) samples.

6.2.2.5 Tensile strength tests

Tensile strength tests for the 2” diameter prototype spoolable pipe have presently not been performed by Airborne.

To qualify for the SPDC envisaged application, a minimum of five tensile strength tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform tensile strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.2.6 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Airborne has not performed these tests, and therefore Airborne spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.2.7 Conclusion

Following summarises present status of the 4” Airborne spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: not qualified;
- Maximum tensile design load: not qualified;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.3 Egeplast spoolable pipe

Egeplast, manufacturer of spoolable pipe, type HexelOne, is located in Germany. The HexelOne spoolable pipe consists of (i) HDPE liner, (ii) stretched mono-oriented HDPE film, developed by Solvay and (iii) HDPE outer sheath.

6.2.3.1 Product identification

For the SPDC envisaged application, the manufacturer may offer a 4” spoolable pipe, type HexelOne, for a design pressure of 25 bar, and design temperature of 65 ºC. Details on dimensions (diameter, thickness) for the 25 bar spoolable pipe are presently not available.

- Product:
  - Pipe size: 4 inch:
  - Type: HexelOne;
  - Joint type: mechanical.
- Dimensions: presently not available.
- Material:
  - Liner: PE 100;
  - Reinforced wall: stretched mono-oriented PE 100 film;
  - External: UV resistant PE 100 sheath.
- Technical specification:
  - Pipe size: 4 inch;
  - Design pressure / temperature: 25 bar / 65 ºC;
  - Design tensile load: not specified;
  - Vacuum resistance: not specified;

6.2.3.2 Short-term burst tests

Egeplast has performed a limited number of in-house short-term burst strength tests for 4” HexelOne spoolable pipe samples, resulting in an average burst strength of 70 bar. The burst tests were performed at SLT (23 ºC +/- 2 ºC) and at 55 ºC.

However, to qualify for the SPDC envisaged application, a minimum of five short-term burst tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform burst confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.3.3 1000 hr qualification test

Egeplast has only performed one test, i.e. 300 hr at a pressure of 43 bar, for a 4” pipe sample. However, to qualify for the SPDC envisaged application, 1000 hr tests are required for two replicate 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform 1000 hr confirmation tests for two 4” diameter spoolable pipe (+joint) samples.

6.2.3.4 Tensile strength tests

Presently, Egeplast has not performed tensile strength tests for Egeplast pipe (+joint) samples. To qualify for the SPDC envisaged application, a minimum of five tensile strength tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform tensile strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.3.5 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Egeplast has not performed these tests, and therefore Airborne spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.3.6 Conclusion

Following summarises present status of the 4” Egeplast spoolable pipe, to be used for the SPDC envisaged application:

- Maximum design pressure / temperature: not qualified;
- Maximum tensile design load: not qualified;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.4 Fiberspar spoolable pipe

Fiberspar, manufacturer of spoolable pipe, is located in the USA. The spoolable pipe system consists of (i) HDPE liner and (ii) structural layer of helical wound glass-fibre reinforced epoxy (GRE). The liner is adhesive bonded to the GRE wall. During an earlier technical evaluation [1], Fiberspar 4.5” spoolable pipe has been qualified in compliance with DEP 31.40.10.20-Gen.

6.2.4.1 Product identification

For the SPDC envisaged application, the earlier qualified 4.5” Fiberspar spoolable pipe may be used. Following summarises details of the Fiberspar product:

- Product:
  - Pipe size: 4.5 inch;
  - Type: series 1500;
  - Joint type: mechanical.
- Dimensions:
  - Inside diameter: 101 mm;
  - Outside diameter: 122 mm;
  - Thickness liner: 5.3 mm;
  - Thickness reinforced wall: 5.1 mm.
- Material:
  - Liner: HDPE;
  - Reinforced wall: glass-fibre reinforced epoxy (GRE);
  - External layer: resin rich layer (UV resistant);
- Technical specification:
  - Design pressure / temperature: 100 bar / 65 ºC;
  - Short-term burst strength: 414 bar;

- Design tensile load: 79 kN;
- Minimum bend radius: 2.0 m.

6.2.4.2 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Presently Fiberspar has not performed such tests, and therefore Fiberspar spoolable pipe is not qualified for the SPDC envisaged application.

6.2.4.3 Overall qualification results

Following summarises present status of the 4.5” Fiberspar spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: 100 bar / 65 ºC.
- Maximum tensile design load: 79 kN.
- Minimum bend radius: 2.0 m.
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.5 Future Pipe Industries spoolable pipe

Future Pipe Industries (FPI), manufacturer of standard GRP piping components, has recently taken over Hydrill USA, manufacturer of spoolable GRP pipe. The “ex” Hydrill spoolable pipe system offered by FPI consists of (i) HDPE liner and (ii) structural layer of helical wound glass-fibre reinforced epoxy (GRE).

6.2.5.1 Product identification

For the SPDC envisaged application, FPI may offer the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4 inch;
  - Type: Cobra;
  - Joint type: mechanical.
- Dimensions:
  - Inside diameter: 99.1 mm;
  - Outside diameter: 115 mm;
  - Total wall thickness: 8.0 mm.
- Material:
  - Liner: HDPE;
  - Reinforced wall: glass-fibre reinforced epoxy (GRE);
  - External layer: resin rich, UV resistant.
- Technical specifications:
  - Design pressure / temperature: 100 bar / 60 ºC;
  - Design tensile load: 49 kN;
  - Minimum bend radius: 2.3 m.

6.2.5.2 Short-term burst tests

FPI has not made available performed short-term burst strength tests for their 4” spoolable pipe. To qualify for the SPDC envisaged application, a minimum of five short-term burst tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions - GSEI/2 must perform burst confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.5.3 1000 hr qualification test

FPI has not made available 1000 hr tests for their 4” spoolable pipe. To qualify for the SPDC envisaged application, 1000 hr tests are required for two replicate 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform 1000 hr confirmation tests for two 4” diameter spoolable pipe (+joint) samples.

6.2.5.4 Tensile strength tests

FPI has not made available tensile strength tests for their 4” spoolable pipe. To qualify for the SPDC envisaged application, a minimum of five tensile strength tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform tensile strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.5.5 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. FPI has not performed these tests, and therefore FPI spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.5.6 Conclusion

Following summarises present status of the 4” FPI spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: not qualified;
- Maximum tensile design load: not qualified;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.6 Pipelife spoolable pipe

Pipelife, manufacturer of spoolable pipe, is located in the Netherlands. The Pipelife spoolable pipe system consists of (i) polyethylene (PE) liner, (ii) structural layer of helical wound aramid-fibre reinforced PE tapes, and (iii) external PE protection layer (UV resistance). For high-pressure application, a steel cord reinforced, so-called sRTP spoolable pipe system is available.

6.2.6.1 Product identification

For the SPDC envisaged application, the manufacturer has selected the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4 inch;
  - Type: Soluforce M480 (aramid fibre) or Soluforce H415 (steel cord);
  - Joint type: electro-fused (welded) + GRE sleeve (in-line coupler).
- Dimensions:
  - Inside diameter: 100 mm;
  - Outside diameter: 125 mm;
  - Total wall thickness: 12.5 mm.

- Material:
  - Liner: PE 100;
  - Reinforced wall: Aramid fibre / PE80 or steel cord / PE80 (sRTP);
  - External: UV resistant PE 100 sheath.
- Technical specification:
  - Design pressure / temperature: 90 bar / 65 ºC (M480) or 150 bar / 65 ºC (H415);
  - Design tensile load: 10 kN;
  - Minimum bend radius: 3.0 m.

6.2.6.2 Short-term burst tests

The following short-term burst tests have been performed for Soluforce spoolable pipe samples:

- Soluforce 4”, M480 spoolable pipe:
  - Pipelife tests: short-term burst tests have not been performed;
  - Shell Global Solutions has performed a limited number of short term burst tests for Soluforce M480 spoolable pipe (+joint) samples, with following results: 336 bar, 362 bar, and 380 bar, i.e. average burst pressure of 359 bar +/- 22 bar. A photograph of the “virgin” sample is presented in Figure 7. Typical burst fracture of the Soluforce M480 pipe is presented in Figure 8.

  The STHP (lower deviated) is calculated at 315 bar. Based on a minimum safety factor of 3.75 on STHP, as specified in DEP 31.40.10.20-Gen, the maximum allowable design pressure for the 4.5” Soluforce M480 pipe is calculated at 84 bar.

  However, to qualify for the SPDC envisaged application, a minimum of five short-term burst tests are required for 4” pipe (+joint) spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform burst strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.
- Soluforce 4”, H415 (steel cord) spoolable pipe:
  - Pipelife has performed an extended number of in-house short-term burst tests, witnessed by DNV. The average burst pressure is calculated at 478 bar, with standard deviation 10 bar. The STHP (lower deviated) is calculated at 458 bar. Based on a minimum safety factor of 2.5 on STHP, as specified in DEP 31.40.10.20-Gen for steel cord reinforced, the maximum allowable design pressure for the 4.5” Soluforce H415 pipe is calculated at 183 bar;

  To qualify for the SPDC envisaged application, Shell Global Solutions must also perform short term burst “confirmation” tests for the steel cord reinforced Soluforce H415 spoolable pipe system. Presently, these confirmation tests have not been performed.

6.2.6.3 1000 hr qualification test

Pipelife has performed in-house 1000 hr qualification tests for M480 spoolable pipe, witnessed by DNV. To verify the Manufacturers test results for Soluforce M480, Shell Global Solutions have also performed 1000 hr confirmation tests for 4” diameter spoolable pipe (+joint) samples. For the steel cord reinforced spoolable pipe, type H415, Pipelife has not performed 1000 hr tests. Following summarises the test results:

- Pipelife in-house tests:
  - Two 4” (M480) spoolable pipe samples have been 1000 hr tested at a pressure of 154 bar and 65 ºC. Based on DEP 31.40.10.20-Gen, the maximum design pressure is calculated at 70 bar (154 bar / 2.2), i.e. lower, when compared to the maximum design pressure of 84 bar based on STHP / 3.75. For the steel cord reinforced Soluforce H415 system, 1000 hr tests have not been performed by Pipelife;

- To qualify for the maximum specified design pressure of 90 bar for Soluforce M480, Shell Global Solutions has performed 1000 hr confirmation tests for two 4” pipe+joint samples at 200 bar, and 65 ºC. However, one sample failed after 220 hrs, and the other sample failed after 312 hrs. Consequently the M480 4” spoolable pipe does not qualify for 90 bar, and only for maximum 70 bar.

To qualify the Soluforce H415 (steel cord) spoolable pipe system for the SPDC envisaged application, 1000 hr tests are required for two replicate 4” pipe+joint pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform 1000 hr confirmation tests for two 4” diameter spoolable pipe (+joint) samples.

6.2.6.4 Tensile strength tests

Pipelife has performed in-house tensile strength tests for M480 spoolable pipe. Tensile strength tests for H415 (steel cord) spoolable pipe, however, have presently not been performed. To verify the Manufacturers test results for the M480 spoolable pipe, Shell Global Solutions has performed confirmation tensile tests for two 4” M480 Soluforce spoolable pipe (+joint) samples. Following summarises the test results:

- Pipelife tensile test results for type M480 pipe: 60 kN, 80 kN, 100 kN, and 120 kN, i.e. average tensile strength of 90 kN, and standard deviation 26 kN. The lower deviated tensile strength (mean value minus two standard deviations) is calculated at 38 kN. Based on a safety factor of at-least 3, as specified in DEP 31.40.10.20-Gen, the maximum tensile design load is calculated at 12 kN.
- Confirmation tensile test results:
  - Test sample 1, maximum load: 68 kN;
  - Test sample 2, maximum load: 68 kN;
  - Testing speed: 10 mm / minute;
  - Effective length (L_0) for pipe sample: 770 mm.

For maximum applied tensile load values are lower when compared with the Manufacturers in-house performed tests. A photograph showing the tensile test set-up for the Pipelife M480 pipe sample is presented in Figure 9.

From the “load-displacement” curve, as shown in Figure 6, onset of non-linear behaviour for the Soluforce M480 pipe sample occurs at approximately 30 kN. Based on a safety factor of 3 on the elastic limit strength, the maximum tensile design load is calculated at 10 kN, in agreement with the Manufacturers specified value.

It is concluded that the 4” diameter, Soluforce M480 spoolable pipe is qualified for a maximum tensile design load of 10 kN.

6.2.6.5 Corrosion aspects

The steel cord reinforced HDPE tape used for Pipelife Soluforce H415 pipe, are manufactured by Bekaert. To protect the steel cords against corrosion, a Zinc coating has been applied, which acts as a corrosion barrier, and sacrificial anode. Permeation of corrosive fluids through the HDPE layer may result in corrosion attack of the Zn-coated steel cords, and consequently pose the potential threat for strength degradation of the load bearing steel cords. Bekaert, manufacturer of the steel cord reinforced HDPE tape, has performed extensive corrosion testing and has provided test reports and documentation to support their findings, and therefore it may be expected that the Zinc coating is capable to protect the steel cords for at-least 20 years operation in a 1 bar CO_2 environment.

The risk of corrosion also applies to the 316L material used for the fittings of Soluforce spoolable pipe. Especially in an air (oxygen), and/or chloride environment, external pitting and/or cracking of the fitting material may be expected.

Before the steel cord reinforced system from Pipelife can be accepted for the SPDC envisaged application, further work is required, and will be reported separately.

6.2.6.6 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Pipelife has not performed these tests, and therefore Soluforce spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.6.7 Conclusion

Following summarises present status of the 4” Soluforce spoolable pipe, which may be used for the SPDC envisaged application:

- Soluforce M480 (aramid fibre) pipe:
  - Maximum design pressure / temperature: 70 bar / 65 ºC;
  - Maximum tensile design load: 10 kN;
  - Hydrocarbon emission < 190 gr./km/year: not qualified.
- Soluforce H415 (steel cord) sRTP pipe:
  - Maximum design pressure / temperature: not qualified;
  - Maximum tensile design load: not qualified;
  - Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.7 Polyflow spoolable pipe

Polyflow, manufacturer of Thermoflex spoolable pipe is located in the USA. The spoolable pipe system consists of un-bonded layers, i.e. (i) polyphenylenesulphide (PPS) liner, (ii) structural layer of helical wound aramide-fibre reinforced polypropylene (PP) tape.

6.2.7.1 Product identification

For the SPDC envisaged application, the manufacturer may offer the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4.5 inch;
  - Type: Thermoflex - Class 500 psi;
  - Joint type: mechanical.
- Dimensions:
  - Inside diameter: 98 mm;
  - Outside diameter: 115 mm;
  - Thickness liner: 2 mm;
  - Thickness reinforced wall: 4 mm;
  - Thickness outer layer: 2.5 mm.
- Material:
  - Liner: PPS;
  - Reinforced wall: Aramid Fibre reinforced polypropylene (PP).
- Technical specification:
  - Design pressure / temperature: 34 bar (500 psi) / 65 ºC;
  - Design tensile load: not specified;
  - Vacuum resistance: full vacuum.

6.2.7.2 Short-term burst tests

Polyflow has performed five short-term burst test for 4.5” Thermoflex 500 psi spoolable pipe samples, witnessed by DNV, and with following results: 99 bar, 105 bar, 106 bar, 110 bar, 112 bar, i.e. average burst pressure of 106 bar, and standard deviation 5 bar. The STHP (lower deviated) is calculated at 96 bar. Based on a minimum safety factor of 3.75 on STHP, as specified in DEP 31.40.10.20-Gen, the maximum allowable design pressure is calculated at 26 bar. Shell Global Solutions has not performed confirmation tests.

6.2.7.3 1000 hr qualification test

Polyflow has performed 1000 hr qualification tests for two 4.5” Thermoflex spoolable pipe, at a pressure of 1150 psi (79 bar) and 65 ºC, witnessed by DNV. Shell Global Solutions has not performed 1000 hr confirmation tests.

Based on DEP 31.40.10.20-Gen, the maximum allowable design pressure is calculated at 36 bar (79 bar / 2.2), i.e. higher than the value of 26 bar based on STHP. Based on the STHP and 1000 hr results, the maximum qualified design pressure is 26 bar, and not 34 bar, as specified by the Manufacturer.

6.2.7.4 Tensile strength tests

Polyflow has performed five tensile strength tests for 4.5” Thermoflex spoolable pipe samples, witnessed by DNV, with the following results: 66.8 kN, 75.7 kN, 66.8 kN, and 75.7 kN, i.e. average tensile strength of 72 kN, and standard deviation 5 kN. The lower deviated ultimate tensile strength is calculated at 62 kN. Based on a safety factor of at-least 3, as specified in DEP 31.40.10.20-Gen, the maximum allowable tensile design load is calculated at 20 kN. Shell Global Solutions has not performed confirmation tensile tests.

6.2.7.5 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Polyflow has not performed these tests, and therefore Thermoflex spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.7.6 Overall qualification results

Following summarises present status of the 4.5” Polyflow Thermoflex spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: 26 bar / 65 ºC;
- Maximum tensile design load: 20 kN;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.8 Technip spoolable pipe

Technip manufacturer of spoolable pipe, is located in France. The spoolable pipe system called “Coflexlite” consists of un-bonded layers, i.e.: (i) high density polyethylene (HDPE) liner, (ii) structural layer of Aramid-fibre / HDPE tape, and (iii) HDPE outer sheath.

6.2.8.1 Product identification

For the SPDC envisaged application, the manufacturer has selected the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4 inch;
  - Type: COF4-1500;
  - Joint: mechanical.
- Dimensions:
  - Inside diameter: 101.3 mm;
  - Outside diameter: 138.4 mm;
  - Thickness liner: not provided;
  - Thickness reinforced wall: not specified;
  - Thickness external layer: not specified.
- Material:
  - Liner: High-density polyethylene (HDPE);
  - Reinforced wall: Aramid Fibre (Kevlar) / HDPE tape;
  - External: UV resistant HDPE sheath.
- Technical specification:
  - Design pressure / temperature: 100 bar / 60 ºC;
  - Design tensile load: not specified;
  - Vacuum resistance: not specified;
  - Minimum bend radius: 1.8 m.

6.2.8.2 Short-term burst tests

Technip has not made available short-term burst strength tests for their 4” Coflexlite COF4-1500 spoolable pipe. To qualify, a minimum of five short-term burst tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen.
In addition, Shell Global Solutions - GSEI/2 must perform burst confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.8.3 1000 hr qualification test

Technip has not performed 1000 hr tests for their 4” Coflexlite COF4-1500 spoolable pipe. To qualify for the SPDC envisaged application, 1000 hr tests are required for two replicate 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform 1000 hr confirmation tests for two 4” diameter spoolable pipe (+joint) samples.

6.2.8.4 Tensile strength tests

Technip has not performed tensile strength tests for their 4” Coflexlite COF4-1500 spoolable pipe. To qualify, a minimum of five tensile strength tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform tensile strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.8.5 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Technip has not performed these tests, and therefore Coflexlite spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.8.6 Conclusion

Following summarises present status of the 4” Coflexip spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: not qualified;
- Maximum tensile design load: not qualified;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.2.9 Wellstream FlexSteel spoolable pipe

Wellstream, manufacturer of FlexSteel spoolable pipe is located in the USA. The spoolable pipe system consists of the following (i) high density polyethylene (HDPE) liner, (ii) two spirally wound layers of steel strips, and (iii) external HDPE protection sheath.

6.2.9.1 Product identification

For the SPDC envisaged application, the manufacturer may offer the following spoolable pipe system, i.e.:

- Product:
  - Pipe size: 4 inch;
  - Type FlexSteel - Class 600 (1500 psi);
  - Joint: mechanical.
- Dimensions:
  - Inside diameter: 93.2 mm;
  - Outside diameter: 119.3 mm;
  - Thickness liner: not provided;
  - Thickness structural wall: not specified;
  - Thickness external layer: not specified.
- Material:
  - Liner: HDPE;
  - Structural wall: two helical wound steel strips;
  - External: UV resistant HDPE sheath.
- Technical specification:
  - Design pressure / temperature: 100 bar / 60 ºC;
  - Design tensile load: not specified;
  - Vacuum resistance: full vacuum;
  - Minimum bend radius: 1.1 m.

6.2.9.2 Short-term burst tests

Wellstream has performed two in-house short-term burst tests for 4” - 1500 psi FlexSteel spoolable pipe, with the following results: 286 bar and 291 bar. However, to qualify, five short-term burst tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform burst confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.9.3 1000 hr qualification test

Wellstream has performed two 1000 hr qualification tests for 4” - 1500 psi FlexSteel spoolable pipe, at a test pressure of 170 bar and 65 ºC, witnessed by DNV. Based on the test pressure of 170 bar, the maximum “qualified” design pressure is calculated at 77 bar (i.e. 170 bar / 2.2), in compliance with DEP 31.40.10.20-Gen. The qualified design pressure, based on the 1000 hr test, is lower than the Wellstream specified design pressure of 100 bar. Shell Global Solutions has not performed confirmation tests.

6.2.9.4 Tensile strength tests

Wellstream has performed two in-house tensile strength tests for 4” - 1500 psi FlexSteel spoolable pipe, with the following results: 159 kN, and 164 kN. However, to qualify, a minimum of five tensile strength tests are required for 4” pipe+joint spoolable pipe samples, in compliance with DEP 31.40.10.20-Gen. In addition, Shell Global Solutions must perform tensile strength confirmation tests for at-least two 4” diameter spoolable pipe (+joint) samples.

6.2.9.5 Corrosion aspects for steel reinforcement

Permeation of corrosive fluids through the HDPE may result in corrosion attack of the steel reinforcement strips of the Wellstream FlexSteel spoolable pipe, and consequently pose the potential threat for strength degradation of the load bearing steel.

The risk of corrosion also applies to the 316L material used for the fittings of the FlexSteel spoolable pipe. Especially in an air (oxygen), and/or chloride environment, external pitting and/or cracking of the fitting material may occur.

Wellstream claim to have performed exposure tests for FlexSteel pipe material in CO_2 (10 bar) service, resulting in very low corrosion attack (0.001 mm/year). Wellstream has presently not supplied sufficient supporting documentation to verify their claim.

Before the steel strip reinforced FlexSteel system from Wellstream can be accepted for the SPDC envisaged application, further work is required, as detailed in Appendix C.

6.2.9.6 Hydrocarbon emission

Before the spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emission does not exceed the maximum allowable level of 190 gr./km/year. Wellstream has not performed these tests, and therefore FlexSteel spoolable pipe is presently not qualified for the SPDC envisaged application.

6.2.9.7 Conclusion

Following summarises present status of the 4” FlexSteel spoolable pipe, which may be used for the SPDC envisaged application:

- Maximum design pressure / temperature: 77 bar / 65 ºC;
- Maximum tensile design load: not qualified;
- Hydrocarbon emission < 190 gr./km/year: not qualified.

6.3 Overall qualification results - compliance with DEP

The results of the qualification tests, including ranking order, are summarised in Table 1.

Table 1 *Summary of qualification results for RTP spoolable pipe systems*

Manufacturer / Type	Size (inch)	STHP (bar)	TS (kN)	1000 hr pressure (bar)	Design pressure (bar)	Design temp (ºC)	Design Tensile load (kN)	Status / ranking SPDC (*)
Fiberspar - GRE	4.5	392	223	227	100	60	74	Qualified Rank **no 1**
Pipelife M480 (aramid)	4	315	38	154	70	65	10	Qualified Rank **no 2**
Aerosun	4.5	251	147	140	64	65	17	Qualified Rank **no 3**
Polyflow	4.5	96	62	79	26	65	20	Qualified Rank **no 4**
Wellstream rating 100 bar	4	**X(2)**	**X(2)**	170	77	65	**X**	Not qualified Rank **no 5**
Pipelife - sRTP H415 (150 bar)	4	458	**X(0)**	**X(0)**	**X**	**X**	**X**	Not qualified Rank **no 6**
Technip rating 100 bar	4	**X(0)**	**X(0)**	**X(0)**	**X**	**X**	**X**	Not qualified Rank **no 7**
FuturePipe - GRE rating 100 bar	4	**X(0)**	**X(0)**	**X(0)**	**X**	**X**	**X**	Not qualified Rank **no 8**
Egeplast rating 25 bar	4	**X(0)**	**X (0)**	**X(0)**	**X**	**X**	**X**	Not qualified Rank **no 9**
Airborne prototype status	4	**X(0)**	**X(0)**	**X(0)**	**X**	**X**	**X**	Not qualified Rank **no 10**

X: Insufficient test data – not compliant with DEP 31.40.10.20-Gen.

Note 1: To meet the Shell hydrocarbon emission restriction requirement, all systems require additional measures, i.e. application of an impermeable outer sheath, or adequate venting system.

Note 2: The steel reinforced systems from Wellstream and Pipelife may suffer from corrosion attack.

7. Discussion

It is encouraging to conclude that the number of Manufacturers of spoolable pipe that have designed and qualified their products in compliance with DEP 31.40.10.20-Gen, has increase from only one in 2007 to four in 2008, i.e. Fiberspar, Pipelife, Aerosun, and Polyflow, therefore allowing competitive bidding. It is also positive that the six other Manufacturers showed willingness to comply with DEP 31.40.10.20-Gen requirements for future Shell projects.

From an earlier study it was concluded that fibre-reinforced thermoplastic material, as typically used for spoolable pipe, results in unacceptable high emission of hydrocarbons, and therefore require further measures, e.g. application of an impermeable barrier, or an adequate venting system.

Before any spoolable pipe system can be accepted for the envisaged SPDC application, the manufacturer must demonstrate by tests that the hydrocarbon emissions of their spoolable pipe system, including permeation barrier, or venting system, does not exceed the maximum allowable level of 190 gr./km/year, as specified by the Shell HSE department. Presently none of spoolable pipe manufacturers have performed these tests, and therefore do not qualify for the SPDC envisaged application.

Two evaluated spoolable pipe systems, i.e. from Pipelife, and Wellstream, are based on steel reinforcement, and may therefore suffer from corrosion due to permeation of corrosive fluids through the polymer material, and consequently pose the potential threat for strength degradation of the load bearing steel. Before the steel reinforced spoolable pipe system from Pipelife and Wellstream can be accepted for the SPDC envisaged application, the manufacturer must demonstrate by testing that corrosion attack of the steel reinforcement material is within acceptable limits, i.e. safe and reliable operation of the spoolable pipe within 20 years service life at the SPDC envisaged operating conditions.

Only DEP qualified spoolable pipe systems, including application of a qualified hydrocarbon permeation barrier system, are acceptable for the SPDC envisaged application.

8. Conclusions

(a) Four of the in total ten approached Manufacturers have designed and qualified their products in compliance with DEP 31.40.10.20-Gen. The other six Manufacturers, however, showed willingness to comply for future Shell projects;

(b) None of the Manufacturers have demonstrated by tests that the hydrocarbon emission for their spoolable pipe system, including an emission barrier system, can meet the requirement of maximum allowable emission level of 190 gr./km/year, as specified for the SPDC envisaged application;

(c) None of the Manufacturers have demonstrated by tests that corrosion attack of the steel reinforcement material is within acceptable limits, i.e. safe and reliable operation of the spoolable pipe within 20 years SPDC service life.

9. References

1. Janssen, F.A.H, van Loon P.J.M. “Technical assessment of spoolable reinforced plastic pipe for SEPCO”, GS.07.50734.

Amsterdam, July 2008
wk

Figure 1
Photograph showing the spoolable pipe sample placed in a metal housing for the burst test

Figure 2 *Photograph showing the Aerosun test pipes "as received"*

Figure 3 *Photograph showing rupture of the Aerosun test pipes after burst test*

Figure 4
Photograph showing detail of the rupture of the Aerosun test pipe after burst test

Figure 5 *Photograph showing the tensile test set-up for Aerosun pipe sample*

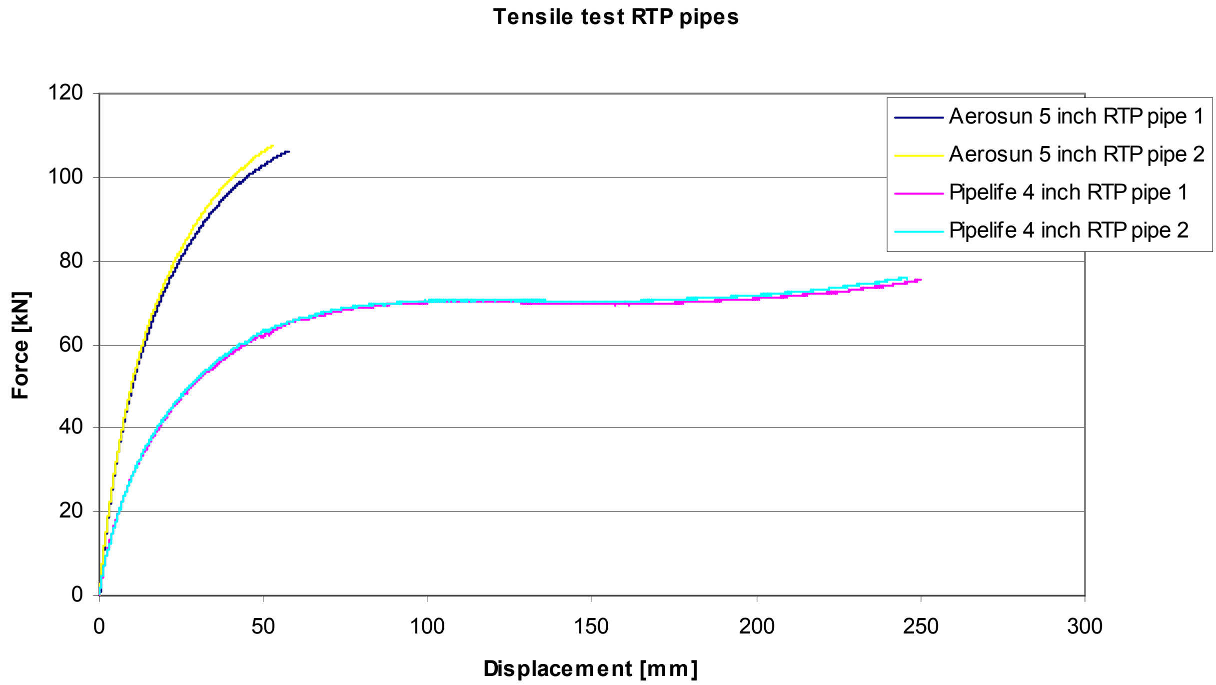

Figure 6
Tensile load versus displacement curves for Aerosun and Pipelife test samples

Figure 7 *Photograph showing the Pipelife M480 test pipe "as received"*

Figure 8 *Photograph showing rupture of the Pipelife M480 test pipe after burst test*

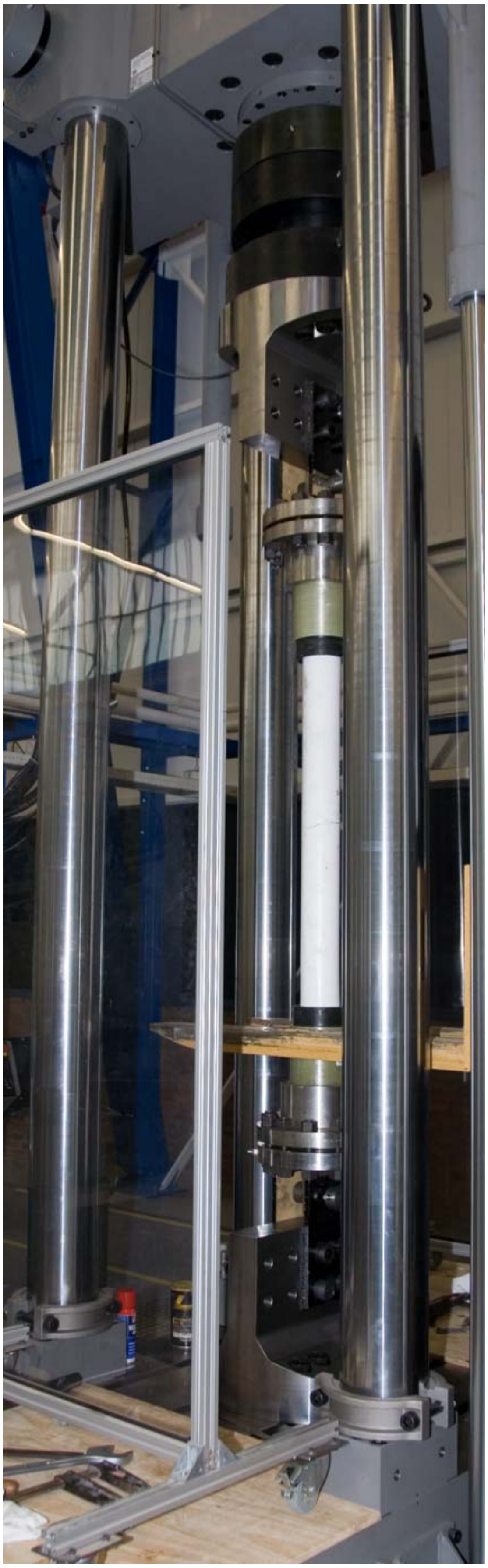

Figure 9 *Photograph showing the tensile test set-up for Pipelife M480 pipe sample*

Appendix A. Permeability of Reinforced ThermoPlastic (RTP) for hydrocarbons

Shell Global Solutions

GSEI/0068/07
RESTRICTED

Materials & Inspection Engineering Group

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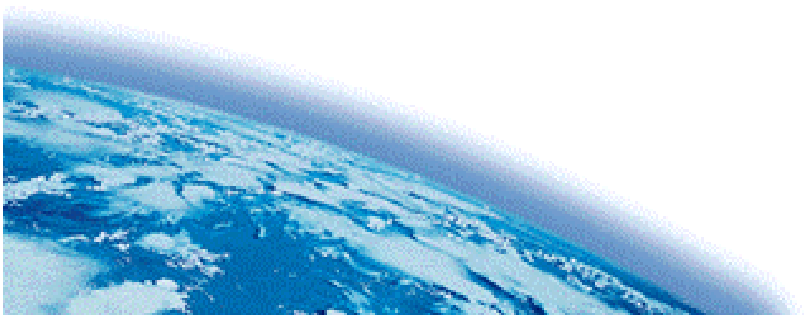
SUBJECT	: The feasibility of using trenched Polyethylene based re-inforced thermoplastic pipes for crude oil flowlines by SPDC in Nigeria	
PROJECT IDENTIFICATION	: 54012002	
DATE OF ISSUE	: 27 August 2007	
KEYWORDS	: Flowlines, Emission, Thermoplastic, Crude oil, venting, Contamination	

Summary

SPDC has to replace hundreds of kilometres of stolen flowlines used in crude oil service. For flowlines with a typical diameter of 3"-6", Re-inforced Thermoplastic Pipe (RTP) might offer an economically and technically attractive alternative to carbon steel. The materials used for RTP are inherent corrosion resistant. RTP is further light in weight, which facilitates transport and can be supplied in continuous lengths, which typically results in high installation rates.

A field pilot is planned in Nigeria in 2007 to understand the local challenges for implementation. The envisaged trenching in swamp areas, including a number of river crossings, is different from previous RTP applications within Shell that so far have been mainly surface laid.

SPDC contracted Shell Global Solutions for technical assistance on various issues related to the envisaged use of RTP. The issue discussed in this note is the permeability of RTP for (hydrocarbon) fluids.



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E&P HSE was consulted for advice on how the As Low As Reasonably Practicable (ALARP) HSE rule as given in the E&P HSE guideline has to be applied for the specific SPDC conditions.

E&P HSE stated that the use of material/equipment that will by design result in the pollution of soil and groundwater and surface water is not acceptable. Standard RTP is therefore unsuitable for the transport of hydrocarbons in buried systems and in aquatic environments. Fugitive emissions i.e. surface laid systems are to a certain extent acceptable but when practicable pre-cautions should be taken to limit these emissions as much as possible.

To quantify the issue, in order to define required precautions for a buried system, the crude oil emission of a Polyethylene based RTP as considered by SPDC was calculated using existing experimental data. The estimated Nigerian (Nkali) crude oil emission of a typical 4″ RTP at 40 °C is approx. 30 kg per kilometre per year. Based on risk limits used in the Dutch environmental policy, it was confirmed that such a crude having a Benzene content of 0.12 % could seriously impair humans, plant and animal life after one year of operation. Benzene is one of the most hazardous components in crude oil.

This finding confirms that the buried application of RTP is not feasible for the envisaged application without further measures to prevent the emission. Suitable measures would be the use of metal permeation barriers or a venting system with controlled release.

1. Background

SPDC operates an extensive network of pipelines and flowlines. Two of the main concerns regarding the integrity of this network are corrosion and third party interference. Recently there has been a high rate of vandalisation of Carbon Steel (CS) flowlines in swamp areas of SPDC Western Division. Beginning of 2007, 501 km of CS flowlines have been stolen since production was halted on 18 February 2006. If operations were to resume today, approximately 130 Mbopd will be locked in as a result of stolen flowlines. SPDC Internal studies have shown that approx. 390 km of flowlines in the SPDC Western Division will require replacement upon re-entry into the fields. For flowlines with a typical diameter of 3″-6″ Re-inforced Thermoplastic Pipes (RTP) might offer an economically and technically attractive alternative to CS. RTP are produced using polymers and synthetic fibres that are inherently corrosion resistant. RTP is further light in weight, which facilitates transport and can be supplied in continuous lengths, which typically results in high installation rates[i].

Based on RTP temperature and pressure limitations, it is possible to replace 161 km using RTP especially in Jones Creek & Odidi fields. A field pilot is planned in Nigeria in 2007 to understand the local challenges for implementation. The envisaged trenching in swamp areas, including a number of river crossings, is different from previous RTP applications within Shell that so far have been mainly surface laid. RTP pipe systems for use within Shell should comply with TECHNICAL SPECIFICATION SPOOLABLE FIBRE-REINFORCED PLASTIC PIPES, DEP 31.40.10.20-Gen. SPDC contracted Shell Global Solutions for technical assistance on various issues related to the envisaged use of RTP e.g. influence of hydrocarbons, installation and qualification according to the DEP[ii]. This note discusses the issue of the permeation of hydrocarbons through the RTP pipe wall and potential environmental issues arising from this permeation.

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i Installation rates of surface laid RTP in PDO Oman reached 1km/day, Lekwhair Oman 2001.

ii See Contract number 115868 for further details.

2. Scope

The material that RTP is made of, High Density Polyethylene allows to a certain extent the permeation of hydrocarbons. If RTP is applied trenched, special precautions have to be taken to prevent the hydrocarbons to enter into the soil or (ground) water[iii]. To define the need for any special precautions to be taken by SPDC to limit or prevent emission of hydrocarbons into the environment following actions were taken:

- E&P HSE was consulted for advice on how the As Low As Reasonably Practicable (ALARP) HSE rule as given in the E&P HSE guideline has to be applied for the specific SPDC conditions.
- The crude oil emission of a Polyethylene based RTP as considered by SPDC was calculated, based on available permeation data. This result was used as input for the HSE assessment.

3 Theory

All polymeric materials permit to a larger or smaller extent the permeation of fluids. Permeation is the transmission of fluid (gas and liquid) right through the polymer. The transmission is driven by the surface concentration difference between the inside and the outside of the pipe. A clear distinction must here be made for liquids and gasses. For liquids the surface concentration is essentially **pressure independent** until very high pressures (typical several hundreds of bar) are reached. The amount of liquid permeating through a polymer pipe can be calculated using the following equation:

$$Q = P \cdot \frac{\pi \cdot d_i \cdot L \cdot t}{x} \qquad (1)$$

In which;

Q: quantity of permeating liquid [gr];

P: permeability coefficient [g mm / m^2 day];

di: inside diameter of the pipe [m];

L: length of the pipe [m];

t: duration [s];

x: wall thickness of the pipe [mm].

In the current RTP designs the reinforcement fibres (aramid) are not expected to have a significant influence on the permeation rates. This assumption is supported by literature [4]. For permeation calculations the sum of the liner thickness and the outer cover thickness is therefore used as the "effective" wall thickness of the pipe.

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iii Example. In 2001 the NAM (Netherlands) considered the trenched use of RTP for water, gas condensate (WaCo) transport. The condensate typically contains high concentrations of Benzene, Toluene and Xylene. Based on an HSE assessment the application of the standard RTP was not considered feasible for the envisaged application.

4. E&P HSE statements

Maarten Smies, Senior Environmental Adviser for E&P was consulted on the subject of hydrocarbon emission as a result of permeation[iv]. The conditions in Nigeria were recognised as specific with respect to the probability of finding the soil and water in the areas where the installation of the RTP is planned already contaminated because of leakage as a result of vandalisation etc. The existence of pollution should however never by used as an ''excuse" to generate further pollution irrespective of how practically insignificant this additional pollution might appear in comparison.

- E&P HSE concluded that the use of material/equipment that will by design result in the pollution of soil and groundwater and surface water, is not acceptable.
- E&P HSE position is that RTP is unsuitable for the transport of hydrocarbons in buried systems and in aquatic environments.
- Surface laid RTP causing fugitive emissions are to a certain extent acceptable but when practicable pre-cautions should be taken to limit these emissions as much as possible. The emissions have to be reported in HSE performance reports.

5. Permeability coefficients of HDPE

The permeability coefficient of HDPE for crude oil had previously been determined as part of two HDPE lined pipe projects one for PDO Oman and one for SPDC Nigeria. Measurements were performed using a light crude from Oman (Yibal) and a light crude from Nigeria (Nkali). Yibal and Nkali crude are similar in composition and properties. Results obtained for both crudes were therefore used in the estimations. Details on the crudes are given in Table 1. Whether the Nkali crude is fully representative for the RTP application currently considered by SPDC needs to be verified. Variations in crude oil compositions have a direct effect on the permeability coefficients.

Membrane and immersion tests were used to determine the permeability coefficients. In the membrane test HDPE disk are used to cover aluminium cups filled with crude oil. The weight loss due to the permeation of the crude oil through the HDPE membrane is measured as a function of time. The experiment was performed at two different temperatures i.e. 38 °C and 60 °C. In Table 2 the Yibal crude oil permeability of HDPE is given as a function of temperature. The permeability coefficient at 23 °C and 50 °C were calculated assuming that the coefficient exhibits an Arrhenius type behaviour as indicated in general literature about this subject.

In the immersion test the weight change and rate of change of in crude oil immersed HDPE specimens are determined. From this data the permeation coefficient can be determined. These tests were done at different temperatures. Data is given in Table 2.

6. Results

The crude oil emission of a 4" and a 6" RTP were calculated using previous experimental data. The results are given in Tables 2 and 3. Temperatures of the produced oil in SPDC are approx. 40 °C. The estimates at 40 °C are therefore considered to give the best estimate for SPDC conditions.

iv Meeting held in Rijswijk in May 2007 and captured in an E-mail date 31.05.2007.

7. Discussion of results

E&P HSE position is that RTP is unsuitable for the transport of hydrocarbons in buried systems and in aquatic environments without further measures. The estimated Nkali crude oil emission of a typical 4″ RTP at 40 °C is approx. 30 kg per kilometre per year, which cannot be classified as practically insignificant. For the sole purpose to demonstrate that this level of emission could seriously impair humans, plant and animal life the following assessment has been performed. Note that Dutch law benzene level criteria were used in absence of Nigerian law criteria. Benzene was selected as it is one of the most hazardous components in crude oil.

The Dutch law defines environmental quality standards for soil and ground water based on scientific studies such as contained in the report "Environmental Risk Limits in The Netherlands"[v]. The target values (healthy soil) for benzene (as an example) in dry soil and ground water, as mentioned in this report are given in Table 4, as well as the values for the "intervention level" i.e. the concentration above which the risk of adverse effects (on human beings and ecosystems) is unacceptable. Intervention levels indicate when the functional properties of the soil for humans, plant and animal life, are seriously impaired or threatened. They are representative of the level of contamination above which there is a serious case of soil contamination and action must be taken to remediate the soil. The intervention levels should not been seen and certainly not be used as upper limits to which chemicals can be emitted into the soil or water without breaching the law.

Table 4 shows that the intervention level for Benzene pollution in the Netherlands is 1 mg/kg soil. To be legally considered as soil pollution at least 25 m^3 of soil should have this level on average. Knowing the specific weight of sand is 1400 kg/m^3 the maximum legally allowed amount of a polluting chemical in 25 m^3 can be calculated:

$$Q = V \cdot \rho \cdot \frac{conc_i}{1000} \qquad (2)$$

Q: quantity of chemical [g]

V: Volume of soil [m^3]

ρ: Density of soil [kg/m^3]

$conc_i$: Intervention level [mg/kg]

For Benzene with a $conc_i$ of 1 this gives a quantity of:

$$Q = 25 \cdot 1400 \cdot \frac{1}{1000} = 35g$$

---

v Environmental Risk Limits in The Netherlands [Risiconiveaus voor milieukwaliteit in Nederland] Bruijn J de, Crommentuijn T, Leeuwen K van, Plassche E van der, Sijm D, Weiden M van der 1999, RIVM Rapport 601640001. This report, produced by the National Institute of Public Health and the Environment (RIVM), documents risk limits, i.e. Maximum Permissible Concentrations (MPCs) and Negligible Concentrations (NCs) for approximately 200 substances in water, soil, sediment and air from the last decade in the framework of the project, 'Setting Integrated Environmental Quality Standards'. The objective was to present the procedures to derive the environmental risk limits to interested parties involved in environmental policy or environmental risk assessment of chemical substances. These risk limits are the non-regulatory standards used in the Dutch environmental policy. These environmental quality standards, their application and policy framework are described in the policy document: Setting Integrated Environmental Quality Standards: environmental standards for soil, water and air. (Ministry of VROM 97759/h/12-97).

This level would be exceeded by 1 km of RTP after one year of service at 40 °C having a Benzene content of 0.12 %. Typical Benzene content values for Nigerian crude are around 1 %, which means that this level would already be reached after a few months.

7.1 Feasibility of using standard HDPE based RTP for the envisaged application

The application of standard HDPE based RTP is not feasible for the envisaged application without further measures to prevent the emission into the environment. Suitable measures would be the use of permeation barriers or a venting system with controlled release.

7.1.1 Permeation barrier

Permeation barrier can be made from other polymers, having a lower permeability, or metal. Polymeric barriers will still have a certain level of permeability; while with metal barriers zero permeation can be obtained. Permeation barriers can be applied in the cross-section of polymer pipe at different locations:

(a) In the bore in direct contact with the transported fluids.

(b) Integrated in the pipe wall.

(c) On the outside of the pipe.

For pipe systems considered for the transport of non-abrasive fluids a barrier can be placed directly in the bore. Due to the direct contact with the transported fluids good chemical resistance (e.g. corrosion resistance for metals) is required. For reasons of protection against abrasion and the transported fluid, barriers are in most applications integrated in the pipe wall. In 2001, the use of an integrated metal foil was and still is seen as the most attractive option to resolve the permeation issue of RTP pipe. The development of such a barrier was therefore pursued by Shell Global Solutions sponsored by NAM and other operating units [1]. Resource constrains seriously hampered the development. Integrated metal permeation barrier are commercially available in Non-reinforced HDPE pipe systems such as the SLA system from EGAPLAS. The impermeability of this system has been proven up to 1780 mg/litre benzene in water (almost the maximum solubility of Benzene in water). The Dutch KIWA Institute carried out the verification of the diffusion resistance and has certified the system for use in the Netherlands. Within Shell the SLA system has been applied in Pernis and Moerdijk for drinking water lines in contaminated soil. This permeation barrier technology offers a good basis for a fast track development of a barrier for reinforced pipes. Commercial interests however seem to hamper a cooperation between the IP owners and the RTP manufacturers.

In 2005 an external permeation barrier based on a metal foil has been applied on a RTP for hydrocarbon service in Brunei (BSP). The foil was not bonded to the pipe. Such a system is only possible when the gas and vapour pressure build up between the pipe and the foil is less than 5 bar. For higher pressures venting would be required. Limiting factor is the tear strength of the foil and or the bonding strength of the foil overlaps.

7.1.2. Venting of the gasses and vapours

Venting of permeated gasses and vapour is quite common, many polymer pipe systems in petrol stations are based on this concept. Another typical example oil and gas industry example is the venting of the annular space of flexible pipes used offshore. Suppliers such as Wellstream and Technip claim that the permeated gases and vapour through the liner of their RTP pipes can effectively be transported along the reinforcement of their pipes and vented of at the joints. These claims will have to be validated since no validated performance test reports were provided.

Alternatively to transport along the reinforcement, fluids emitted through the RTP pipe wall can be collected in a separate carrier pipe. The annulus between RTP and carrier pipe can be vented either periodically of continuously. This technique is similar to the operation of thermoplastic lined pipes as used by Shell in Oman and Canada. To avoid again permeation of hydrocarbons through the external pipe wall in the environment, the external pipe is best equipped with an aluminium permeation barrier. To limit the cost of the carrier pipe the partial pressure of the gas inside the annulus should be low for example below 1 Bar.

Compared to an integrated barrier, venting will have an impact on CAPEX/OPEX. Continuous venting at a certain rate could require the installation of a blower. Depending on how much gas and vapour will permeate through RTP into the annulus, the air blown into annulus might at a certain point along the line, possibly form an explosive mixture. Having an explosive mixture should be avoided but when it forms then how to dispose it in a save way. Also the possible environmental impact needs to be assessed. Using Nitrogen is an option but most likely will result in high OPEX.

8. Conclusions

- The use of Polyethylene based re-inforced thermoplastic pipes for crude oil transport is based on environmental reasons not feasible without further measures.
- A system with an integrated aluminium permeation barrier would be an alternative but is currently not on the market. Several suppliers indicate to be able to prevent emission of the fluids into soil and or (ground) water by venting. These claims need to be validated and the operational impact assessed.

9. Reference

[1] OGEI/0005/04, 16 January 2004, Frans Janssen, Non-Metallic Pipe Systems, Permeation barriers for hydrocarbons and corrosive fluids, Potential cost reductions using RTP for WACO transport by the NAM.

[2] Shell U.K. Exploration and Production, ENGINEERING REFERENCE DOCUMENT,VENTILATION RATE BASED ON FUGITIVE EMISSIONS, Document Number: ES/292 Rev: 3.

[3] Performance Monitoring and Reporting, EP 95-0325, HSE MANUAL.
FACTORS AFFECTING MOISTURE ABSORPTION IN POLYMER C.

[4] JOURNAL OF REINFORCED PLASTICS AND COMPOSITES, 1984 Vol. 3 Nr. 3 pp. 232 – 245.

FJ/mv

Table 1 *PI Gravity, Viscosity and Aniline point of Yibal and Nkali crude*

Crude	API Gravities	Viscosity	Aniline Point
	ASTM D1298		[°C]
Yibal crude	34.9	thin	68.3
Nkali crude	36.1	thin	67

Table 2 *Yibal and Nkali crude oil permeability coefficient of HDPE (density 0.955 gr/cm^3)*

Temperature °C	Permeability coefficient YIBAL **membrane** test Measured at 38 °C and 60 °C (S and P curve fitting) $\frac{gr \cdot mm}{m^2 \cdot day}$	Permeability coefficient YIBAL **ring** uptake Measured at 23 °C, 60 °C and 70 °C $\frac{gr \cdot mm}{m^2 \cdot day}$	Permeability coefficient NKALI **Strip** uptake Measured at 60 °C, 70 °C and 80 °C $\frac{gr \cdot mm}{m^2 \cdot day}$
23	0.2	1.5	0.8
38	1.7	5.4	3.2
50	6.9	13.8	9.0
60	21.0	28.0	20.1

Table 3
Calculated Yibal and Nkali Crude Oil emission
4" RTP dimension:
Inside diameter 88 mm
*Effective wall thickness 12.3 mm**
liner thickness plus protective cover thickness

Temperature °C	Yibal Crude oil emission Data Membrane test method $\frac{gr}{km \cdot day}$	Yibal Crude oil emission Data Membrane test method $\frac{kg}{km \cdot year}$	NKALI Crude oil emission Data strip test method $\frac{gr}{km \cdot day}$	NKALI Crude oil emission Data strip test method $\frac{kg}{km \cdot year}$
23	5	2	18	7
38	37	14	72	26
50	155	57	202	74
60	472	172	452	165

Table 4
Calculated Yibal Crude Oil emission
6" RTP dimension:
Inside diameter 142 mm
*Effective wall thickness 9 mm**
- *liner thickness plus protective cover thickness*

Temperature °C	Yibal Crude oil emission Data membrane test method $\frac{gr}{km \cdot day}$	Yibal Crude oil emission Data membrane test method $\frac{kg}{km \cdot year}$	NKALI Crude oil emission Data strip test method $\frac{gr}{km \cdot day}$	NKALI Crude oil emission Data strip test method $\frac{kg}{km \cdot year}$
23	12	4	40	14
38	82	30	159	58
50	343	125	446	163
60	1041	380	996	364

Table 5 *Target and Intervention levels for Benzene in dry soil and ground water*

	Target value [mg/kg dry soil]	Intervention level [mg/kg dry soil]
Benzene	0.01	1
	Target value (µg/l) Ground water	Intervention value (µg/l) Ground water
Benzene	0.2	30

Appendix B. Application of geo-membrane permeation barrier system

N O T E

Restricted

DATE	28 July 2008	
FROM	F.A.H. Janssen and A. Mesman	GSNL-GSEI/2
TO	E.N. Onuigbo	SPDC-EPG-PN-TEEA
	E.O. Ejiogu	SPDC-EPG-PN-TEEA
	A.S. Akinseloyin	SPDC-EPG-PN-TEWX
	C.C. Oranyeli	SNEPCO-EPF-G-SCSS
	H.O. Nkwonta	SPDC-EPF-G-SCNJG
	A.O. Ojo	SPDC-EPG-PN-TEEA
COPY	P.J.M. van Loon	GSNL-GSEI/1
	L.M. de Mul	GSNL-GSEI/2, GSEI/0
FILE	GSEI.A032.08.pdf	
REG	GSEI/A032/08	
PROJECT	54014817	
SUBJECT	ASSESSMENT OF A VENTED EXTERNALLY APPLIED GEOMEMBRANE HOSE AS PERMEATION BARRIER FOR TRENCHED SPOOLABLE FIBRE REINFORCED PLASTIC PIPE IN HYDROCARBON SERVICE. TENSILE TESTING OF A WELDED GEOMEMBRANE AT 23 °C, 52 °C, 65 °C AND 82 °C	

1. Introduction

The use of Re-inforced Thermoplastic Pipe (RTP) is considered by SPDC to replace crude oil flowlines with a typical diameter of 3"-6". A feasibility study[1] indicated that the buried application of reinforced thermoplastic pipe for hydrocarbon service is a HSE concern. DEP 01.00.01.30-Gen defines that the use of buried pipe systems where the emission of hydrocarbons and/or toxic fluids is a HSE concern, e.g. pollution of soil and (ground) water, measures shall be taken to prevent emissions occurring.

A vented, externally applied geomembrane hose with controlled release is considered a suitable measure assuming certain requirements are met.

Uche-Chyke Holdings Ltd proposed for a RTP installation demonstration project of SPDC a permeation barrier system consisting of a commercial gas barrier (foil), welding equipment and an end fitting design with venting capability.

The geomembrane hose will be produced in situ by welding the foil using a "hot air combi-wedge welding machine". As part of the assessment of the permeation barrier system GSEI/2 determined the strength of the welded foil in the range of 23 °C up to 82 °C

[1] GSEI/0068/07 The feasibility of using trenched Polyethylene based re-inforced thermoplastic pipes for crude oil flowlines by SPDC in Nigeria.

2. The foil and welding equipment

The tested foil, PAGeotechnical type PAG standard, consists of a 0.2 mm thick aluminium foil gas barrier, which is covered at both sides with a polyethylene layer. In total the foil thickness is 0.4 mm. In Appendix A the manufacturer data sheet of this barrier foil is shown.

The welding machine is a "Twinny S Combi wedge welding machine" manufactured by Leister. The welding machine was demonstrated by the representative of the Leister manufacturer (Fa. Verder B.V. Vleuten, The Netherlands). A technical data sheet of the welding machine is shown in Appendix A.

A welding demonstration was performed and a photograph can be seen in Figure 1.

3. Tensile tests

3.1 The specimen sizes

Tensile testing was carried out at specimens as shown in Figure 2

The effective foil specimen length i.e. the clamp distance of 100 mm.

The specimen width of the various specimens varied between 23-25.5 mm. The width of the welded area i.e. the seam, is identical to the specimen width.

The polyester scrim used to reinforce the foil has a mesh of approximately 8 x 8 mm and is not always evenly distributed as can be seen in Figure 2.

3.2 Testing machine

The foil specimens were fixed between clamps as shown in Figure 3 and located in a climate air circulation stove.

The stove was installed in a Instron testing machine facility. The clamp extension speed was 10 mm/min. The load cell has a maximum capacity of 1000 N.

Tests were performed at 23 °C, 52 °C, 65 °C and 82 °C.

4. Results

The graphs of load versus extension lines at 4 temperatures have been collected in Figure 4. In the tests at lower temperatures multiple discontinuities (so-called 'pop-in' events) were observed before the maximum load was achieved.

The tensile strength (N/mm) was obtained by dividing the measured load (N) at "pop-in" load value and the maximum load value by the width (mm) of the seam.

Results are collated in Table 1.

Figure 5 shows the seam strength versus temperature. All specimens failed at the edge of the seam. Local crazes occurred in the aluminium foil at stresses far below the maximum load.

5. Discussion of the results

The supplier of the foil reports a tensile strength of 10.5 N/mm (original unit kN/m).

The "pop-in" value and maximum value measured of the welded foil at 23 °C were 5.7 N/mm and 6.6 N/mm respectively. The strength of the weld is therefore lower than the main material and should therefore be used in design calculations. The results further show a reduction of the strength of the welded area with increasing temperature, Figure 5. When installation temperatures above 23 °C are expected this effect must be taken into account.

As can be seen in Figure 5, the difference between ""pop-in" strength and maximum strength is reducing at elevated temperatures.

5.1 Required strength

According to the specification in Technical Note GSEI/A031/08, the required strength during leak and acceptance test after installation is:

$$\sigma = \frac{P_d \cdot f_1 \cdot D}{20}$$

σ : Tensile strength of welded membrane [N/mm]

Pd: Design Pressure [Bar]

f_1: factor for acceptance test, 3.75

D: Maximum diameter of the foil hose, without size reduction due to soil load [mm]

Uche-Chyke Holdings Ltd indicated a design pressure of 0.2 Bar, letter 7 February 2008 (see Appendix B).

The diameter of the hose was indicated to be 125 mm.

Using Equation 1 this gives:

$$4.7 = \frac{0.2 \cdot 3.75 \cdot 125}{20}$$

The established strength temperature relation as shown in Figure 5 indicates that for temperatures below 40 °C this criteria is met. Acceptance test with this foil should therefore be performed below 40 °C.

The factor for the 1000-hour test is 2.2 and has to be performed at 65 °C this requires a minimum strength of 2.75 N/mm.

$$2.75 = \frac{0.2 \cdot 2.2 \cdot 125}{20}$$

The foil is meeting this criterion though without any margin.

The 1000-hour test will therefore determine whether the strength of the proposed system is sufficient.

6. Conclusion

- The measured tensile strength of the welded geomembrane is lower than specified by the supplier.
- All specimens failed at the edge of the weld/seam.
- The tensile strength decreases with increasing temperature
- The strength of the welded foil, meets the criteria for leak and acceptance test at temperatures below 40 °C. Field acceptance tests with the foil should therefore be performed at a temperature below 40 °C.
- The 1000-hour test of the total system will determine whether the long-term strength of the proposed system is sufficient.

Table 1 *Tensile test results, Welded geomembrane*

Temperature [0°C]	Load POP-in [N]	Load Max [N]	Seam width [mm]	SS (Pop-in) [N/mm]	SS Max [N/mm]
23	133	154	23.5	5.66	6.56
52	87	93	24.2	3.57	3.83
65	62	62	23.2	2.62	2.65
82	46	46	25.4	1.77	1.77

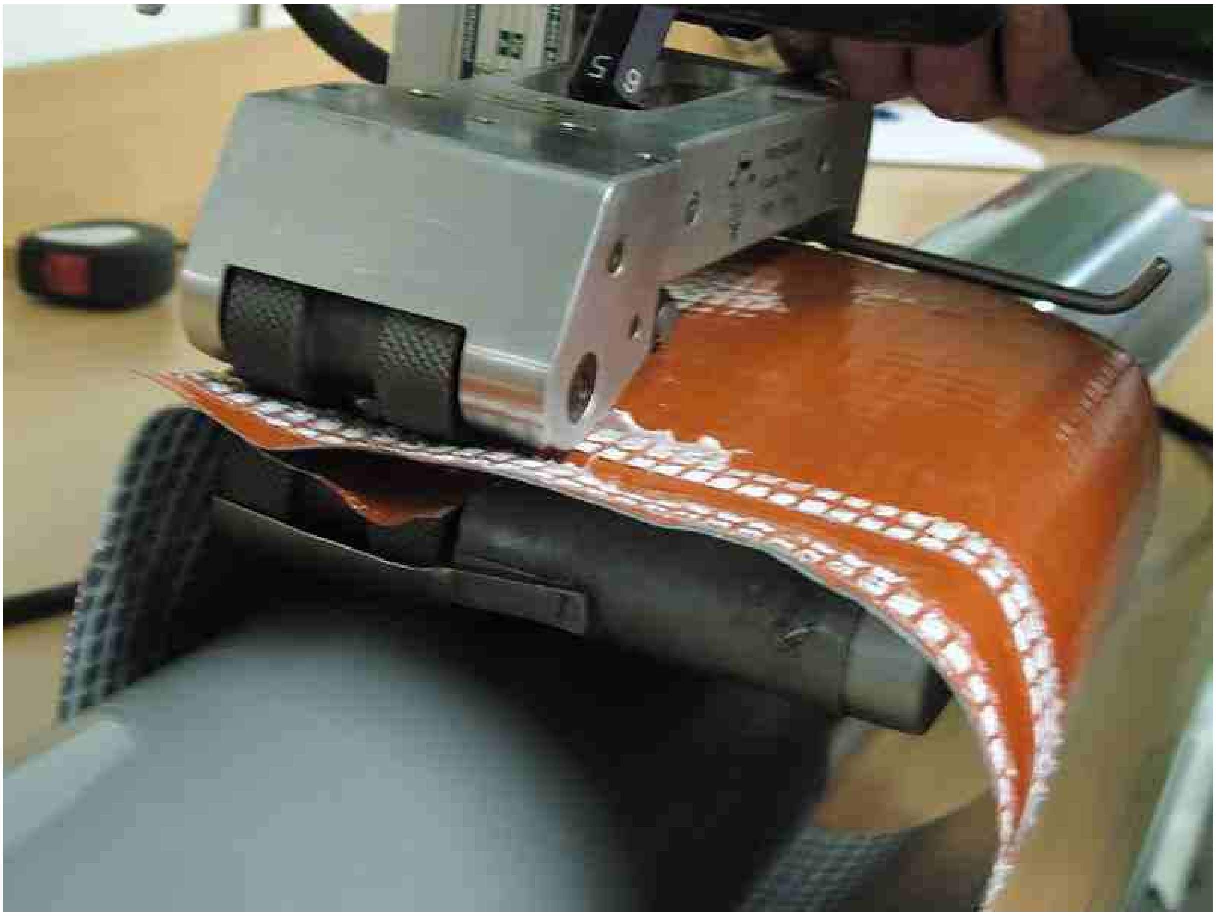


Figure 1 *Demonstration of welding the foil around a pipe*

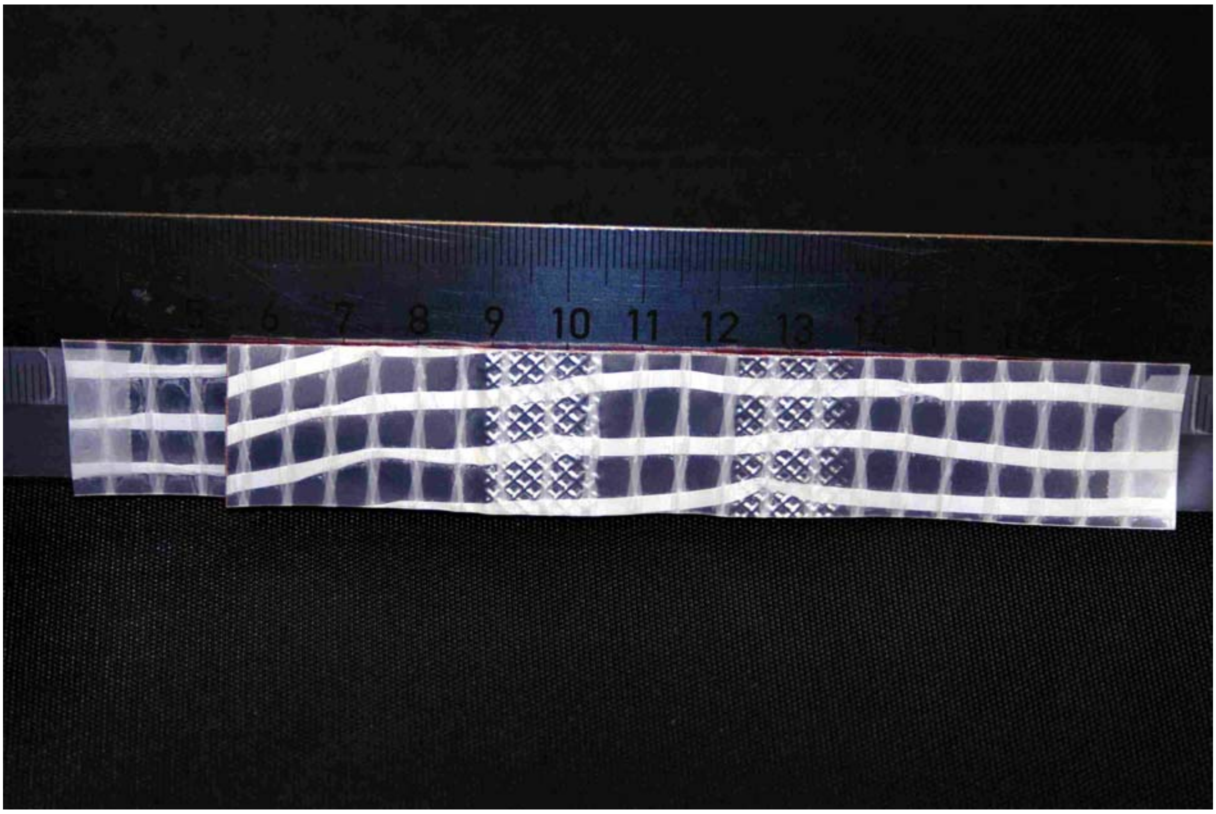


Figure 2 *Welded Foil Tensile Specimen*

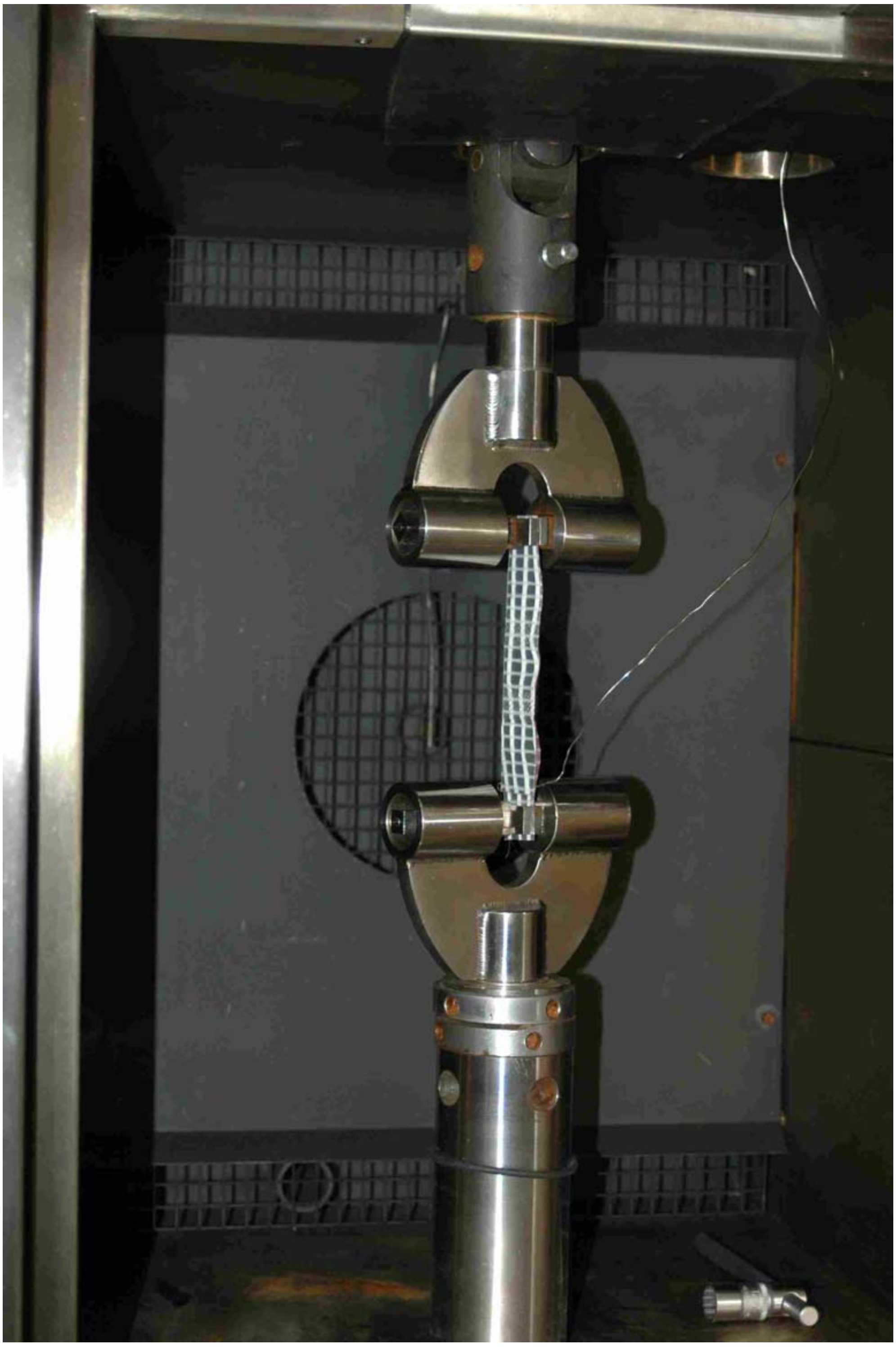


Figure 3 *Tensile Specimen set up in Climate stove*

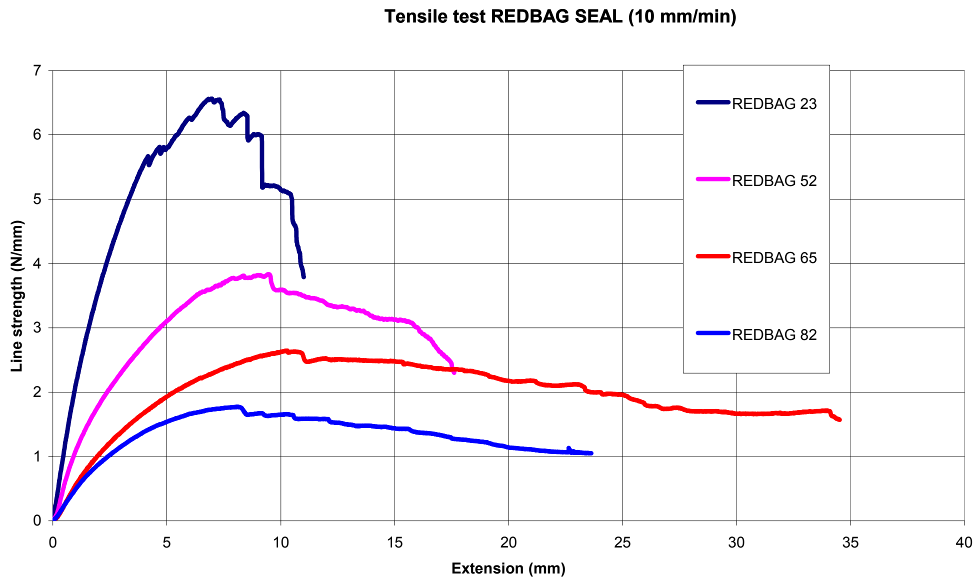


Figure 4 *Load versus clamp distance displacement curves*

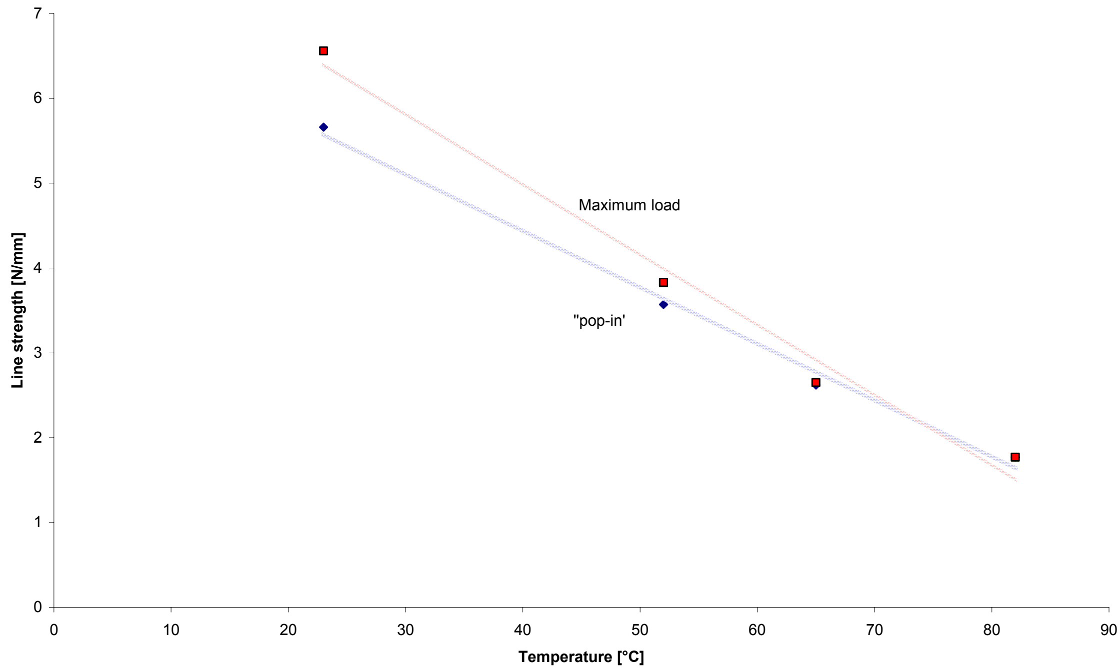


Figure 5 *Tensile strength of welded geomembrane PAGstandard as function of temperature*

Appendix A Data sheet foil barrier material

Technical data

Gas barriers

	PAG Super*	PAG Standard**
Composition	Scrim reinforced polyethylene and aluminium.	
Min. weight/unit area	415 g/m²	370 g/m²
Minimum thickness	0.46 mm	0.40 mm
Tensile strength	9.47 kN BS EN ISO 10319	10.5 kN/m BS 4415 Pt 2
Methane permeability	< 0.005 cm³/h/m²	< 0.001 ml/m²/day
Moisture transmission	< 0.01 g/m²/day	< 0.01 g/m²/day
Radon improvement factor	500-1	500-1
CBR	708 N	na
Roll size	1.2 x 50 m	2 x 50 m

Suggested Specifications
"The gas barrier shall be [PAG Super Gas Barrier]* [PAG Gas Barrier]** loose laid on to prepared substrate. The membrane shall contain aluminium foil encapsulated in polyethylene and be reinforced with polyester scrim, minimum thickness [0.46 mm]* [0.40 mm]** methane transmission less than [0.01 cm³/m²/h]* [0.001 ml/m²/day]**. It shall be sealed with cross linked butyl gas tape or welded to quality assurance standards."

Cross linked butyl sealant

Density	1.6 g/cm²	**Service life (predicted)**	> 20 years
Elongation at break	220%	**Service temperature range**	-4C – 110C
Force to compress by 20%	220 N	**Shrinkage**	< 0.5%
Movement accommodation	15%	**Shear strength**	17.1 N
Moisture vapour transmission rate	0.24 g/m²/24h	**Slump**	Nil
Paintability	Good	**Tack**	Very good
Resistance to mould	Good	**UV resistance**	Very good

PAG 25 Geocomposite voidformer

Values are typical, with the exception of thickness, which is nominal. Typical indicates the mean value derived from samples taken for any one test as defined in the BS EN ISO standard - usually the mean of five samples. Nominal is a guide value.

Properties			**Performance**		
Geotextile type Geotextile material	Non woven & heat-bonded Polypropylene		In plane gas flow at 20 / 100 / 200 kPA	20 / 19 / 18 l/s/m width	
Geotextile pore size	85 microns	EN ISO 12956	Thickness at 2 kPa	25 mm	BS EN 964-1
Core material	Single cuspated HDPE (High Density Polyethylene)		Roll size / weight	0.9 x 50 m / 67.5 kg	
Tensile strength MC/CD	8/9 kN/m	EN ISO 10319			
CBR puncture resistance	1.5 kN	EN ISO 12236			
Compressive strength	180 kPa				
Shear strength	1 kN	prEN ISO 13426-2			

Suggested Specification
"Cuspated HDPE (High Density Polyethylene) drainage core former thermally bonded to a geotextile filter."

PAGeotechnical Ltd.,
Perth House,
Corby Gate Business Park,
Priors Haw Road., Corby
Northants. NN17 5JG

Telephone: 01536 740040
Fax: 01536 740044
Email: office@pageo.co.uk
Web: www.pageo.co.uk

PAGeotechnical

Technical data sheet of Leister welding machine

LEISTER® 3

Combiwedge – Welding machines

Tunnel construction
– Guide handle and travelling wheels

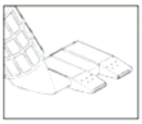
Civil Engineering
– Guide handle, travelling wheel

Prefabrication model on request

Welding speed
2 – 3.5 m/min. depending on formulation and thickness of the geomembrane liner as well as ambient temperature.

Welding pressure (recommended)
PVC-P, ECB 300 – 500 N
PE-HD, PP 600 – 1000 N

Short Combiwedge
for material thickness of 0.3 mm or more for thin and flexible films. With or without test channel



Long Combiwedge
for material thickness of 0.8 mm or more for films and geomembrane liners. With or without test channel

TWINNY T

CE

- High-tech version
- Display of welding parameters

Technical Data

Type	**TWINNY T**	
Voltage	V~	100, 120, 200, 230
Power consumption	W	1600, 1900, 2200, 2300
Frequency	Hz	50 / 60
Temperature	°C	max. 560 steplessly
Welding pressure	N	max. 1000 steplessly
Drive	m/min.	0.8 – 3.2 steplessly
Air flow	l/min.	Step 2: 150 Step 3: 190
Air pressure stat.	Pa	Step 2: 1500 (15 mbar) Step 3: 2100 (21 mbar)
Emission level	L_{pA} (dB)	71
Memory card	optional	
Size L×W×H	mm	340 × 340 × 270
Weight	kg	7.9 civil engineering 6.9 tunnel construction

Approval mark:

TWINNY T with test channel welding 1.5 mm PE-HD liners in a landfill.

TWINNY S

CE

Technical Data

Type	**TWINNY S**	
Voltage	V~	100, 120, 200, 230
Power consumption	W	1600, 1900, 2200, 2300/2900
Frequency	Hz	50 / 60
Temperature	°C	max. 600 steplessly
Welding pressure	N	max. 1000 / max. 500
Drive	m/min.	0.2 – 2.5 / 0.8 – 4
Air flow	l/min.	Step 2: 150 Step 3: 190
Air pressure stat.	Pa	Step 2: 1500 (15 mbar) Step 3: 2100 (21 mbar)
Emission level	L_{pA} (dB)	71
Size L×W×H	mm	350 × 390 × 270
Weight	kg	6.9 civil engineering 6.5 tunnel construction

Approval mark: CCA certified

TWINNY S with combi-wedge short welding in a tunnel.

.

Appendix B Barrier test conditions

UCHE-CHYKE HOLDINGS LTD.

CORPORATE HEADQUARTERS
12, Mbamalu Close
Off Praise Drive
Off Jakpa Road
Effurun, Delta State

Tel: ***+234 (0)53 253470***
Fax: ***+234 (0)53 250069***
Mobile: ***+234 (0) 80232582***
Email: ***uchechykeholdings@yahoo.com***

Our Ref. Barrier test conditions *Your Ref:* *Date:* February 7, 2008

Shell Global Solutions International bv
Mr. Frans Janssen
P.O. Box 38000,
1030 BN Amsterdam

Dear Mr. Janssen,

This is to confirm our verbal communications on the testing of barrier material for the application around RTP pipes to prevent permeation of light HC's into the soil.
Two membranes are being offered for testing:

- Sisalex 871 which is obtained from Ampack
- PAG Standard Gas Barrier which is obtained from PAGeotechnical

The materials are very similar and we have provided you with the specifications as obtained from the mentioned companies. Please let us know in case you need more or other information on the specification than you have received.
The test specimen consist of 1 meter wide and about 2 meter long seal (back to front with a double seam and tunnel) welded at known conditions with a welding tool that will be used in the field.
We have assed the operation pressure in the space contained by the membrane to be no more than 0.1 barg. As you know the space will be vented to a collection drum at the end of the flow line. The RTP pipe will be wrapped with a net structured material to prevent transport blockage by soil pressure and to enable transportation alongside the pipe into the collection drum. We expect only some gases to come out into the collection drum. The total permeation is assessed at 30 kg per year per km of pipe. If assumed that 50% is volatile at the ambient conditions, it can be calculated that the accumulated non volatile HC's can form a 1cm layer around a 5-inch outer size pipe in 20 years time. This makes it unlikely that non-volatile material will come out into the collection drum.

On the above basis we agree with the following testing conditions:
Operating pressure 0.1 barg
Design pressure 0.2 barg
Burst pressure at 20°C: 3.75 * 0.2 = 0.75 barg
1000 hr test pressure at design temperature: 2.2 * 0.2 = 0.44 Barg
The testing is then in conformity with DEP 31.40.10.20-Gen.

Kind regards,

Ir. M.H.M. Graat
For Uche-Chyke Holdings Ltd

Appendix C. Corrosion aspects for Wellstream FlexSteel spoolable pipe

Shell Global Solutions

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Materials & Inspection Engineering Group

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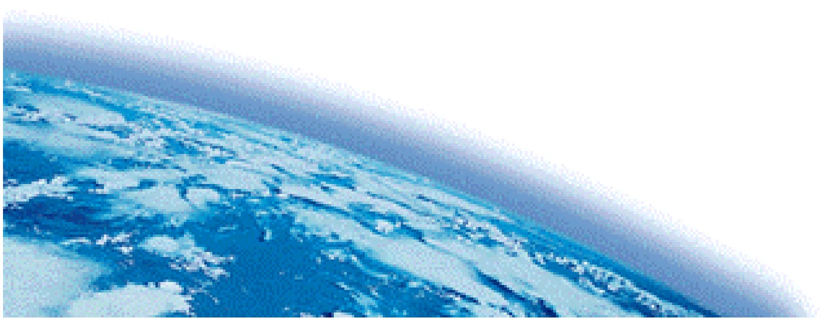
Summary

SPDC is looking into the feasibility of applying spoolable reinforced thermoplastic lines to replace its vandalised Carbon Steel (CS) pipelines. This review focuses on the potential degradation issues of the metallic reinforcements and end fittings of a spoolable thermoplastic pipe (FlexSteel™) from Wellstream, one of the potential suppliers of spoolable pipes.

The reinforcements are available in two material options: CS and Low Alloy Steel (LAS). Based on the operating data provided by SPDC, CO_2 corrosion and oxygen corrosion were identified as the potential degradation mechanisms for these materials.

Wellstream has carried out corrosion tests on the CS reinforcements and reported very low CO_2 corrosion rates for this material. The results reported for bare steel in bulk solution with high CO_2 were found to be too low when compared with the results from HYDROCOR 2007. For the simulated FlexSteel annulus, tests conducted by Wellstream resulted in a corrosion rate of 0.001 mm/yr, which is low and considered acceptable. The results could not be validated with HYDROCOR due to the model limitations but there are publications supporting such low corrosion rates. If the results need to be validated, corrosion testing would have to be carried out.



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Wellstream does not have test data on oxygen corrosion rates and has reported that negligible oxygen corrosion was found on field segments after 24 months service. Oxygen corrosion is not considered a potential threat to the reinforcements since the pipeline will be buried in swamp environment (oxygen concentration < 8 ppm) and diffusion through outer polyethylene (PE) sheath will be very slow.

Trace amounts of H_2S are reported in the system and the system can be considered as non-sour.

The end fittings material is normally 316L, though CS end fittings are also available. CS is predicted to corrode internally at high rates and is as such not a suitable end fittings material. 316L will be resistant to uniform corrosion and to potential hydrogen damage. In the given conditions, 316L will not be susceptible to external Chloride Stress Corrosion Cracking (CSCC). However, in swamp environment, it will be susceptible to external localised corrosion (pitting, crevice corrosion and microbiologically influenced corrosion). 316L can be used as the end fittings material when one of the following external protection techniques is applied:

- Shrink sleeve,
- Cathodic protection (CP),
- CP + coatings.

FlexSteel appears to be a suitable system for the conditions in SPDC but is not qualified yet. Reported CO_2 corrosion rates need to be validated by reviewing Wellstream's confidential testing documentation (if made available) or long-term corrosion testing. When the CO_2 corrosion rates are validated, FlexSteel will be qualified for the envisaged application in SPDC with respect to the corrosion resistance.

1. Introduction

SPDC has suffered high rates of vandalisation of its Carbon Steel (CS) flowlines in the recent past. When operations resume, huge amounts of oil will be locked as a result of the stolen flowlines. To avoid this, SPDC is looking into the feasibility of replacing 3-6" stolen CS lines by spoolable reinforced thermoplastic lines spoolable reinforced thermoplastic lines [1], which might be a better option, both technically and economically. Shell Global Solutions is reviewing technical and implementation feasibility of products from different suppliers of spoolable pipes.

FlexSteel[TM] is a proprietary material of Wellstream International Limited and is an unbonded flexible steel pipe (a type of spoolable thermoplastic pipe). It finds application for onshore use and has been designed to largely comply with API 17J.

The operating conditions in the pipe provided by SPDC are given in Table 1. The flow is multiphase and contains CO_2 (and traces of H_2S; insufficient to consider the system as sour). The pigged debris from the old CS pipelines showed presence of different types of solids including sand, carbonates and some wax.

Wellstream provided FlexSteel technical manual[i] to Shell Global Solutions to review the product and its feasibility in the envisaged application.

i Wellstream FlexSteelTM Flexible Steel Pipe: Technical, Operating and Maintenance Manual, WSI Eng. Doc. No.: R092E004, Revision 05, 13 November 2006

There are two options for the reinforcements material in FlexSteel: CS or Low-Alloy Steel (LAS). As the base case, CS was reviewed for the reinforcements material. The end fittings material is normally 316L. On request, CS end fittings can also be provided. The composition and mechanical properties of these materials are provided in Table 2.

Table 1 *Envisaged operating conditions in SPDC*

Sr. No.	Design/operating conditions	Value
1	Design pressure (bar)	Low: 5-25 Medium: 25-65 High: above 65
2	Associated Gas (AG) pressure	5-38 bar
3	Ambient pressure (bar)	1 (atmospheric)
4	Design temperature (°C)	55
5	Ambient temperature (°C)	25-40
6	Cude+water flow rate (bbl/day)	NA[ii]
7	Water cut (%)	20-40
8	GOR	NA
9	Superficial liquid flow velocity[iii] (m/s)	3
10	CO_2 concentration (dissolved in water, ppm)	30-80
11	H_2S concentration (dissolved in water, ppm)	< 1
12	pH (back calculated from dissolved CO_2)[iv]	4.50-4.75
13	Chlorides	NA
14	Solids concentration (% of total solids)	Wax: 0-5 CaCO3: 55-75 MgCO3: 5-10 Sand: 10-25% Iron oxides: 0-1%

ii NA = Not available

iii Liquid velocity if the liquid were flowing through the full area of the pipe

iv In data provided to GS, pH = 7.2-7.5 was given. This, however, is not in accordance with the dissolved CO_2 data given in the table. The pH given in the table was back calculated from the dissolved CO_2 concentration using the tool pH_{Calc}.

Table 2 *Properties of CS reinforcements and 316L end fittings materials*

Properties	Material	
	CS	*316L*
Chemical composition		
C	0.17-0.23	NA
Mn	0.3-0.6	NA
P	0.025 (max)	NA
S	0.015 (max)	NA
Microstructure	Ferritic	Austenitic
Mechanical properties		
Yield strength (ksi)	90 (min.)	30
Tensile strength (ksi)	100-140	75
Hardness (HRB)	94 (min.)	97 (max.)
Min. elongation (%)	3.5	40
Charpy impact toughness	Not applicable	NA
Manufacturing method	NA	NA
Coating (yes/no)	No	No
Corrosion/erosion allowance	Not applicable	Not applicable

2. Corrosion assessment

2.1 Introduction

2.1.1 Reinforcements

In FlexSteel, the reinforcements are placed in an annulus environment sandwiched between the inner and the outer polyethylene (PE) sheaths. In the given operating conditions, water, CO_2 and CH_4 will permeate into the annulus through the inner PE sheath. Similarly, water and O_2 will permeate into the annulus through the outer PE sheath. Thus the environment inside annulus will have corrosive species (CO_2 and O_2; CH_4 is benign), which will result in uniform corrosion of the reinforcements[v].

Depending on the operating environment, the reinforcements in flexible pipes will be susceptible to different hydrogen damage mechanisms, including Hydrogen Embrittlement (HE), Hydrogen Induced Cracking (HIC), Sulphide Stress Cracking (SSC). SSC is not considered a threat since H_2S concentration is very low. Further, no Cathodic Protection (CP) systems will be applied to the reinforcements. Hence, there is no HIC or HE threat.

v It should be noted that given the design and positioning of the reinforcements in the annulus, some areas might not get exposed to the corrosive environment at all whereas other areas might be regularly exposed. In such a case, if corrosion occurs, it would occur only on the exposed areas and hence the morphology would be that of a localised general corrosion.

If CP were to be applied to the end fittings, it would not pose HIC or HE threat to the reinforcements since the outer PE sheath will serve as a barrier between the reinforcements and the CP system.[vi]

2.1.2 End fittings

316L

If the end fittings material is 316L, it would be immue to CO_2 and any other form of general corrosion. However, 316L will be susceptible external pitting and crevice corrosion in oxygenated, chloride containing environments. It will also be susceptible to Microbiologically Induced Corrosion (MIC) in the buried swamp environment. For T > 60 °C, it will be susceptible to external Chloride Stress Corrosion Cracking (CSCC). Depending on the solids loading and flow, it will also be susceptible to erosion and erosion-corrosion.

CS

If CS is used for the end fittings, there will be internal CO2 and external oxygen corrosion. Similar to 316L material, it will be susceptible to MIC, erosion and erosion-corrosion.

The degradation mechanisms identified for the reinforcements and the end fittings are listed in Table 3.

Table 3
Possible degradation mechanisms for the reinforcements and the end fittings materials

Materials		Possible degradation mechanisms
Reinforcements (CS/LAS)		1. CO_2 corrosion 2. Oxygen corrosion
End fittings material	316L	1. External CSCC 2. External pitting, crevice corrosion 3. External MIC 4. Erosion and erosion-corrosion
	CS	1. Internal CO_2 corrosion 2. External O_2 corrosion 3. External MIC 4. Internal erosion and erosion-corrosion

2.2

vi Wellstream has carried out tests for sour service compatibility of its reinforcement materials. On the basis of its test results, Wellstream reported that the materials were found to be HIC/SSC resistant for the following conditions:
1. CS: ppH2S < 5.5 kPa (H2S partial pressure in the bore)
2. LAS: ppH2S < 1 bar (H2S partial pressure in the bore) and pH range 4.5 – 5.0 (or above)

Reinforcements

Wellstream has carried out corrosion testing in an autoclave by exposing both bare steel strips and strips that simulated FlexSteel annulus to $ppCO_2$ (CO_2 partial pressure) = 10 bar and T = 60 °C. While the temperature is representative of the expected conditions in the application in SPDC, the $ppCO_2$ is much higher than the $ppCO_2$ expected in SPDC (approximately 100 times!), thus making the conditions unrealistically severe. The testing was carried out for a period of 30 days.

2.2.1 General corrosion

2.2.1.1 CO_2 corrosion rates

With such severe testing conditions, Wellstream reported the following CO_2 corrosion rates for the CS reinforcements material to Shell Global Solutions:

- 0.15 mm/y for bare steel strips
- 0.001 mm/y for steel strips sandwiched between PE sheaths that simulated FlexSteel annulus

HYDROCOR 2007 was used to predict CO_2 corrosion rates for bare steel strips to compare with the result reported by Wellstream for the same conditions. To predict worst-case bulk corrosion rates (conservative approach), it has been assumed that the reinforcements will be permanently ‘wet’.

Using HYDROCOR, CO_2 corrosion rate of 11.3 mm/y was predicted for bare steel for almost stagnant conditions (film velocity = 1 mm/s). This prediction is of two orders of magnitude higher than the corrosion rate provided by Wellstream.

HYDROCOR was not used for corrosion prediction in an environment that simulates the annulus conditions in FlexSteel pipe since its model is suitable only for bulk flowing conditions, whereas in flexible pipes like FlexSteel, the amount of free water is low and the flow is highly restricted.

Very low corrosion rates in restricted annulus environment, as reported for FlexSteel, are supported by other publications [2, 3]. The reason of such low corrosion rates is very low V/S ratios (free volume in annulus/surface area of steel) in the annulus environment resulting into increased pH and iron supersaturation – factors that decrease the corrosion rate. However, since there is a big difference in the bulk corrosion rates reported by Wellstream and predicted by HYDROCOR, it was decided that the reported corrosion rate in FlexSteel simulated environment shall be accepted only after verifying Wellstream’s testing procedures or by confirming the reported rates by independent testing. Further, a testing duration of 30 days was considered insufficient because given the permeation rates of CO_2, O_2 and water through PE, it is expected that it will take more than 30 days (test duration) for CO_2 to reach steady state concentration inside the annulus.

Wellstream was requested to provide the testing documentation to Shell Global Solutions to review its testing procedures and to ensure that the test conditions cover at least the anticipated worst-case conditions in SPDC. Wellstream, however, stated that they could not provide the documentation due to its confidential nature. Wellstream offered to provide these documents once a commercial agreement would be in place.

2.2.1.2 Oxygen corrosion rates

In the swamp environment, oxygen will permeate from the external wet soil into the annulus and pose a potential corrosion threat.

Oxygen concentration in water, which is in equilibrium with 0.21 bar (210000 ppm) oxygen in the air, is 8 ppm. Since the pipeline will be buried, oxygen concentration in the wet soil is expected to be even lower. Oxygen concentration of 8 ppm was taken as the worst-case scenario to predict the extent of oxygen corrosion.

Using a diffisuion model for oxygen permeation, it was predicted that even if the flexible pipe were to be installed in air, it would take 10 years for oxygen to build up a pressure of 0.21 bar inside the annulus. Even this pressure would build up in the annulus when oxygen is only allowed to enter and not leave the annulus at all.

Conditions in the envisaged application in SPDC (line buried in swamp) are much less severe. With an external concentration of 8 ppm (<< 210000 ppm) and regular venting, significant build up of oxygen is not expected. Adding to that, there is highly restricted annulus environment and thus, oxygen corrosion does not pose a threat to the integrity of the reinforcements and the flexible pipe.

However, it should be noted that if there is any damage to the external polyethylene, bare reinforcements would be exposed to 8 ppm of oxygen and the resulting corrosion could then be significant.

2.3 End fittings

2.3.1 316L as the end fittings material

2.3.1.1 General corrosion

316L is a Corrosion Resistant Alloy (CRA) and if used as the end fittings material, it will not undergo general corrosion in the conditions given in Table 1. The passive oxide film on the material will protect it from CO_2 and oxygen corrosion.

2.3.1.2 Localised corrosion

The 316L material will be susceptible to external pitting and crevice corrosion at ambient temperatures in presence of oxygen. The material will also be susceptible to external MIC in the swamp environment. Without any additional protection, it is not considered a suitable material for the given operating conditions.

2.3.1.3 Susceptibility to external CSCC

According to the DEP [4], 316L will be susceptible to CSCC when exposed to chloride environments above 60 °C. The design temperature of the SPDC flowlines (55 °C) is below this limit. Further, the buried swamp environment would also ensure that the temperature of the end fitting's external surface is lower than the design temperature. Hence, 316L end fittings will not be susceptible to external CSCC in the given conditions.

2.3.1.4 Erosion and erosion-corrosion

The biggest benefit of the flexible pipe design against erosion and erosion-corrosion is that the geometry of the end fittings will be that of a straight pipe. Erosional effects like sand impingement are much less severe in a straight pipe than in a bend. If there were to be any bends in the spoolable pipe, they will be in the reinforced PE. Further, the reported superficial velocity of 3 m/s is considered low to result in significant erosion. It was decided to confirm these reasoning with the Shell erosion model.

However, the sand content in the production stream reported by SPDC was not suitable for predicting the susceptibility of material against potential erosion and erosion-corrosion since it was reported as a percentage of the total solids and not as a fraction of the production. No data was provided by SPDC on further request on solids content in terms of amount of solid/unit volume of liquid.

The SPPS Erosion tool Version 3.2 was used to evaluate the potential erosion and erosion-corrosion rates of the end fittings for different sand production rates. The tool is not applicable for multiphase flow in straight pipes, but it is applicable for multiphase flow in long radius elbows. An extremely long radius elbow with R/D = 100 was used to approximate a straight pipe and predict the erosion and erosion-corrosion rates. Even with a high sand charging of 1000 ppm, superficial liquid velocity of 3 m/s and a superficial gas velocity of 40 m/s, insignificant erosion and erosion-corrosion were predicted.

Up to the sand charging and gas velocity limits identified above, erosion and erosion-corrosion are not considered as threat to the end fittings material. If SPDC anticipates more aggressive sand charging or flow conditions, erosion and erosion-corrosion effects shall be revaluated.

2.3.2 CS as the end fittings material

2.3.2.1 General corrosion

If CS is used as the end fittings material, both (internal) CO_2 and (external) oxygen corrosion will occur and at much higher rates than the reinforcements since it will be directly in contact with the production (internally) and the wet soil (externally). Using HYDROCOR, the internal CO_2 corrosion rate was predicted to be: 3.0 mm/y (no iron saturation) or 0.9 mm/y (iron saturation). Using HYDROCOR, the external corrosion rate due to oxygen was predicted to be in the order of 0.5 - 1.0 mm/y in near stagnant conditions.

The combined corrosion rate due to CO_2 and oxygen corrosion is considered to be too high. Although corrosion allowance for the CS end fittings is not known, the CS end fittings are not expected to survive the total corrosion estimated for the service life.

2.3.2.2 Localised corrosion

CS is normally not susceptible to either pitting or crevice corrosion. However, it will be susceptible to external MIC.

2.3.2.3 Erosion and erosion-corrosion

Similar to 316L, erosion and erosion-corrosion are predicted to be insignificant in the CS material up to a sand charging of 1000 ppm and a superficial gas velocity of 40 m/s.

3. Discussion

3.1 Reinforcements

The degradation mechanisms identified for the reinforcements were CO_2 and oxygen corrosion.

Wellstream reported very low CO_2 corrosion rates for FlexSteel simulated annulus environment. Although the reported results are of an order that is supported by other publications [2,3], the results could not be validated in absence of testing documentation, which were not provided to Shell Global Solutions, as they were Wellstream's confidential documents. Further, the duration of tests (30 days) is considered too short to create steady state worst-case environment in the FlexSteel annulus.

Wellstream did not provide potential oxygen corrosion rates for its FlexSteel product. Wellstream reported that negligible oxygen corrosion was found on field segments after 24 months service. Also, considering low oxygen in the swamp environment, slow diffusion through the external PE sheath and the restricted annulus environment, oxygen corrosion is not considered a threat to the reinforcements.

Note: Oxygen corrosion has been considered for FlexSteel in buried swamp environment (wet soil). However, if it is exposed to areas of high oxygen concentration (eg. riser section, dry soil etc.), higher oxygen diffusion and potentially higher corrosion rates can be expected. If such exposures are anticipated, extent of oxygen corrosion shall be revaluated.

3.2 End fittings

The end fittings material can be either 316L or CS. With respect to degradation, the mechanisms applicable to 316L and CS are summarized in the table below:

Table 5 *Summary of degradation mechanisms identified for end fittings material*

Degradation mechanisms	**316L**	**CS**
CO_2 corosion (internal) and oxygen corrosion (external)	N	Y
External pitting and crevice corrosion	Y	N
External MIC	Y	Y
External CSCC	N	N
Erosion and erosion-corrosion	N	N

CS

Whereas CS is resistant to external pitting and crevice corrosion and external CSCC, it will be susceptible to external MIC. Further, the internal corrosion rates were predicted to be very high, making CS an unsuitable material for the life cycle. External corrosion rates are also expected to be substantial but can be mitigated by using sacrifical anodes. Erosion and erosion-corrosion were predicted to be insignificant.

With such high CO_2 corrosion rates, which could not be mitigated, it was concluded that CS is not a suitable material for the end fittings.

316L
316L on the other hand will not suffer general corrosion, will not susceptible to external CSCC, but will be susceptible to external pitting, crevice corrosion and MIC at ambient conditions. The following options are available to mitigate/prevent the aforementioned damage:

- Use of shrink sleeves to cover the external surface of the end fittings and avoid any direct water contact
- Application of CP using sacrificial anodes.
- Application of CP using sacrificial anodes + coatings. Coatings offer greater benefit, as they would reduce the consumption of sacrificial anodes. The DEP [4] recommends that conventional coatings can be applied to prevent pitting and crevice corrosion if the material is not susceptible to external CSCC. However, coating system will have to be applied after swaging since swaging process may damage the coating.
- Wellstream was enquired on the availability of end fittings with coatings. Wellstream stated that it does not supply fittings with coatings.

The 316L will not be susceptible to significant erosion or erosion-corrosion.

4. Conclusions

As far as the degradation mechanisms for the metallic materials are concerned, FlexSteel pipe with CS as the reinforcements material[vii] and 316L as the end fittings material (with protection against external localised corrosion) appears to be a suitable choice for the flowlines for the envisaged conditions in SPDC. However, its suitability has not been fully validated yet, because evidence confirming sufficiently low CO_2 corrosion rates, is still not in place.

5. Recommendations

FlexSteel has not yet been qualified as a suitable product for the envisaged application in SPDC. To qualify it for application in SPDC, CO_2 corrosion rate data for reinforcements provided by Wellstream shall be validated by either of the following:

- Reviewing testing documentation from Wellstream,
- By performing long-term corrosion testing on the FlexSteel pipe sections and measuring actual general corrosion rates.

If the above steps are carried out and the suitability is confimed, FlexSteel, with CS as the reinforcements material and 316 L as the end fittings material (with protection against external localised corrosion) will be qualified with respect to corrosion resistance for the envisaged application and conditions in SPDC.

vii It should be noted that LAS would also be a suitable material for the reinformcements. However, it should be the choice of material for sour service. The Wellstream reported limits for sour service operation for both CS and LAS reinforcements are provided in Footnote 6 of this note. CS is thought to be a more cost-effective option for the conditions given in Table 1.

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Bibliographic Information

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