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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 <u>appears</u> to be a suitable system for the conditions in SPDC but is <u>not qualified yet</u>. 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™ 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.

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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.

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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.

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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.

References

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