

AL 2003™ (S32003) Lean Duplex Case Study: Flexible Flowlines for an Offshore Oil Field Development

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1. Abstract:

A newly developed subsea oil field offshore of Sabah, Malaysia utilized a Lean Duplex Stainless Steel (LDSS) for the flexible flow lines. The project name is Kikeh and is in the final commissioning stages for owner and operator, Murphy Oil. While 22% Cr Duplex Stainless Steel (S31803 or S32205) and austenitic stainless steels have been in use for flexible pipe carcass for many years, this project represented the first use of S32003 lean duplex in this application. The lean duplex was delivered on time and within budget leading to a successful deployment of pipe in the 4Q06.

This paper will discuss the particular environment at Kikeh, along with the driving forces that led to the selection of S32003 lean duplex. It will also address further considerations for use in additional projects, by reviewing the qualification and test regime along with comparisons to 316L and 22%Cr DSS.

2. Introduction:

Unbonded flexible pipe has been successfully used throughout the world to transport produced fluids from subsea oil & gas fields. From the deep waters offshore Brazil, to the hydrate forming low temperature conditions in West Africa, to the High Temperature/High Pressure (HT/HP) wells in the Gulf of Mexico and the North Sea, Far East Asia and Australia, flexible flowlines have adapted to every condition. Flexible pipe is extremely well suited for use in conjunction with Floating Production Storage Offloading (FPSO) vessels due to its ability to accommodate the dynamic nature of their positioning systems. FPSOs have emerged as one of the leading top side technologies and are being used for new fields such as Kikeh, offshore of Sabah, Malaysia (**Figure 1**).

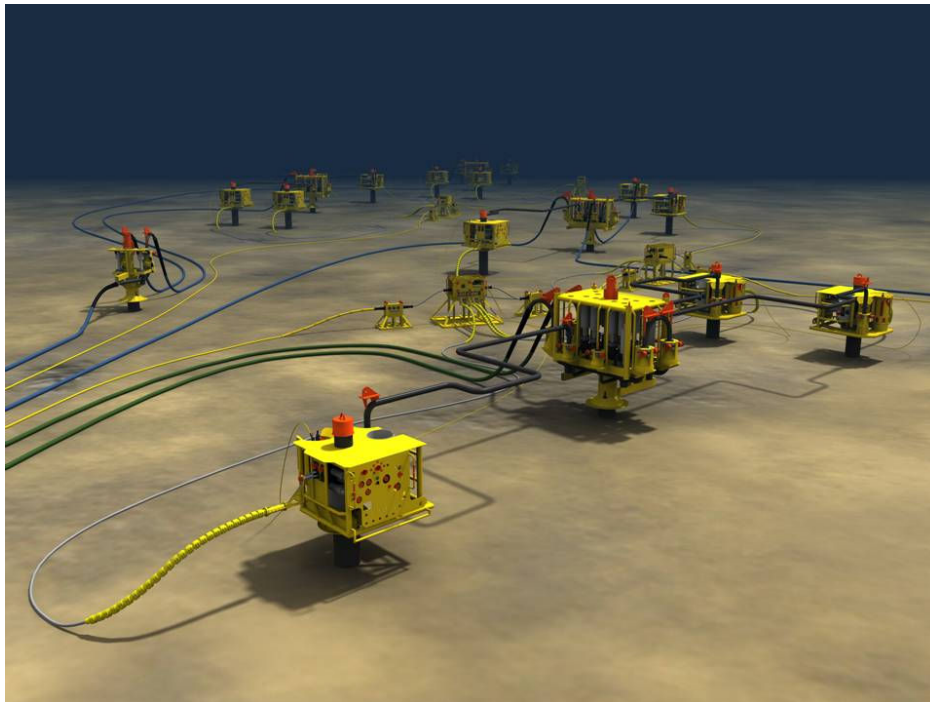
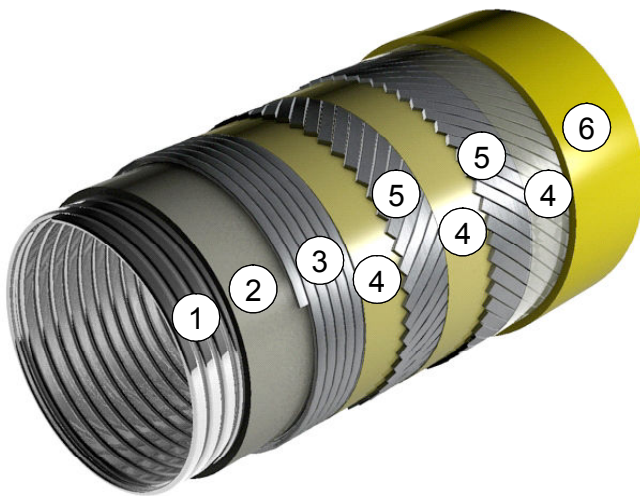


Figure 1 – Kikeh subsea production system consisting of 16 “christmas trees”, 5 manifolds, 21km of flowlines and umbilicals. Image courtesy of Aker Kvaerner.

For flexible pipe carcass, the corrosion performance of the stainless steel is critical to the performance of the pipe as a whole, and so it must be carefully characterized in order to allow accurate and confident material selection decisions to be made during pipe design. Recent and future applications of floating production systems are increasingly in more severe environments with design temperatures up to 145°C (293°F), design pressures from 345 to 690 bar (5,000 to 10,000psi), sour production fluids, water depths exceeding 2,000M (6,561ft.), and severe wave and current conditions^{1,2}. Flexible pipe typically employs polymer and carbon steel materials extruded and helically wound around the inner stainless steel carcass, to give axial, hoop and tensile stress reinforcement (**Figure 2**).



1) Stainless steel carcass, 2) Polymer fluid barrier, 3) Carbon steel pressure armour, 4) Anti-wear / friction tapes, 5) Carbon steel tensile armours, 6) Polymer external sheath

Figure 2 – Flexible pipe cross-section showing inner carcass layer. Image courtesy of Wellstream International Ltd.

As flexible pipes are used in deeper water, the tension loads induced by the hanging weight of the pipe increase causing higher stress levels in the pipe structure and higher deck and installation loads. As pipe stress levels increase, larger cross sectional areas of the steel members are required, further increasing the weight.

To reduce overall pipe weight, duplex stainless steels have been employed for carcass material, due to their inherent high strength as compared to conventional 300 series stainless steels (**Table 1**).

Table 1 – Chemistry, mechanical properties and PREN comparisons.

GROUP	Alloy	Rp0.2 MPa	Rm MPa	Cr	Ni	Mo	N	PREN
Austenitic	316L	170	485	18.2	10	2.2	-	24
LDSS	S32003	450	620	21.5	3.5	1.8	.16	30
DSS	2205	450	655	22.5	5.5	3.3	.16	36

$$\text{PREN} = \%Cr + 3.3\text{Mo} + 16\text{N}$$

In particular, the Kikeh field at 1400m water depth was too deep to effectively use 316L carcass material. Lean Duplex Stainless Steel S32003 was of particular interest as a replacement candidate for type 316L, since it was a lower cost alternative to 22%Cr DSS.

Extensive qualification of S32003 in accordance with API 17J was undertaken by Wellstream in order to confidently and cost effectively design with the new alloy

instead of using 316L or 22%Cr DSS.³ That qualification program along with the Kikeh field conditions are now described in greater detail.

3. Kikeh Field Conditions

Kikeh is considered the first deepwater development of its kind in the Asia – Pacific region, utilizing a spar for drilling and production in conjunction with an FPSO⁴. The field will be operated by Murphy Sabah Oil Company (80%) with Petronas Carigali (20%). Recoverable reserves are put at more than 400 million barrels of 39° API oil.⁴ The field was discovered in August 2003 and is targeted for production in the second half of 2007, at a rate of 120,000 bpd. Total project capital expenditure was estimated at \$1.4 billion.⁵

The subsea production system involves 16 “christmas trees”, 5 manifolds, 21km of flowlines and umbilicals, and 9 risers plus 4 additional risers in the future. Of the 21km of flowlines, more than 15km utilized lean duplex S32003 for the carcass material. The flowlines consisted of oil production, gas export and seawater injection lines (**Table 2**). This necessitated delivery of 600t of S32003 LDSS strip in a relatively tight delivery window, in order to meet the production schedule for pipe delivery.

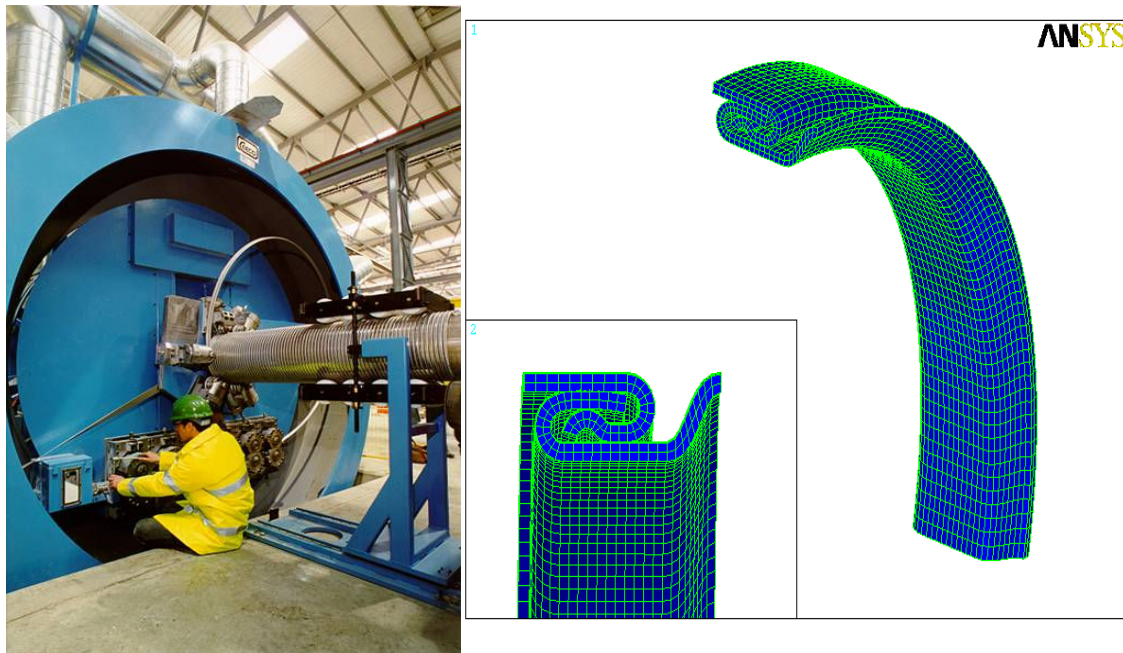
Table 2 – Kikeh field conditions, fluids being transported by pipe

	Wet/Dry	CO ² (Mol%)	Design Temp. (°C)	Operating Pressure (bara)
Production	Wet	0.44	75	235.4
Gas Export	Dry	0.71	50	373.4
Seawater Injection	Wet	0.01	50	220.7

4. Material and Manufacturing Considerations

Carcass material considerations include strength, corrosion resistance of the formed strip and welds, resistance to injection chemicals, erosion resistance, collapse resistance and experience. Allegheny Ludlum has a long track record in the production of flat-rolled 22%Cr DSS, including strip used for subsea flexible flowlines and risers by Wellstream in the 1990s and 2000s for various Petrobras fields located offshore Brazil and in other areas of the world including Australasia, West Africa and the Gulf of Mexico. As additional experience, Allegheny Ludlum also acquired Norsok M650 accreditation for production and supply of their flat products in 22%Cr DSS, S32003 LDSS, and 6Mo (N08367) alloys. Wellstream also completed testing in conformance with API 17J for S32003 LDSS.

Figure 2 illustrates the inner carcass layer encased by additional layers of carbon steel and polymer. To manufacture the carcass, flat strip is formed into an s-profile, which is then interlocked to form a flexible pipe as illustrated in **Figure 3 and 4**.



Figures 3 and 4 – Strip forming into pipe with cross profile of s-interlock.

The carcass tube is reeled before the remaining layers of carbon steel and plastic are constructed over the carcass. The finished pipe is packaged and shipped to the field for installation where it is unreeled on the vessel and then laid in position on the seabed.

For Kikeh, carcass material comparisons were performed as follows:

4.1 Corrosion Resistance

Table 1 shows the alloy comparisons for austenitic 316L, S32003 LDSS, and 22%Cr DSS. The Kikeh field required a level of corrosion resistance at least equal to 316L in the as-welded condition (strip to strip welds are required in order to form long lengths of pipe). Based on the chemical composition, the Pitting Resistance Equivalence Number (PREN) predicts that S32003 LDSS has higher pitting resistance, calculated at 30, compared with 316L at 24. This was confirmed initially by Allegheny Ludlum on GMA welds produced with 2209 wire on plate samples, through ferric chloride testing in accordance with ASTM G48A, where the as-welded lean duplex had a Critical Pitting Temperature (CPT) in excess of 10°C, compared to 316L at 0°C.^{6,7} Wellstream also tested formed S32003 strip and strip-weld samples using ASTM G48A and in accordance with ASTM G150 modified with CO₂ in an autoclave, and found little difference in CPT up to 100,000ppm chlorides as compared to 22%Cr (**Figure 5**) and a good performance by the strip welds.⁸ This information was necessary to demonstrate the compatibility of S32003 with production fluids and cool, treated seawater.

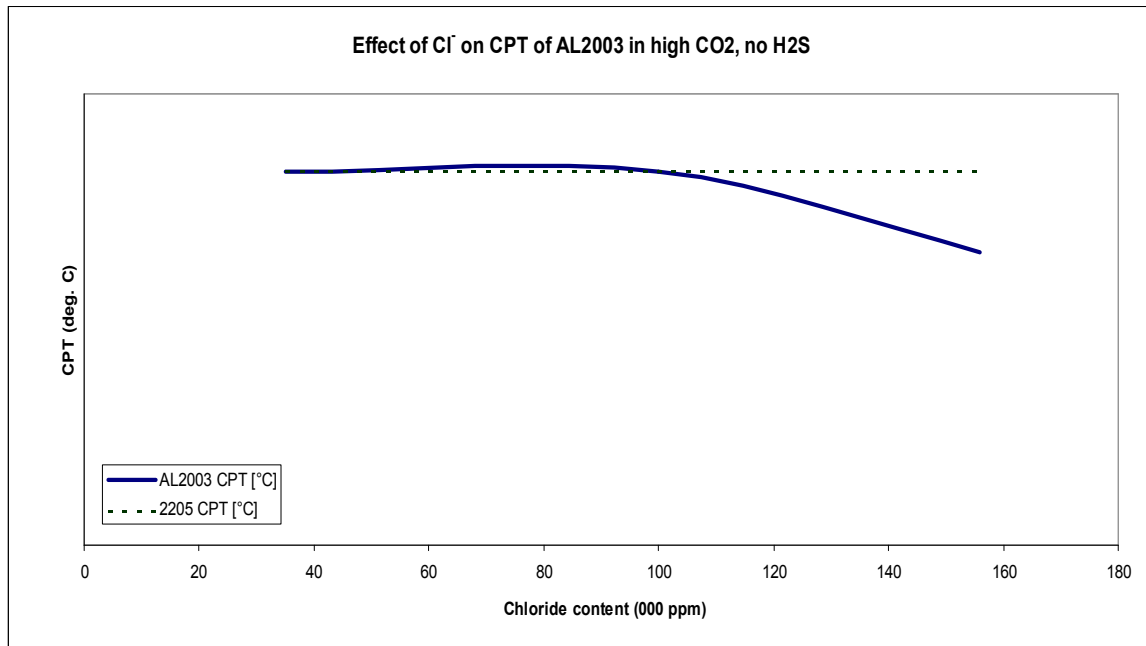


Figure 5 – Modified ASTM G150 Critical Pitting Temperature comparison.

Autoclave exposure testing was also conducted by Wellstream in order to confirm the CPT results and provide a longer term corrosion rate evaluation of the alloy in various corrosion environment combinations.

Corrosion resistance to chemicals and acids, being introduced through injection or as a result of the production fluids, is also a consideration. In **Table 3**, S32003 LDSS was compared to 316L, 317L with higher Mo (S31703), and 22%Cr DSS for a number of different acid conditions.⁹ The lean duplex showed equivalent or improved performance over 316L and 317L in most instances.

Table 3 – Alloy comparisons to resistance to various chemical solutions (MPY)

Boiling Solution	S32003	316L	317L	2205
10% Oxalic Acid	4	48	45	8
10% Sulfuric Acid	259	636	298	206
45% Formic Acid	15	23	18	5
1% Hydrochloric Acid	50	59	58	1
20% Phosphoric Acid	0.3	0.6	0.7	0.8
ASTM A262 Method B	21	26	21	20
ASTM A262 Method C	31	22	48	21
ASTM A262 Method E	Passed	Passed	Passed	Passed

4.2 Strength

Weld properties were also examined by Allegheny Ludlum for impact strength at low temperatures. In comparison to the acceptance criteria established by ASTM A923 and Norsok M-630, S32003 GMA welds in plate samples exceeded the requirement

as shown in **Table 4**.^{10,11,12} These results are worst case values for testing of the weld zone (2209 filler), fusion line and HAZ.

Table 4 – Impact properties of GMA welds - comparison of 316L to S32003 LDSS

	-51°F (-46°C)	-40°F (-40°C)	Room Temp.
T 316 Base	N/A	155 ft-lbs (210 J)	140 ft-lbs (190 J)
T 316 Weld	N/A	75 ft-lbs (100 J)	80 ft-lbs (110 J)
S32003 Base	80 ft-lbs (110 J)	100 ft-lbs (135 J)	180 ft-lbs (245 J)
S32003 Weld	50 ft-lbs (70 J)	60 ft-lbs (80 J)	150 ft-lbs (200 J)
NORSOK / ASTM CRITERIA	45 J avg. 35 J individual	40ft-lbs min	

The ASME allowable design strength (**Figure 6**) also shows a distinct advantage for lean duplex and 22%Cr DSS versus 316L.¹³ This advantage could contribute to wall reductions for pressure vessels or pipe, and improvement in collapse resistance for deep water applications.

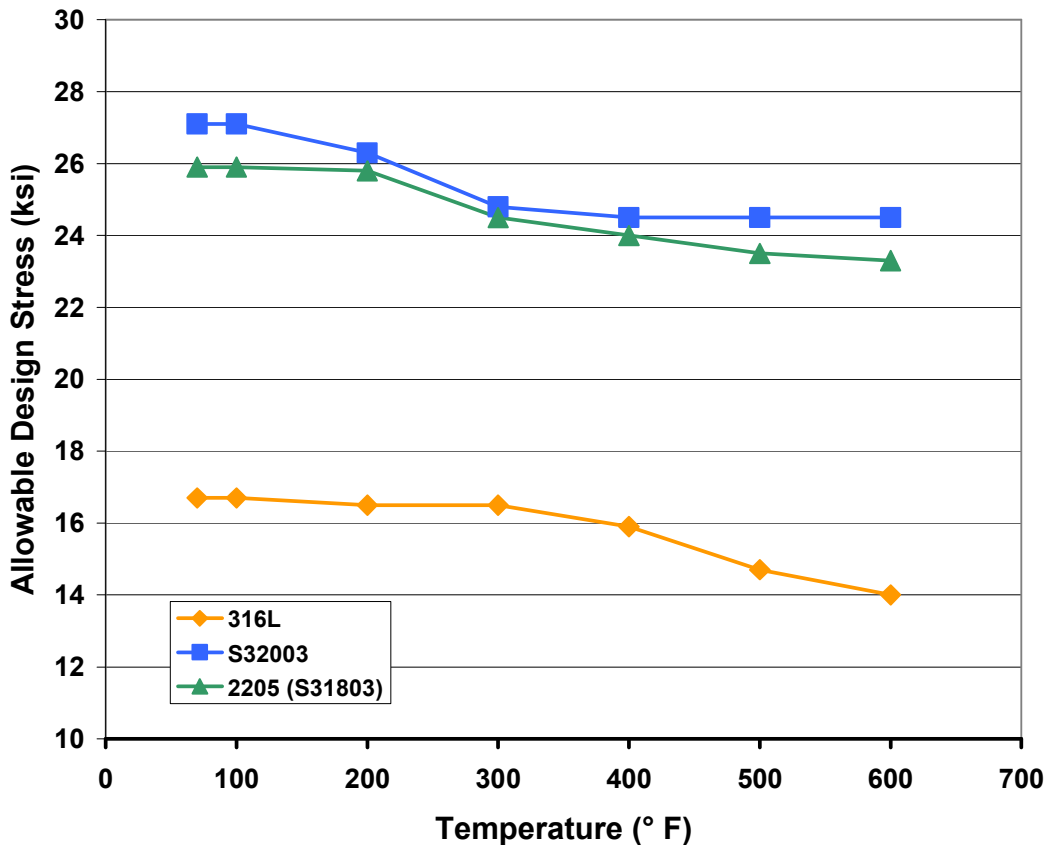


Figure 6 – ASME design strength comparisons

4.3 Collapse Resistance

Collapse tests were performed on the unbonded flexible pipe prototype with various carcass materials. Representative installation crushing loads were simulated. At a depth of 1400m, the Kikeh field was too deep for 316L carcass consideration as illustrated in **Figure 7**. This figure shows predictions for straight collapse, and indicates that even pipes with duplex carcass are challenged at this water depth at larger pipe diameters. However, large diameter water injection lines have the benefit of internal water pressure to combat the external hydrostatic head of seawater, enabling the use of differential pressure. The predicted collapse results clearly show the benefit from the selection of S32003 versus 316L, splitting the difference between the predicted collapse resistance for a pipe with the austenitic grade and that with 22%Cr DSS carcass. The benefit is not as great as might have been predicted from the comparison of alloy strengths, due to the lower work hardening rate of duplex. However, it is still significant.

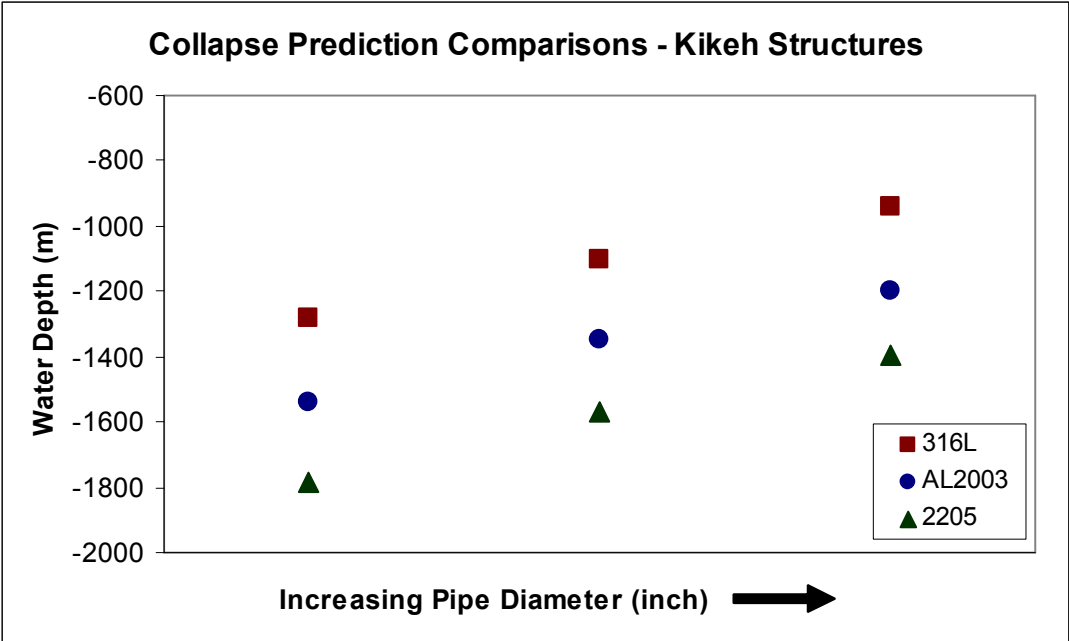


Figure 7 – Collapse resistance of unbonded flexible pipe with different carcass materials.

4.4 Erosion Resistance

Erosion and erosion-corrosion can be a concern for flowlines in fields where there is high sand production or high flow velocities. This can be compounded by the variety of elements being transported with the production fluids (oil, water, and corrosive gasses). Several carcass-only prototypes with 316L, S32003 and 22%Cr DSS were manufactured by Wellstream in order to compare their erosion corrosion resistance in simulated flow conditions. The tests were performed to satisfy API 17J (ISO 13628-2). Testing was performed at DNV’s Norwegian testing facilities using a medium pressure multiphase test rig with set up described by **Figure 8**. Samples taken from

a pipe bend at strategic locations as shown in the figure were assessed through weight loss measurements under various environment combinations.

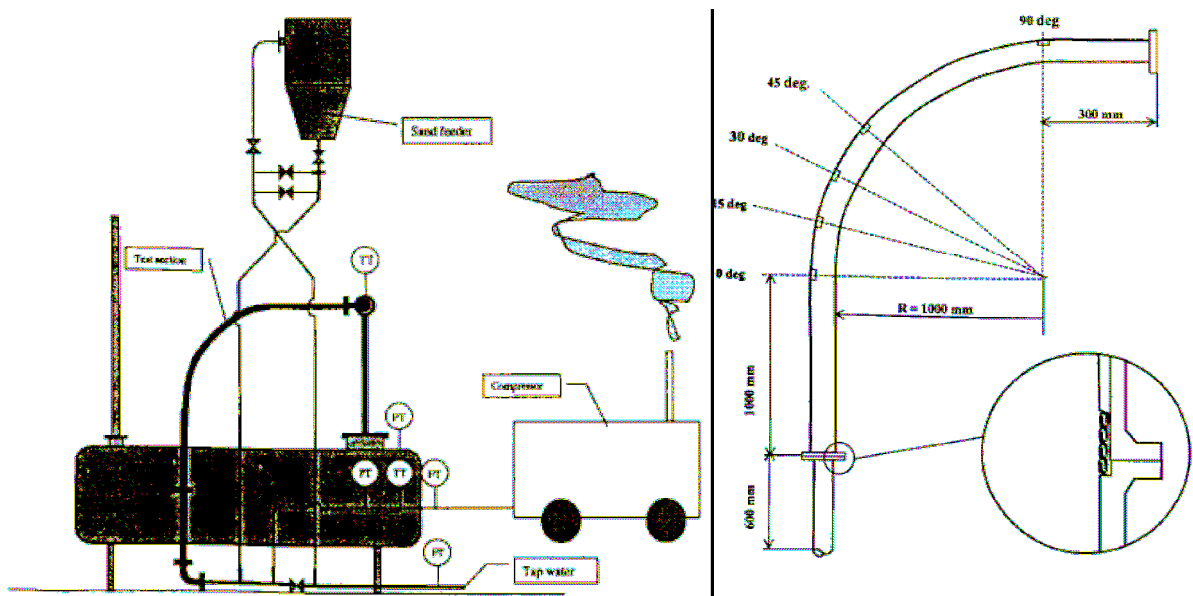


Figure 8 – Erosion corrosion test setup and sampling locations

This rig was especially designed for erosion and erosion-corrosion testing. The S32003 test line consisted of a 2.0 inch bore flexible carcass-only pipe of total length 2.1 meters which included a 1 meter straight vertical section, followed by a 90° bend with radius of curvature of 1 meter and ending in a straight 0.3 meter horizontal section. The rig consisted of a gas compressor, water pump, sand feed system, test line, separator and a heater system. Plain erosion tests were performed with a nitrogen gas pressure of 4.5 bar and the erosion-corrosion tests were performed with a CO₂ gas at 3 bar in order to simulate the same gas density as for the plain erosion tests. The erosion-corrosion tests were conducted at temperatures in the range of 20 – 59°C. The sand was mixed with water before injecting into the gas flow at the gas-liquid mixing point. The rig was a closed loop and the gas and water were recirculated while the sand was not recirculated. During the erosion-corrosion testing the test rig was deaerated to a level <1ppb in the water phase to simulate the oxygen-free atmosphere in a reservoir. Temperature, pressure and differential pressure transmitters were installed and connected to a computer for process control.

At high fluid velocities and high Gas/Liquid Ratios (GLR) (**Figure 9**), results showed similar performance between S32003 LDSS and 22%Cr DSS, versus 316L samples which had substantially higher erosion rates.

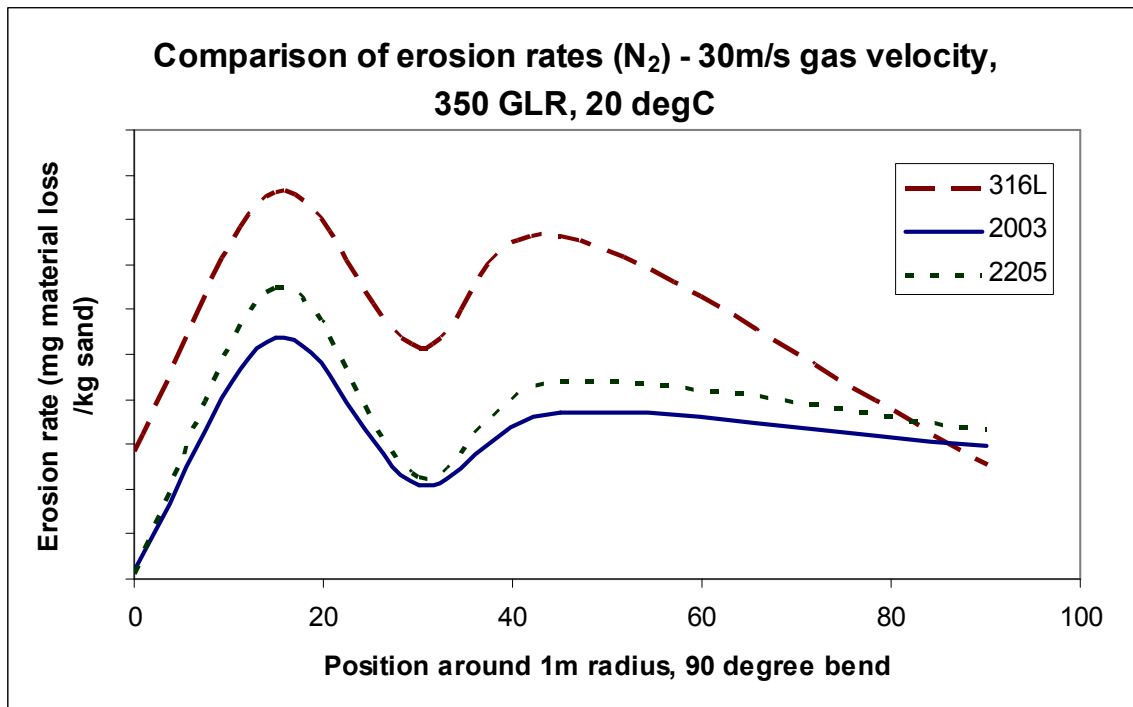


Figure 9 – Comparison of erosion rates for 316L, AL 2003™ alloy and 22%Cr DSS.

At lower gas velocities and/or reduced GLR or increased temperatures, little differences in erosion-corrosion rates were noted for the three grades (**Figures 10a and 10b**). These test results validated the erosion prediction model used by Wellstream.

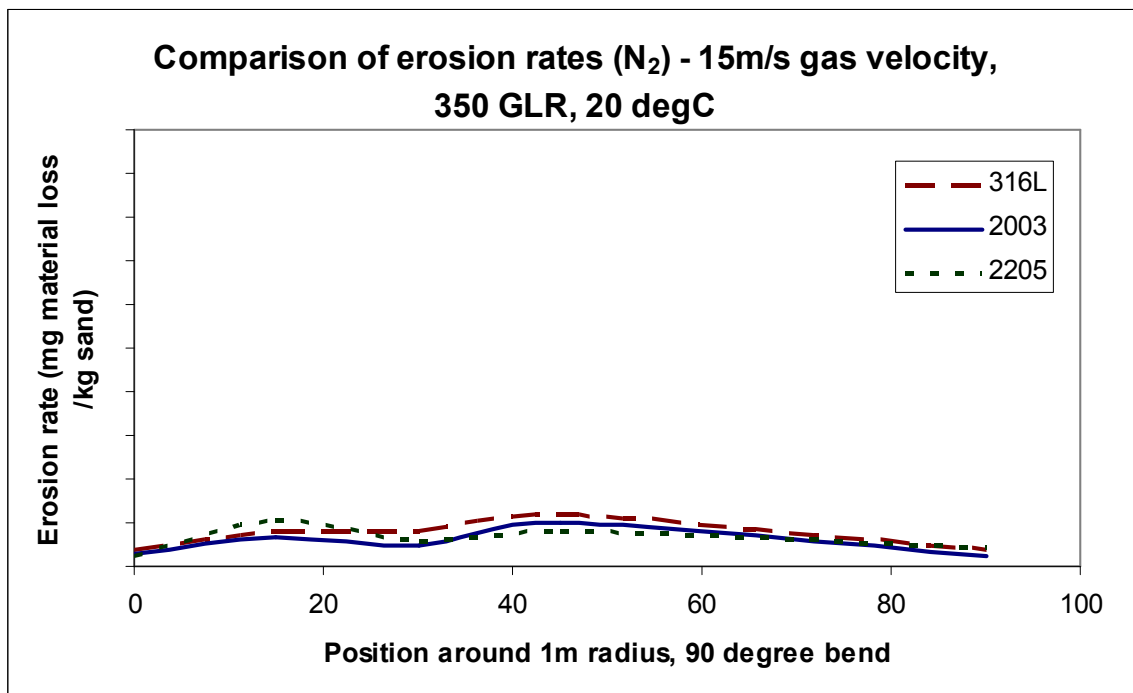


Figure 10a –Erosion rates at low temperature and gas velocity, and high Gas to Liquid Ratio (GLR).

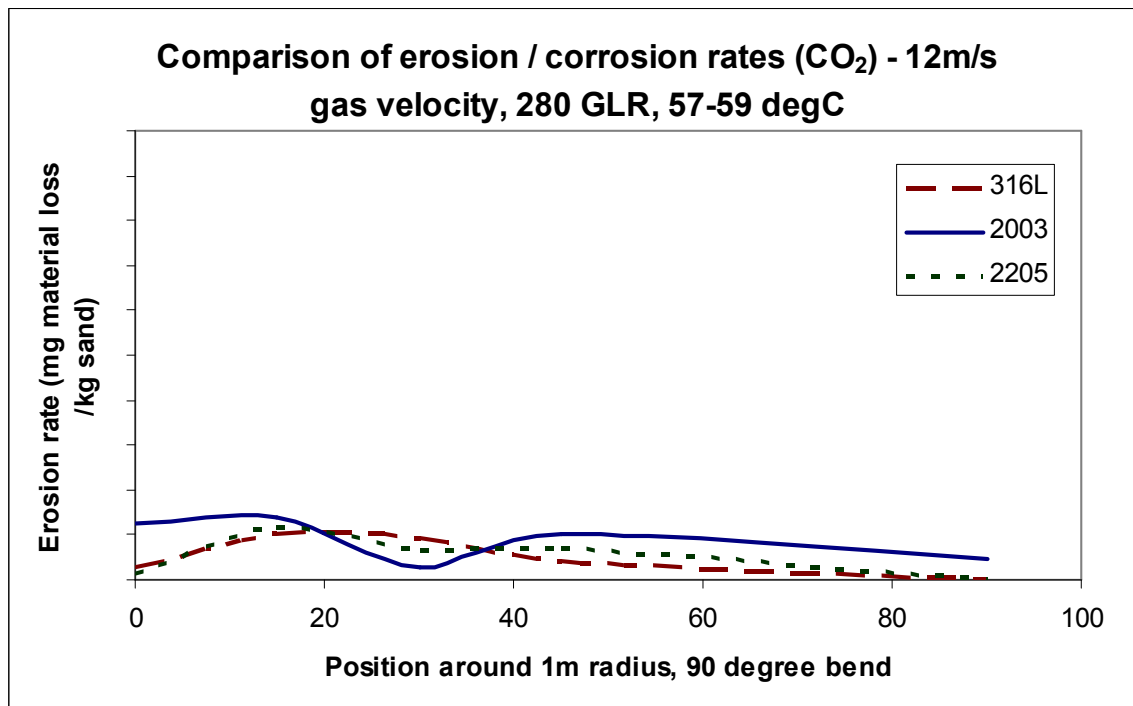


Figure 10b – Erosion-corrosion rates at low gas velocity, high temperature, and high Gas to Liquid Ratio (GLR).

4.5 Fatigue Resistance

Even though fatigue resistance was not a consideration for material selection on the Kikeh flowlines due to static conditions, fatigue could be a concern for dynamic risers. Flexible pipe when bent possesses the inherent ability to allow movement of the unbonded elements that make up the pipe and the carcass, as the innermost layer in the pipe is subject to the least axial movement of any layer in the pipe. The design of the interlocked shape of the carcass is intended to allow sliding of adjacent interlocked wraps, so as to allow flexibility of the pipe and limit the stress in any section of the carcass. Since the stresses are kept low, there is no risk of fatigue failure of the carcass layer so long as its sliding lateral movement is maintained. This is one of the reasons that flexible pipes have excellent fatigue resistance and are ideally suited for use in conjunction with floating production vessels.¹⁴

5. Conclusions

1. New Lean Duplex Stainless Steel S32003 was successfully delivered on time and within budget for use in flexible flowlines for a major deepwater subsea oil and gas project.
2. S32003 carcass was selected due to its combination of corrosion resistance and strength.

3. More than 15km of unbonded flexible pipe with S32003 carcass has already been installed.
4. Cost savings were achieved for the project due to the much lower alloy content of S32003 LDSS as compared with 2205 (which would have otherwise been necessary at the 1400m water depth).
5. Weight savings with S32003 LDSS may have been possible in shallower water where the collapse resistance would not have disqualified 316L.
6. S32003 LDSS met or exceeded 316L in all qualification testing, and is considered an improved alternative to 316L carcass in unbonded flexible pipe.
7. S32003 LDSS can, in some field conditions, be considered an economic alternative for 2205 DSS unbonded flexible pipe.

6. Acknowledgements

The authors wish to thank all the personnel involved with this project at Wellstream International Limited and at Murphy Oil Corporation, who defined the field conditions, which have become a reference point for the use of S32003 LDSS carcass in unbonded flexible pipe.

7. References:

1. M. Kalman, J. Belcher, B. Chen, D. Fraser, A. Ethridge, C. Loper, "Development and Testing of Non-Bonded Flexible Pipe for High Temperature/High Pressure/Deep Water/Dynamic Sour Service Applications", OTC 008263, Houston, 3-6 May 1996.
2. J. Tuohy, A. Avery, S. Martin, "Unbonded Flexible Pipe Technology in Deepwater Developments for Production and Offloading Systems", OWA 2001, Abuja, Nigeria, 21-23 March 2001.
3. American Petroleum Institute Specification API 17J: Specification For Unbonded Flexible Pipe.
4. J. Maksoud, "Malaysia's field of 'firsts'", Offshore, April 2007, pg 92-96.
5. K. Evensen, A. Battersby, "Smedvig in Clover with Kikeh Deal", Upstream, 4 March 2005, pg. 33.
6. ASTM G48: Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution: Method A.
7. "AL 2003 (S32003) Weld Procedures and Evaluation", Allegheny Ludlum Technical Publication, 2005.
8. ASTM G150: Standard Test Method for Electrochemical Critical Pitting Temperature Testing of Stainless Steels
9. B. Ozturk, "Corrosion Properties of AL 2003 Alloy", Achema, Frankfurt, May 19, 2006.
10. ASTM A923: Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels.
11. Norsok M-630: Material data sheets for piping (Rev. 4, January 2004)
12. J. Dunn, D. Bergstrom, "AL 2003 (S32003) Lean Duplex Stainless Steel as a Substitute for Type 316L", SSW, November 2006.
13. J. Grubb, "A Lean Duplex Stainless Alloy for Pressure Vessel Applications – ASME Code Case 2503", Outlook, March 2006, Vol 27, pg. 12-13.
14. Liping Sun et al., "Rationale of Riser System Selection for FPSO Application"; OMAE 2007 paper 29357, ASME Publications 2007.