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Materials Selection for High Pressure Sour Service in the Shah Gas Development Project

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Abstract

Al Hosn Gas Company, a 60/40 JV between ADNOC and Oxy has been undertaking a project for the development of an extremely sour gas reservoir in order to increase production of injection and sales gas. The Al Hosn Gas plant is designed to process 1,000 MMscfd of non-associated sour gas.

The gas reservoir is very sour with H2S levels of 23% together with 10% CO2 and other corroding components such as 20,000 ppm chlorides and 5 bbl/MMSCF water.

The bottom hole conditions make the overall environment very aggressive for any conventional material e.g. carbon and alloy steels.

Processing of such sour feed posed a significant design challenge. Materials selection for production tubular, gas gathering lines and process equipment was the main strategy to ensure plant integrity.

The well fluid can reach high temperatures. To protect against external corrosion the carbon steel backing material for flow and trunk lines was coated with high temperature epoxy.

Four exotic materials were selected and subjected to 30 days exposure test in autoclave at simulating gas gathering lines conditions. Two materials were further subjected to closer scrutiny with a series of potentiodynamic polarization tests and metallurgical analysis.

This paper deals with the materials identification evaluation, test procedures, test details and final selection together with applicable fabrication procedures.

INTRODUCTION

AL HOSN GAS OVERVIEW

Al Hosn Gas is a newly developed, large-scale green field sour gas facility located 240km south west of the city of Abu Dhabi in the United Arab Emirates (UAE). It is a joint venture establishment between Abu Dhabi National Oil Company (ADNOC) and Occidental (Oxy) to develop a very sour gas field. Al Hosn Gas is part of the critical infrastructure strategic program to enable the UAE to meet future gas demand.

Al Hosn Gas facilities consist of onshore wells and production systems, gathering and transfer pipelines, processing plant, product pipelines and a sulphur granulation facility.

The nominal processing capacity is 1,000 MMSCFD of sour well fluid with typical product volumes of 500 MMSCFD sales gas, 4,400 TPD NGL, 33,000 BPD condensate and 9,090 TPD of Sulphur Granules.

The well fluid is extremely sour and contains approximately 23% H2S and 10% CO2. This makes it a unique project in the UAE and presented major technical and HSE challenges to the project team. A combination of proven and innovative solutions was required to ensure delivery of an operating plant with high integrity and safety. The successful outcome of the project places Al Hosn Gas at the leading edge of the extremely sour gas processing community.

The plant is the largest facility of this kind and is designed to be self-supporting and includes a laboratory, fire station, housing, medical, recreation and a mosque to provide a high quality of life for permanent living quarter for the staff. The design life for the main plant, gas gathering system and pipelines is 30 years.

CHALLENGES IN MATERIAL SELECTION

Due to the sourness of the well fluid coupled with the presence of water and chlorides, conventional carbon steel and alloy steel materials for the gas gathering lines and other downstream equipment were considered unsuitable. Although Al Hosn Gas has a wide range of process equipment and plant piping, the present discussion is limited to the high pressure/temperature production tubing plant piping and gas gathering pipelines up to the slug catchers.

The process fluid is three phases (hydrocarbon vapour, hydrocarbon liquid and water). The gas gathering lines are buried and to combat external corrosion required special coating suitable for fluid temperatures of up to 118°C.

While selecting materials for corrosive sour environments the materials of choice must be reliable and cost effective while also meeting the required corrosion resistance and mechanical properties. CRA (Corrosion Resistance Alloys) materials have shown good resistance to stress corrosion cracking (SCC) and Stress Cracking (HIC, SSC).

It has been observed that super alloys with high Nickel, Chromium, Molybdenum and Niobium exhibit high resistance against chloride stress cracking as well as hydrogen induced cracking. The ″resistance to cracking″ property is generally demonstrated by a PREN number (Pitting Resistance Equivalent Number) which can be calculated with the following empirical formula;

$PREN = Cr + 3.3Mo + 1.5\,W + 11N$

With some exceptions, the higher the PREN number the better the pitting resistivity.

Though the initial screening and selection of material was performed using NACE MR 175/ ISO 15156, industrial experience with other operators was also considered for the final screening.

Inconel 625 has a good service history in similar environments and is widely regarded as a safe, conservative choice for the cladding. Incoloy 825 also has a good record as internal cladding material in the various sour gas fields which has very high mol % H_2S content. Since there was a substantial cost difference between the two alloys, laboratory corrosion tests were undertaken to define the functional differences between the two alloys. Two additional alloys 27-7Mo and 865 were also selected and tested for information and comparison.

For the cladding alloy, the primary risk of service failure is pitting corrosion. Environmental cracking (by sulfide stress-cracking or chloride stress-corrosion cracking) is less of a concern since the cladding is not in the pressure boundary, and the manufacturing process forces the clad layer into residual compression, thereby reducing the likelihood of environmental cracking. Consequently these tests concentrated on the pitting corrosion resistance of these alloys in simulated field gathering line conditions.

TEST PROCEDURES

Four test methods were selected to study the pitting corrosion resistance:

1. A 30-day exposure of flat corrosion coupons in an autoclave at simulated gathering line conditions,
2. A series of potentiodynamic polarization scans in autoclaves at simulated partial pressure of acid gas in gathering line acid gas partial pressures, across a range of chloride contents,
3. Metallographic examination of commercial clad pipe samples for evidence of weld flaws, sensitization or bond line defects, and
4. Incoloy 825 C-rings, stressed at 100% of Yield Stress exposed for 30 days to simulated worst case conditions for evidence of pitting.

Test conditions in the two gathering line test procedures were designed to simulate the conditions for the field gas gathering lines, with a small margin of safety on the temperature (225°F and 240°F).

One scan was performed at 225 °F, 317 psia partial pressure H_2S, 144 psia partial pressure CO_2, and 20,000 ppm chloride ion as NaCl.

Subsequent potentiodynamic polarization scans were conducted across a range of chloride ion contents (40,000-120,000 ppm) at 240°F, 317 psia partial pressure H_2S, 144 psia partial pressure CO_2, in an attempt to define an envelope of acceptable environmental conditions for Alloy 825.

Further additional tests for the Alloy 825 C-ring exposure simulated much more severe conditions at 305°F, 1,310 psia partial pressure H_2S, 550 psia partial pressure CO_2 and 20,000 ppm chloride ions as NaCl.

TEST RESULTS DESCRIPTIONS

30 Days Autoclave Exposure Metallographic Analysis

Four commercially available materials (as per Table 1) were tested in simulated gathering line conditions. Alloy 625, Alloy 865 and Alloy27-7Mo were used as solid strip/plate whereas the Alloy 825 sample was prepared from clad pipe with a long seam weld. The long seam was made using Inconel 625 filler material.

Table 1—Typical composition of four commercially available materials selected for 30 days Autoclave Exposure under Gathering Line Condition

Elements	Incoloy 825 Cladding* base metal	Long seam weld material (Equivalent to Inconnel 625)	Inconel 625	Super ASS 27-7Mo	Incoloy 865
Nickel	38.8	56.3	60.6	26.9	21.6
Silicon	0.260	0.179	0.100	0.396	1.18
Manganese	0.408	0.164	0.116	1.11	0.851
Chromium	24.6	21.5	21.7	20.9	24.7
Molybdenum	2.67	7.0	8.83	7.91	2.04
Copper	1.56	0.3432	0.126	0.880	0.150
Iron	30.2	11.4	4.13	41.2	49.0
Cobalt	0.113	0.0591	0.198	0.123	0.0766
Titanium	0.632	0.268	0.214	0.0144	0.0098
Aluminum	0.107	0.0951	0.361	0.0588	0.0258
Niobium	0.0158	2.45	3.30	0.0757	0.0290
Tungsten	0.169	<0.0150	0.155	0.0601	0.0275
Vanadium	0.111	0.0457	0.0343	0.0803	0.0682
Carbon	0.0225	0.0259	0.0311	0.0299	0.0239
Sulfur	<0.0020	<0.0020	<0.0020	0.0156	<0.0050
Hafnium	0.0825	<0.0200	<0.0200	n.d.	n.d.
Magnesium	0.0026	0.0027	0.0037	n.d.	n.d.
Zirconium	0.0203	0.0101	0.0064	n.d.	n.d.
Phosphorous	n.d.	n.d.	n.d.	0.0413	0.0055

***Cladding vs solid manufacturing process discussed later.**
n.d. – not determined

Since the cladding layer carbon content was only 0.022% and with 0.63% titanium, the formation of sensitized micro structures would have been highly unusual. The metallographic examination of the Alloy 825 clad pipe sample showed **no evidence of HAZ sensitization, weld defects or significant bond line defects** (Fig 1).

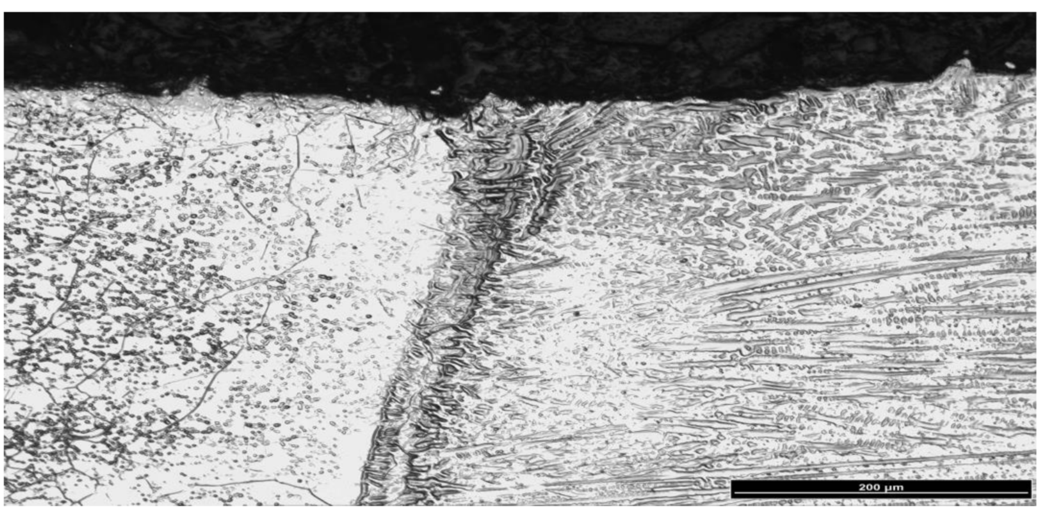

Figure 1—No evidence of Sensitization near seam weld and HAZ

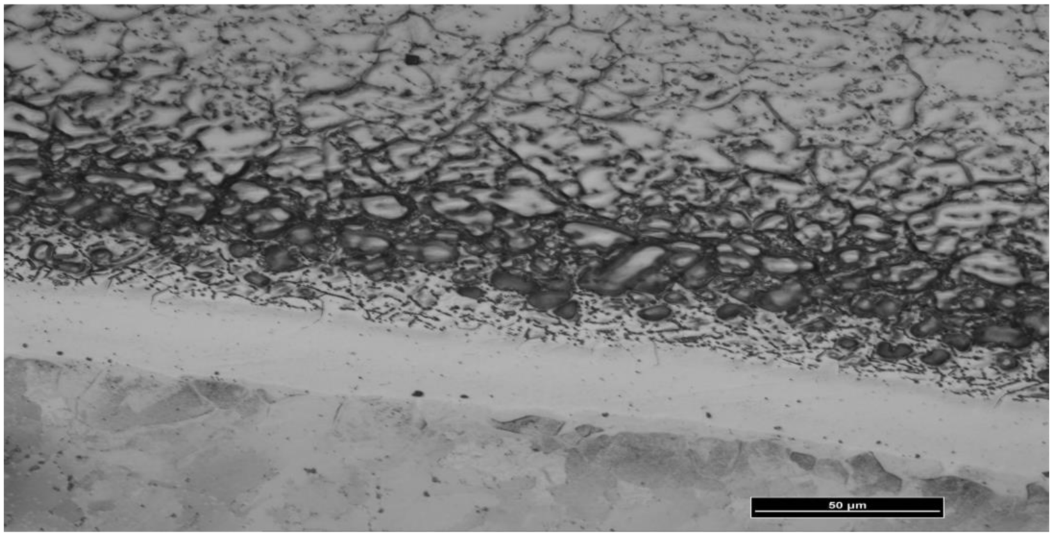

Figure 2—Metallurgical bond line between CRA plate (at bottom) and Carbon steel pipe

The Incoloy 27-7Mo alloy had the most significant corrosion pit (Fig 3) detected after the autoclave exposure. The Incoloy 865 alloy had some small pits, shallow enough to pass the acceptance criterion.

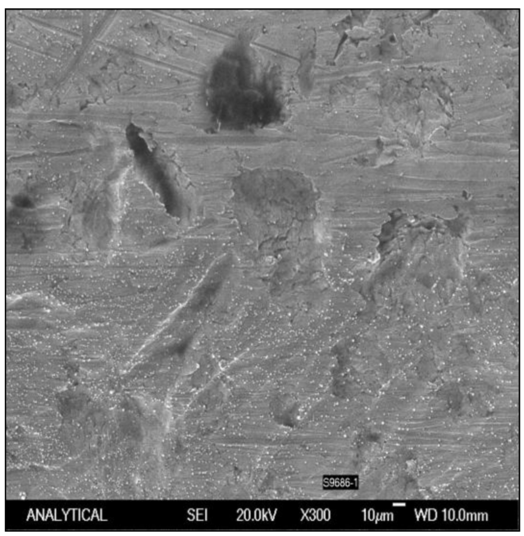

Figure 3—27-7Mo pit depth 78.9μm at 300X

Neither of these two alloys (27-7Mo and 865) appeared to be as resistant as Incoloy 825 in this environment, and since there is no practical experience with cladding steel pipe with these alloys (commercial viability), there was no incentive to proceed with further testing (under potentiodynamic polarization scans) of these two alloys.

Incoloy 865 might be considered for future projects with slightly less severe environments, where its leaner alloy content could provide capex savings compared to Incoloy 825.

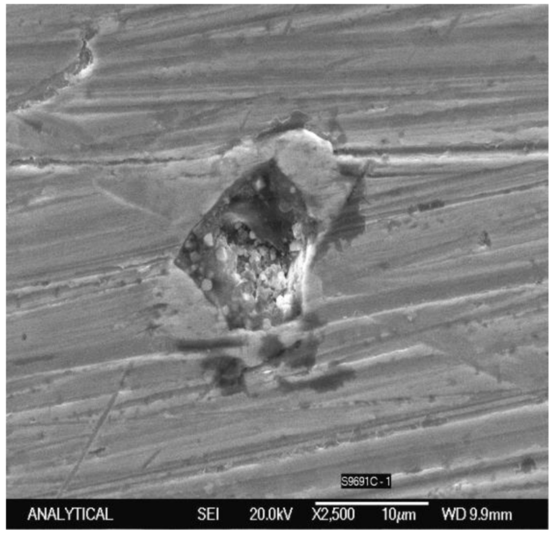

Figure 4—825 pit depth 5μm at 2500X

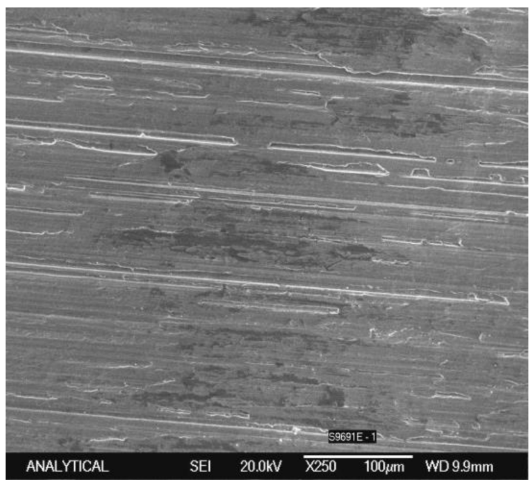

Figure 5—825 Weld HAZ sample. No evidence of pitting

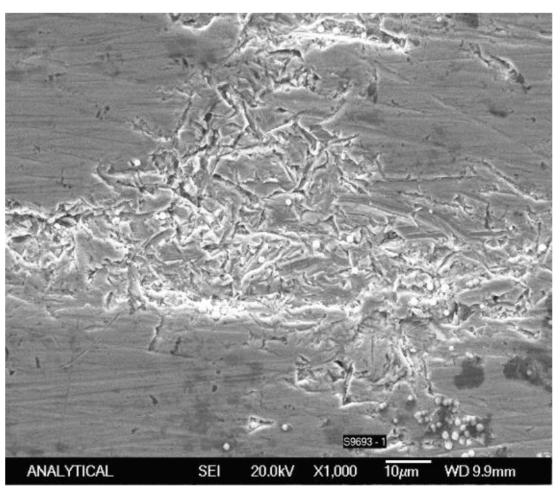

Figure 6—625 showing shallow corrosion pits

The Incoloy 825 alloy C-rings (stressed at 100% of yield stress) were exposed to more severe test conditions with higher temperature and higher acid gas partial pressures than those anticipated for the gathering lines.

Since the Incoloy 825 C-rings did not show any evidence pitting and cracking (fig7) at the test conditions this was taken as a second piece of evidence to suggest that Incoloy 825 would also be adequate for the milder, lower temperature gathering line service.

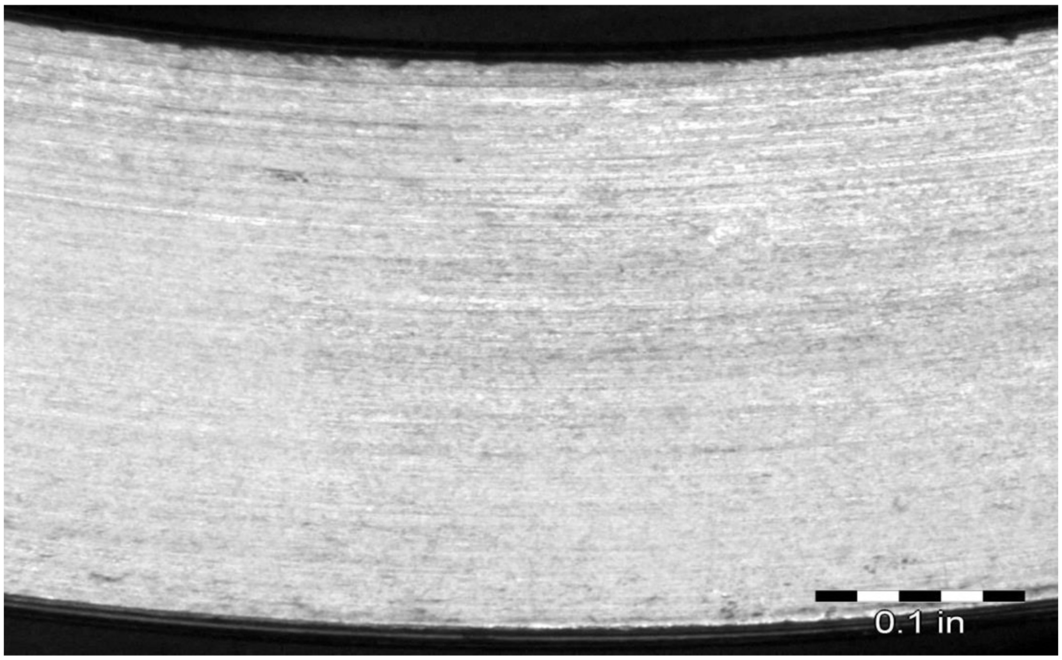

Figure 7—Close-up of the machined surface on the side of Incoloy 825 C-ring at 110X

Potentiodynamic Polarization Scans

Test electrodes of Incoloy 825 and Inconel 625 were prepared for polarization test scan. Each electrode was a 3/8 inch diameter rod ½ inch long, with a blind 3-48 hole drilled and tapped in one end and Hastelloy C-2000 rods were used as the reference electrodes and counter electrodes.

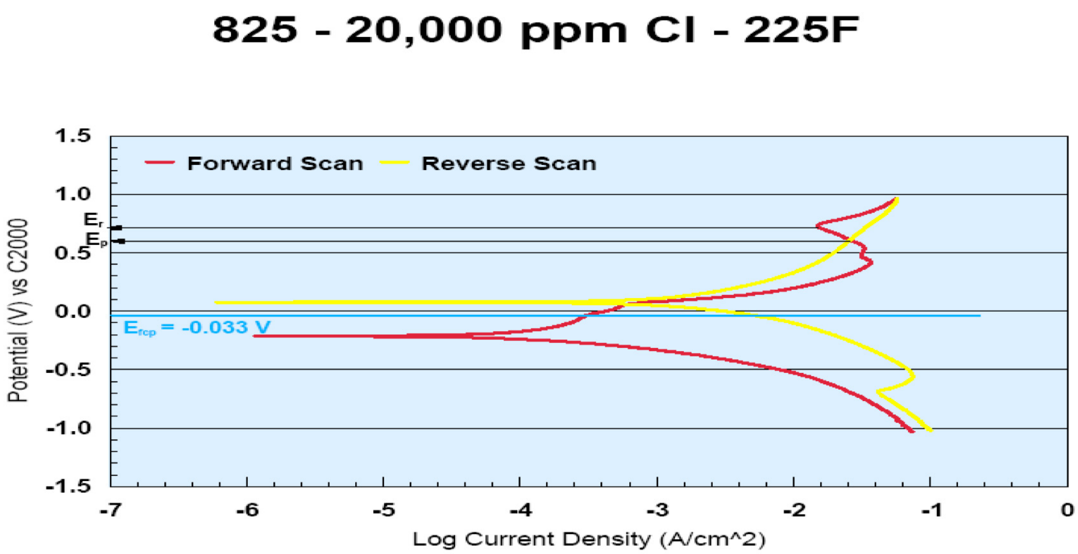

Figure 8—Potentiodynamic polarization scan for Incoloy 825 in 20,000 ppm Cl^- brine at 225°F with Basis of Design acid gas pressures. Current density is in A cm^{-2}. Note the absence of a positive hysteresis loop and the 0.63V spread between E_p and E_{fcp}

The test solutions were brine made up with distilled water and reagent grade NaCl to chloride ion concentrations of 20,000, 40,000, 80,000 and a maximum of 120,000 ppm. The 20,000 ppm chloride ion tests on Incoloy 825 were run at 225°F and all other tests were conducted at 240°F.

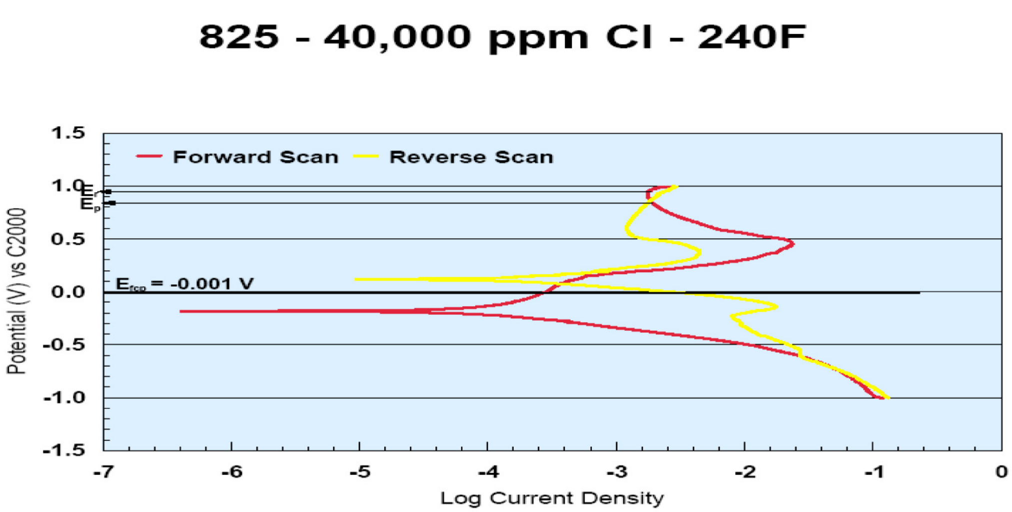

Figure 9—Potentiodynamic polarization scan for Incoloy 825 in 40,000 ppm Cl^- brine at 240°F with Basis of Design acid gas pressures. Current density is in A cm^{-2}. Note the absence of a positive hysteresis loop and the wide spread (0.825 V) between E_p and E_{fcp}

The potentiodynamic polarization scans indicated that any pits which might form on Incoloy 825 should re-passivate even at chloride contents above 80,000 ppm well beyond the Basis of Design level of 20,000 ppm.

Incoloy 825's pitting resistance began to look marginal at 120,000 ppm chloride ion content, and beyond that chloride level, this alloy may not be adequate.

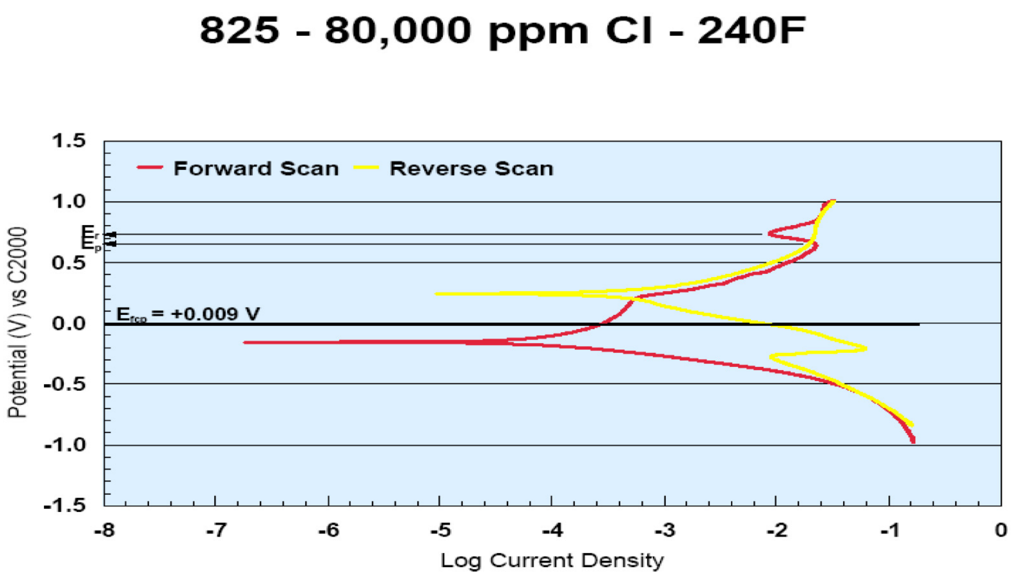

Figure 10—Potentiodynamic polarization scan of Incoloy 825 in 80,000 ppm Cl^- brine at 240°F with Basis of Design acid gas pressures. The potential difference is 0.659V between E_p and E_{fcp}. Current density is in A cm^{-2}

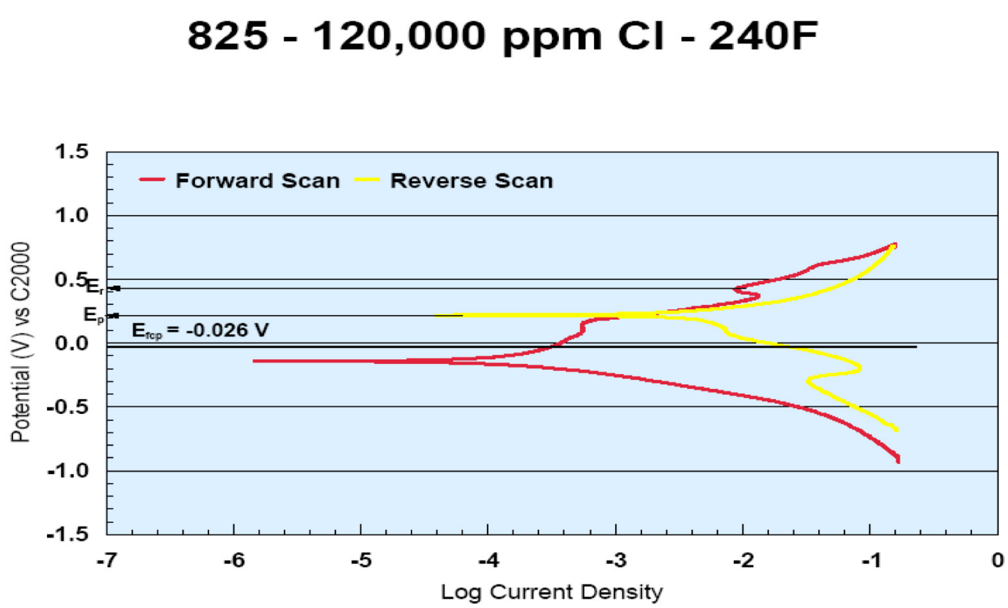

Figure 11—Potentiodynamic polarization scan of Incoloy 825 in brine with 120,000 Cl^- ion at 240°F with test acid gas pressures. Current density is in A cm^{-2}. Note the appearance of a small anodic hysteresis loop and the relatively small potential difference (0.226) between E_p and E_{fcp}

At the gathering line temperatures and acid gas concentrations, the higher alloy content of Inconel 625 was seen to be of advantage only if the chloride content in the brine equals or exceeds 120,000 ppm. (Fig 12).

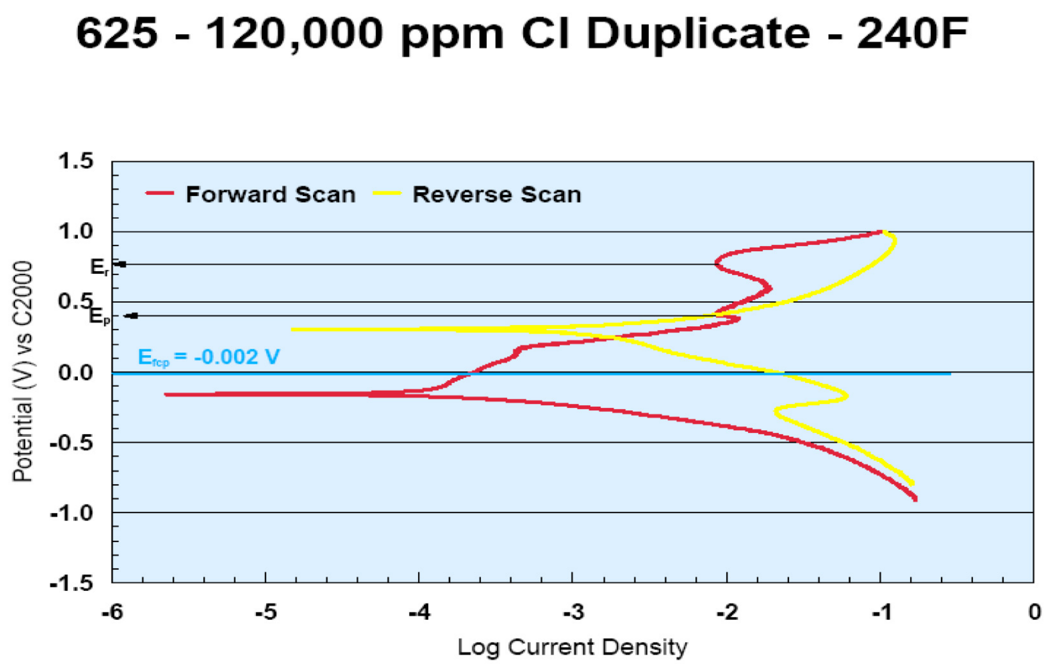

Figure 12—Potentiodynamic polarizations curve for Inconel 625 in 120,000 ppm Cl- brine at 240°F with Basis of Design acid gas pressure with the relatively large potential difference (0.402V) between Ep and Efcp (compared to Fig 11 scan). Current density is in A cm-2

DISCUSSION

Taken together, the information from the four different test procedures described above showed that Incoloy 825 and Inconel 625 are functionally equivalent in the estimated gas gathering line conditions because both alloys have adequate Pitting Corrosion Resistance.

Table 2—Cost Comparison Index- Pipes (Based on 8″ OD 12.7 mm thick CS pipe and 3mm CRA)

Item	Solid CRA	Clad CRA (Metallurgical Bonded)
SS 316L	850 USD /m	790 USD/m
Incoloy 825	1800 USD/m	1400 USD/m
Inconnel 625	3300 USD/m	2200 USD/m

Neither alloy is totally immune to interaction with the environment, but the microscopic pits or zones of attack which form (Figure 4 for Incoloy 825 & Figure 6 for Inconel 625) are too small and too shallow to threaten liner perforation over the course of the design life. The appearance of the coupons from the autoclave tests indicated that there was no practical, significant difference between the pitting resistance of Incoloy 825 and Inconel 625 at the estimated conditions. Both were adequate choices for the gas gathering line cladding alloy.

Pitting data at one time interval always raises the question of whether any zones of attack will re-passivate and stop, take on a linear pit propagation rate, or accelerate with time. The 30 day autoclave tests and potentiodynamic tests together provide good evidence that in the simulated gathering line conditions, on both Incoloy 825 and Inconel 625, any pits which develop should be shallow and are likely to re-passivate. However long term tests of 60 or 90 days exposure time may be used to develop more confidence.

The Cracking Resistance property of CRA containing nickel is governed by their nickel content (refer Fig 13) which shows that alloy containing more than 40% Nickel are fully resistant to cracking under boiling MgCl2 (a very severe environment).

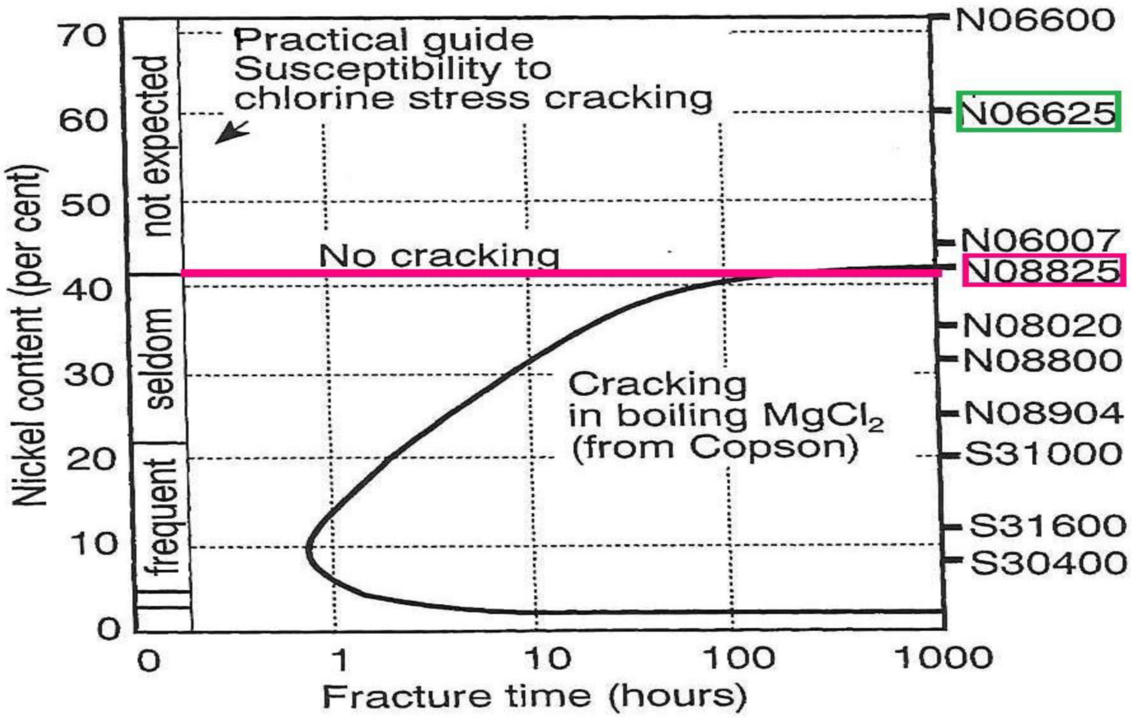

Figure 13—Effect of Nickel on Chloride Stress corrosion Cracking properties of CRAs

CONCLUSIONS AND RECOMMENDATIONS – GAS GATHERING LINES

6.1 For internal cladding, both Incoloy 825 and Inconel 625 (UNS N006625) have comparable and adequate pitting resistance to the expected gas gathering line temperatures and acid gas pressures, up to chloride ion concentrations of 120,000 ppm in the brine.

6.2 The higher alloy content of Inconel 625 would only be of advantage if the chloride ion concentration in the brine equals or exceeds 120,000 ppm.

6.3 The carbon steel pipe internally clad with Incoloy 825 showed good weld quality, good bond line quality and no evidence of sensitization in the HAZ.

6.4 Incoloy 27-7Mo and Incoloy 865 were not recommended for further evaluation for this application.

Inconnel 625 (UNS N006625) was finally recommended as the internal cladding alloy for the field gas gathering line to ensure resistance to the most severe damage mechanisms (pitting and cracking) over the entire design life.

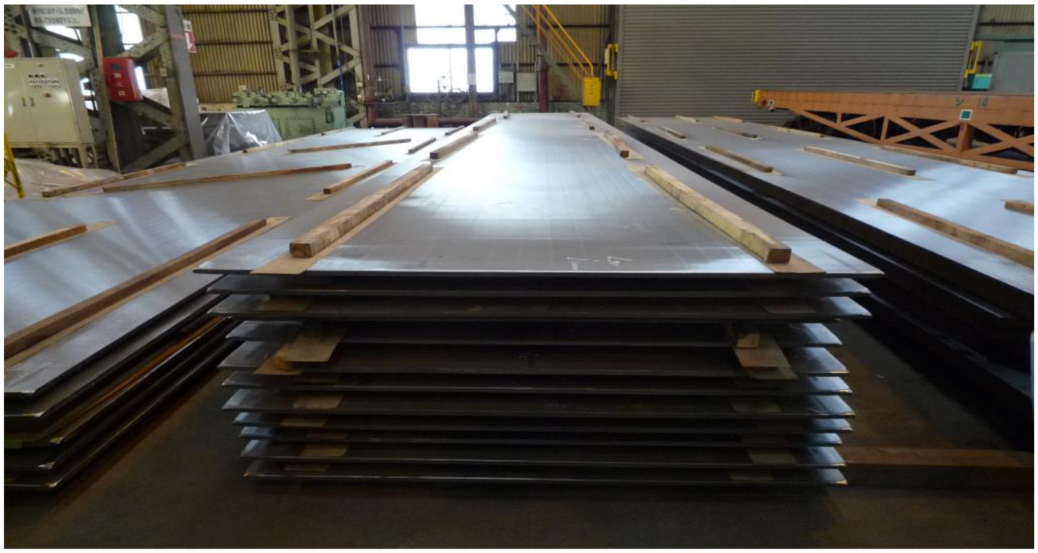

Figure 14—Sandwiched rolled CRA CS plate in the Steel Mill

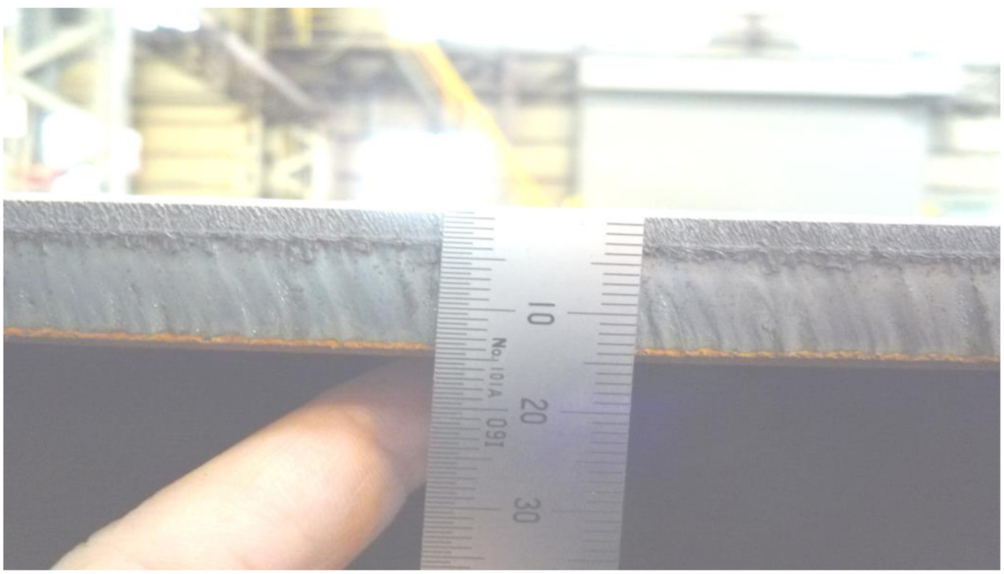

Figure 15—Cross section of Cladded plate showing CRA and Carbon Steel layers

PRODUCTION TUBING

A separate test program was initiated to evaluate various commercially available solid CRA tubing for down hole service.

Most nickel based alloys exhibit corrosion resistance at 230°C (450°F) depending upon chloride concentration, H2S content and the presence of elemental sulfur.

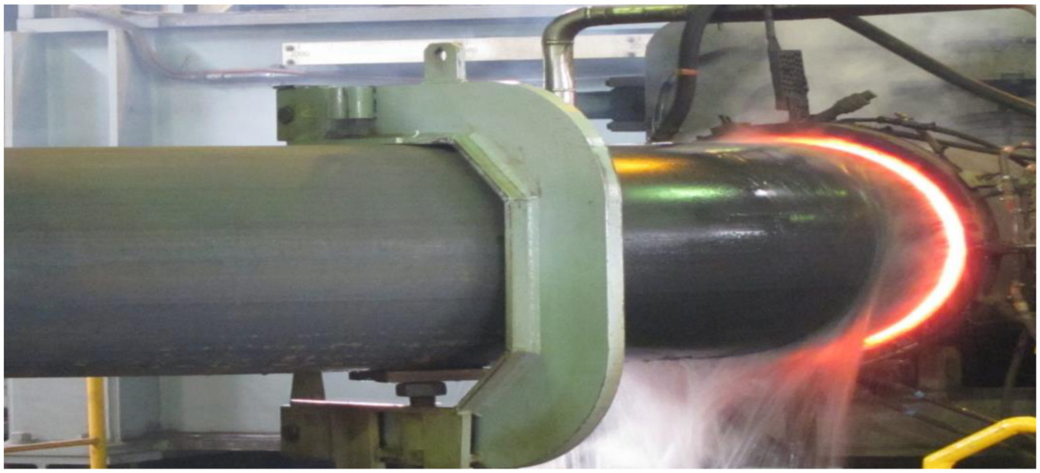

Figure 16—Induction Bending of CRA cladded pipe bends

Figure 17—Induction Bends ready for dispatch

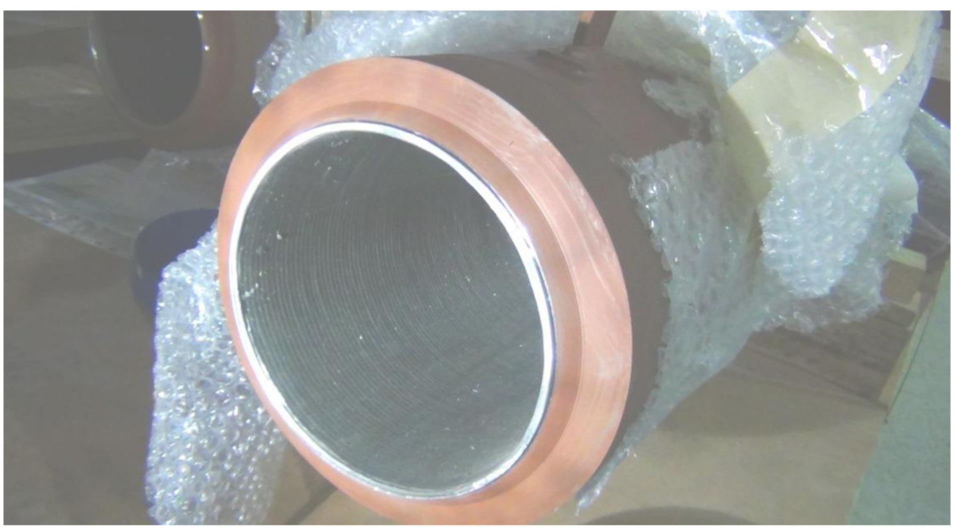

Figure 18—Spiral weld overlay in 16″ pipe header

Figure 19—FBE coated Girth Joint area marked within arrow. Girth weld is at center shown by white arrow

The Corrosion Resistivity Ranking for **OCTG alloys** as cold worked condition is shown below in decreasing order:

Alloy C-276 > Alloy050 > Alloy625 > AlloyG-3 > Alloy825 > Alloy028 > Alloy25-6Mo

In our project we selected down hole tubular material from NACE/ISO 15156 table A.12-A.14 for testing and evaluation:

Table 3—Material Types of Solid-Solution Nickel-based Alloys

Materials types	Cr Min %	Ni+Co mass fraction Min %	Mo mass fraction Min %	Mo +W mass fraction Min %	Metallurgical Condition
Type 4a	19	29.5	2.5		Solution-annealed or annealed
Type 4b	14.5	52	12		Solution-annealed or annealed
Type 4c	19.5	29.5	2.5		Solution-annealed or annealed and cold-worked
Type 4d	19	45	-	6	Solution-annealed or annealed and cold-worked
Type 4e	14.5	52	12	-	Solution-annealed or annealed and cold-worked

*NACE/ISI 15156-3 Page 21 Table A.12 was developed and included into the 2003 version of MR0175 and is based on industry experience that materials within a given classification *(material Type)* should have similar SCC resistance over a range of service temperatures, chloride concentrations and H2S partial pressures.

The data presented in the results of the laboratory SCC test program indicate the following:

a. NACE Type 4c and 4d tubular materials demonstrated acceptable SCC behavior in the simulated service environments
b. Type 4c – UNS N08028, N08825, SM 2535
   Type 4d – SM 2550.
   The Lab Test programs used three different types of tests (C-ring, bent beam and SSR) and multiple heating of the Type 4c materials (UNS N008028, N08825 and SM 2535).
c. No SCC was observed even at elevated chloride concentrations up to and including 160,000 ppm

in aqueous solution at 305 F (152° C) with up to 1,420 psia (96.6 bar) H2S and 550 psia (37.4 bar) CO2.

d. All NACE Type 4c tubular materials included in the lab evaluation programs exhibited similar SCC resistance as would be expected from their listing in NACE MR0175/ISO15156 Part 3 -Table A.12.

CONCLUSIONS AND RECOMMENDATIONS – PRODUCTION TUBING

Based on the testing results, the following conclusions were made:

8.1 The data developed in the laboratory SCC test program indicated that the NACE Type 4c and 4d tubular materials provided acceptable SCC behavior in the simulated test environments.

There was no evidence of SCC in either the autoclave C-ring tests or the more severe and conservative SSR tests for UNS N08028, N08825, SM 2535 and SM 2550. No SCC was observed even at chloride levels up to and including 160,000 ppm in aqueous solution at 305 F (152 C) with up to1,420 psia (96.6 bar) H2S and 550 psia (37.4 bar) CO_2 in the absence of elemental sulfur.

8.2. UNS N08028, N08825, SM 2535 exhibited similar SCC resistance as would be expected from their listing in NACE MR0175/ISO15156 Part 3 where they are all within the same category (Type 4c).

8.3. The data presented in the SCC test program indicated that the NACE Type 4c tubular materials (UNS N08028, N08825, SM 2535) actually showed greater resistance in terms of higher temperature and H2S partial pressure limits than the limits indicated in NACE MR0175/ISO15156 Table A.16 for sour conditions.

8.4 The analysis of the Pitting Resistance Equivalent Number (PREN) for UNS N08028, N08825, and SM 2535 indicated that N08028 and SM 2535 should have a greater resistance to localized corrosion than UNS N08825 based upon PRENs. However laboratory testing showed they had similar resistivity.

Alloy 825 was finally selected for production tubing based upon its higher nickel content (Fig13) and resistance against Chloride Stress Cracking (anticipated future high salinities of up to 220,000 ppm).

FABRICATION PROCEDURES

For fabrication of pipe and vessels the project had approved metallurgical bonded sandwiched rolled plate with interface of nickel barrier between CRA and the base carbon steel plate.

Another fabrication method using weld overlay was also recommended. Selection of welding consumable (filler material) chemistry is one of the key decisions for achieving quality welds with reference to effective depth, sensitization and iron dilution. A typical chemistry/analysis of filler material (with low C & Fe and High Ni) used for WO using GTAW process is given below:

C*	Mn	Si	P	S	Cr	Ni*	Mo	Cu	Fe*	Al	Nb+Ta	N
0.007	0.05	0.06	0.003	0.001	22.85	64.4	8.85	0.01	0.20	0.07	3.633	0.0223

*Key elements

For gas gathering lines, internally clad carbon steel pipe with corrosion resistant alloy (CRA) was preferred over solid pipe as the best technical and economic choice. Commercially available Carbon Steel X-65 grade pipe with internally clad either by Incoloy 825 (UNS N08825) or Inconel 625 (UNS N006625) were considered.

According to industrial experience it is not possible to roll cladded plate in all ranges of pipe diameter with respect to wall thickness.

The rule of thumb is total Wall Thickness (Base CS + CRA) < OD x 7% ~7.5%

Under this situation weld overlay was recommended on piping with higher Wall Thicknesses.

Further it would not be possible (inspection accessibility/limitation) to apply weld overlay for longer length exceeding 6-12 meters especially for small diameter piping. Therefore all piping below 6″ was selected as solid alloy.

Vessels were accepted to be manufactured using both cladded plates and weld overlay.

On welding joint where welding that can be performed form both sides were designed with V groove whereas the all field girth weld were designed using J as well as U configurations in order to approach the interlayer from one side.

HIGH TEMPERATURE EXTERNAL COATING FOR LINE PIPE

10.1 Pre-qualified Onshore New Construction Pipeline coating;

The approved material for the main coating is Fusion Bond Epoxy. FBE is a solid power epoxy for new construction and to be fabricated in a plant. FBE can be a single layer (1LFBE), or dual layers (2LFBE). The top layer FBE in 2LFBE is mainly used as the Abrasion Resistance Overlay (ARO). A laboratory test plan was initiated to evaluate various available coatings (FBE, 3L PE & PP). The test results have indicated that FBE (with high TG – Glass Transition Temperature) exhibits good performance over other conventional coatings (suitable for 120 °C).

10.2 Liquid Epoxy Phenol Novolac (Phenolic Epoxy or Epoxy Novolac) Coating System

Regular liquid epoxy coating has a low TG (around 100°C) with lower service temperature (<65°C). For higher service temperatures, epoxy phenol novolac coating has been used. Though it shows more brittle (<1% fracture strain) properties than that of FBE, it is recommended to be used as either rehabilitation coating applied in the field, or a spot repair for FBE coating.

10.3 A special auto coater was used for the application of 2L FBE on girth joints

REFERENCES

1. Corrosion Resistant OCTG and Matching Age Hardenable Bar Products for a Range of Sour Gas Service Conditions. *Special Metals Corporation*
2. NACE/ISO MR0175/15156
3. *SCC of Ni base alloy Weldment* by D. E. Jordon - Nickel Development Institute Publication.