

Design of Cathodic Protection System for Duplex Stainless-Steel Pipeline: Protection Criteria and Hydrogen Embrittlement Management

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ABSTRACT

Duplex stainless steel (DSS) is selected for wet gas pipeline to minimize OPEX and eliminate maintenance activities for internal corrosion control. DSS, however, requires a combination of coating and cathodic protection (CP) for external corrosion mitigation due to harsh external conditions (e.g., high operating temperature and high chloride level in the soil) in the Middle East. CP design and operation for DSS pipeline faces a major challenge as there is no applicable published industry standard or technical research for protection criteria for DSS.

Laboratory testing was performed with soil samples removed from the field to determine whether an applicable CP potential range exists that can provide the required protection and avoid hydrogen embrittlement at the same time. Overall findings of the lab tests in 2 representative soil samples indicated that a CP potential range exists. This range, which

is between -600 to -800 mV vs copper-copper/sulphate electrode (CSE), is consistent with predicted values from the thermodynamic stability of water. Simultaneously there was no reported hydrogen generation in that range

Field data confirmed DSS pipelines are operating within the protection range and mitigating hydrogen embrittlement (HE) risk accordingly.

Key words: Duplex Stainless Steel (DSS), Cathodic Protection (CP), Three-layer polypropylene (3LPP), Hydrogen Embrittlement (HE).

INTRODUCTION

A life cycle cost assessment led to the selection of DSS for field gas gathering network composing of more than 200 miles of pipelines. Buried portions are provided with external coating. Furthermore, due to high chloride content in the soils, the external corrosion threat was mitigated through the use of an external coating supplemented with CP.

As there was no industrial reference covering onshore DSS pipeline CP criteria, lab testing was conducted to establish the criteria and confirm if the risk of hydrogen embrittlement is managed appropriately. This is further evaluated with field data to confirm pipelines integrity.

EXPERIMENTAL PROCEDURE

Laboratory testing was performed to determine if CP is feasible to mitigate the corrosion threat for DSS pipelines. The primary objective was to determine if a CP potential range exists that can provide protection and avoid hydrogen embrittlement of DSS in field soils.

This study had three phases. In Phase 1, DSS test specimens were machined and the test conditions for Phase 2 and 3 were determined through soil sample analysis and extraction. In Phase 2, cyclic potentiodynamic polarization (CPP) tests were performed in aqueous fluids simulating 2 soils selected from Phase 1. The purpose of the CPP tests was to determine the most noble (positive) potential in which localized corrosion would not occur and the results should indicate if CP was feasible to mitigate external corrosion on the pipelines. Phase 3 testing was required to confirm the lower potential limit where measurable hydrogen generation occurs for DSS in field soil.

To start with, **Phase 1 testing:**

5 soil samples were collected from identified pipeline routes in the field at different layer depths (refer to Table 1 for sample identifications and descriptions). The 5 soils were provided for physical and chemical characterization.

Figures 1 to 5 are photographs of the five soils.



Figure 1: Soil sample 1

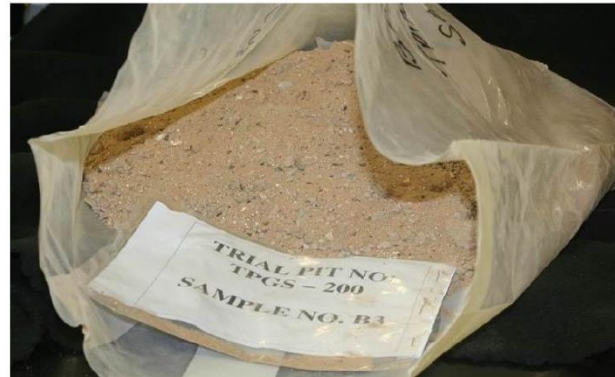


Figure 2: Soil sample 2

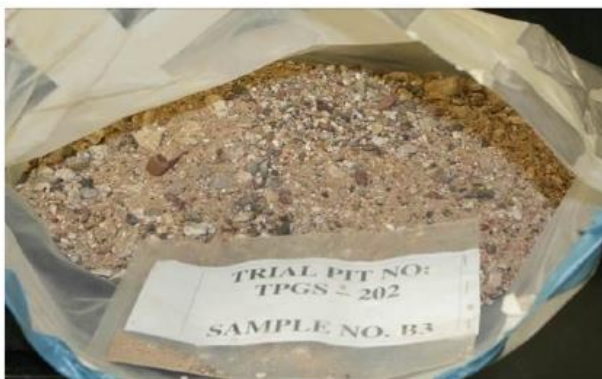


Figure 3: Soil sample 3



Figure 4: Soil sample 4



Figure 5: Soil sample 5

Table 1: Soil Sample identifications and descriptions

Sample No.	Depth (m/ft)	Quantity (kg/lbs)	Morphology description
1	0.5-0.8/1.64-2.62	13.2/29.1	Chunks
2	1.0-1.3/3.28-4.26	13.2/29.1	Coarse sand
3	1.2-1.7/3.93-5.57	13.7/30.2	Coarse sand

4	1.5-2.2/4.92-7.21	14.1/31.08	White Chunks
5	2.5-2.8/8.2-9.18	13.2/29.10	White Chunks

A closer examination of the soil photographs revealed that Soil Samples 1,4, and 5 were in the form of large chunks, while Soil Samples 2 and 3 consisted of coarse sand. Due to the nature of Soil Samples 1,4, and 5, those samples had to be pulverized into smaller pieces for testing. The physical and chemical properties of interest for the soil samples included a range of parameters listed in Table 2 and 3.

Table 2: Summary of cations and anions for soil samples

Sample No.	Soluble Cations (mg/L)				Soluble anions (mg/L)						
	Na ⁺	K ⁺	Ca ⁺	Mg ²⁺	NO ₂ ⁻	NO ₃ ⁻	Cl ⁻	SO ₄ ⁻	S ₂ ⁻	CO ₃ ²⁻	HCO ₃ ⁻
1	2480	102.5	3473	54	0.514	11.2	4490	9100	<0.025	0	73.9
2	1510	36.3	954.2	139.1	0.084	20.4	2640	1900	<0.026	0	106
3	335	<25.1	153.2	29.3	0.033	11.1	428	550	<0.025	0	122.8
4	4340	88.4	1002	173	0.184	22.5	851	2700	0.025	0	111.6
5	927	41.8	3295	0	0.165	6.69	1160	8300	0.030	0	98.4

Table 3: Soil samples chemicals properties

Sample No.	pH soil	Total Acidity mg CaCO ₃ /kg	Total alkalinity mg CaCO ₃ /kg	As received moisture content %	TDS (mg/L)
1	8.79	60.6	60.6	0.82	3900
2	8.51	51.1	86.9	1.82	2640
3	9.27	60.4	100.6	0.50	348
4	8.28	61.0	91.5	1.38	2260
5	7.8	80.6	80.6	0.63	2490

Table 3 summarizes the electrochemical testing performed on the 5 soils and the results of the testing will be discussed in more details in the relevant section.

The purpose of soil analyses (Phase 1 test) was to come up with representative soil samples that would be utilized further for the Phase 2 and 3 testing.

Phase 2 consists of aqueous CPP tests, soil CPP tests, and multi-scan CPP tests.

Aqueous CPP test

As referred to in Phase 1, the scope of Phase 2 consisted of CPP tests performed by the laboratory according to ASTM G61. The testing was performed in 2 selected soils and in aqueous fluids that simulated the 2 soil conditions. The metallic coupons used for the testing were removed from a section of 32.385 cm diameter, 0.10 cm thick, and 213.36 cm long DSS pipe that was provided by the Company.

The testing was performed on plate coupons (8.255 cm * 8.255 cm) that were exposed to aerated and deaerated test solutions of Soil Samples 1 and 2.

The test method was an accelerated corrosion test in which it electrochemically forces the passivity of the test specimen to breakdown (undergo pitting, crevice corrosion, or “trans passive” dissolution) and then allows for repassivation to proceed as the stimulus gradually is removed. The product of the test is a CPP curve which is a product of the applied stimulus (electrode potential) against the specimen’s response (current). A CPP curve is normally presented as a plot of the electrode potential vs current density on a semi-logarithmic scale.

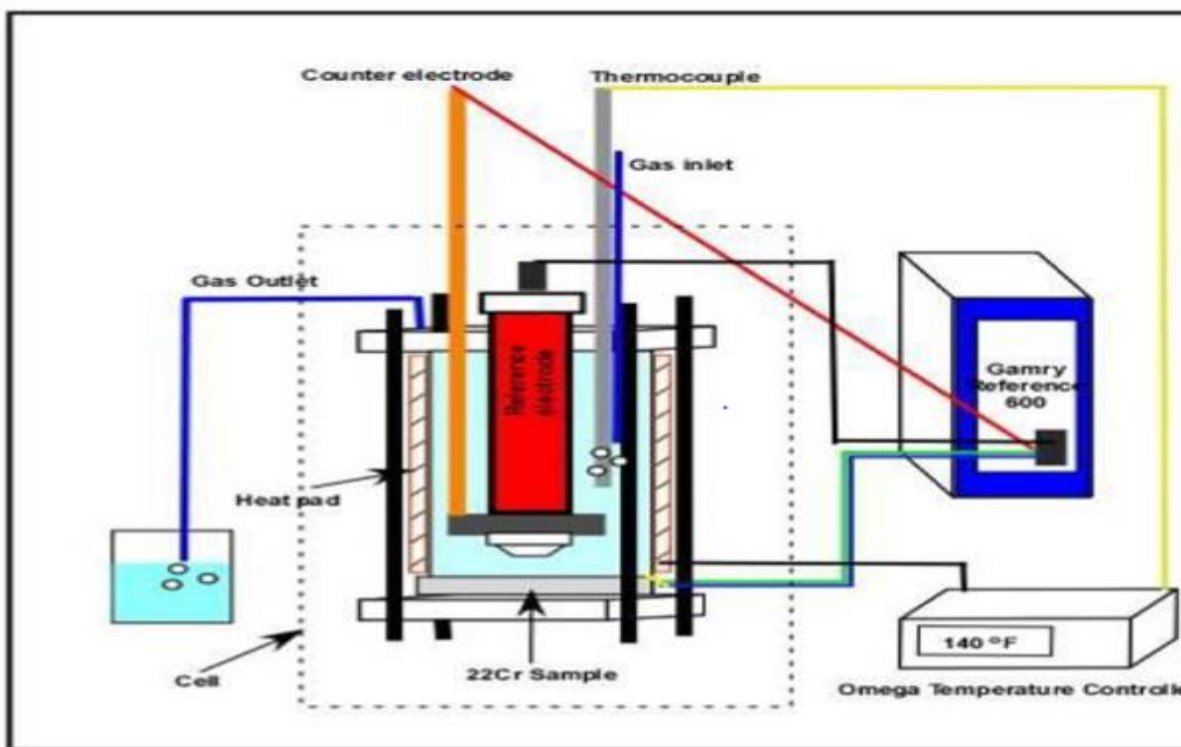
Potentials determined during the CPP test include the open circuit potential (E_{COR}), the pitting breakdown potential (E_{PIT}), and the protection potential (E_{PROT}). The open circuit potential is the potential of a specimen in an electrolyte under freely corroding conditions. The pitting potential is the potential at which the passive film starts to breakdown on the forward positive scan and pits form. The protection potential is the potential at which the passive film recovers on the reverse negative scan.

E_{PROT} represents the positive limit of the CP potential range. In practice, the CP potential used to protect a pipeline must be more negative than E_{PROT} so that pitting is prevented. The negative limit of the CP potential range is related to the hydrogen evolution potential E_{HE} . Potentials more negative than E_{HE} can promote hydrogen embrittlement on susceptible metals.

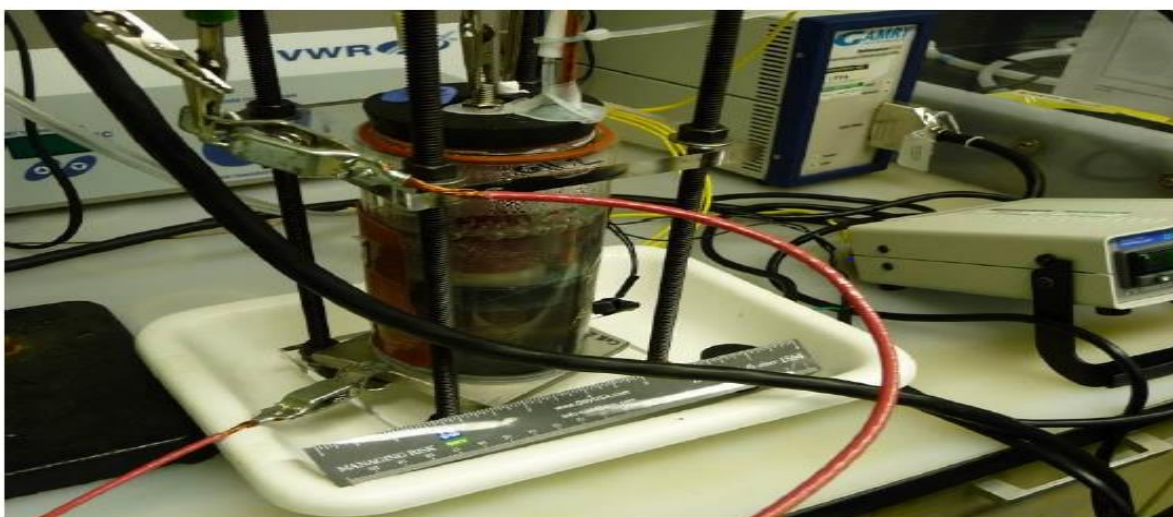
Test Procedure: no machining was performed on the metallic samples to ensure proper representation to field conditions.

Figure 6 is a schematic showing the test setup for the aqueous CPP tests; the specimen is oriented at the bottom of test cell.

300 L aqueous sample was introduced, then the cell was properly sealed, and the system was allowed to stabilize. The aqueous solution used was based on anions and cations measured on Soil Samples 1 & 2 (Refer to Table 2). The pH values of the aqueous solutions were adjusted with NaOH to match the pH values of the soils.



A



B

Figure 6: Test cell for CPP aqueous tests. A) Schematic and B) Photograph

Figure 7 shows solution 1 and solution 2. As it can be seen solution 1 was opaque with white particles associated with the solution, on the other hand, solution 2 is clearer with minimum particles.

The next day, the cell was brought up to a test temperature of 60 C (max operating pipeline temperature) with T monitoring. During that time, cells were aerated or deaerated with N₂ for an hour, depending on test conditions; refer to Table 4.

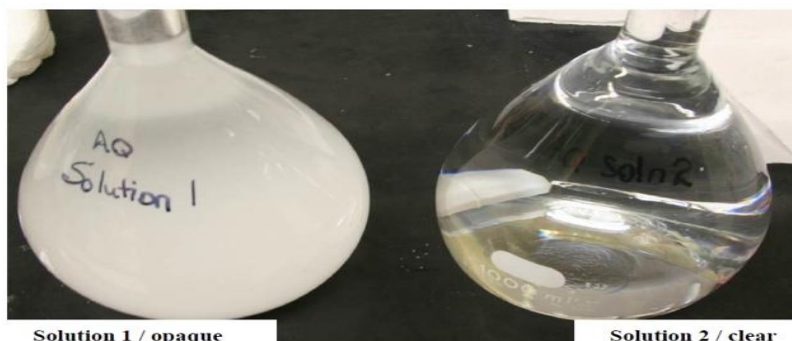


Figure 7: Solution 1 & 2

Table 4: Aqueous CPP test matrix

Test Environment	Oxygen content	No. of test specimens
Simulated aqueous solution from Soil 1	Aerated	3
	Deaerated	3
Simulated aqueous solution from Soil 2	Aerated	3
	Deaerated	3

Chemical composition of aqueous solution representing soil 1 & 2 can be found in Table 5 and 6 respectively.

Table 5: Chemical composition of solution 1 used to simulate soil 1

Chemical Name	Chemical Formula	Composition per 1L of Solution		
		mols	grams	ppm
Water	H ₂ O	55.17	993.0240	–
Sodium Nitrite	NaNO ₂	1.10×10^{-05}	0.0008	0.8
Sodium Nitrate	NaNO ₃	1.81×10^{-04}	0.0154	15.4
Sodium Bicarbonate	NaHCO ₃	1.21×10^{-03}	0.1017	101.8
Sodium Sulfate Anhydrous	Na ₂ SO ₄	6.79×10^{-02}	9.6445	9655.5
Magnesium Sulfate, Anhydrous	MgSO ₄	2.22×10^{-03}	0.2672	267.5
Potassium Sulfate	K ₂ SO ₄	1.31×10^{-03}	0.2283	228.6
Calcium Sulfate, Anhydrous	CaSO ₄	2.33×10^{-02}	3.1721	3175.7
Calcium Chloride Dihydrate	CaCl ₂ ·2H ₂ O	6.33×10^{-02}	9.3064	9317