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SOUR SERVICE CORROSION FATIGUE TESTING OF FLOWLINE WELDS

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ABSTRACT

An examination of the corrosion-fatigue behavior of production quality welds in X65-type pipes was performed. Due to the low cycle operational nature of the production flowline system, the fatigue test frequency was substantially lower (0.01Hz vs. 0.33Hz) than typically utilized during corrosion-fatigue testing. Also the tests were performed at higher stress ranges than previous sour service fatigue tests, which to date have targeted riser fatigue loading regimes. Stress-life (S-N) samples were removed from segments of pipe with outside diameters of 10.75 inch (wall thickness of 1.30 inch) and 9.625 inch (wall thickness of 1.26 inch) containing fully inspected, production-quality circumferential welds. Environments examined included laboratory air conditions as well as deoxygenated brine supplemented by a gas mix of H_2S and N_2. For all environmental tests performed, the dissolved oxygen levels were maintained at less than 10 ppb during all testing. The measured fatigue life decrease in the curved pipe segments was in the range of 8-110 times due to the combined effect of the material and fluid property variables examined. The results of this work clearly illustrated the impact of sour-service corrosion fatigue, in welded carbon steel pipes, to the multitude of variables involved. Nevertheless, the foregoing experimental work clearly demonstrated the importance of performing environmental relevant testing when considering material and process selection for offshore applications.

Keywords: fatigue, corrosion, flowline, hydrogen sulfide

NOMENCLATURE

API	American Petroleum Institute
CO_2	Carbon dioxide
DOE	Department of Energy
H_2S	Hydrogen sulfide
O_2	Oxygen
OD	Outside diameter
ppb	Parts per billion
S-N	Stress life
UHP N_2	ultra high purity nitrogen
$\Delta\sigma$	Stress range (ksi)

INTRODUCTION

Standard API 5L X-65 carbon steel pipe material is to be utilized for a subsea production flowline system for an on-going project within the Gulf of Mexico. The project-produced fluids are corrosive with CO_2 and produced water chemistry being the primary corrosive driving forces. The oil field will utilize water injection for reservoir pressure maintenance and as a consequence souring of the field in the later stages of life could occur.

Corrosion decreases the fatigue strength of the risers by lowering the S-N curve and potentially eliminating the endurance limit of the carbon steel. The magnitude of the reduction in fatigue strength is proportional to the severity of the environment. The focus of the work presented herein is to understand the impact of the combined effect of mechanical loading and corrosion on the fatigue performance of candidate steel welds, so as to calculate the fatigue “knock-down” factor of sour/brine environments compared to that of laboratory air. Due to the low cycle operational nature of the production flowline system, the fatigue testing concentrated on the high stress region of the fatigue curve, which corresponds to lateral buckling of flowlines subjected to thermal expansion during operational start-up and shut-down cycles. Testing was performed under a much lower frequency of 0.01 Hz compared to the more typical environmental test frequency of 0.33 Hz. Testing at much lower frequencies than 0.01 Hz is possible, however, both budget and schedule limit how slow the test can realistically be performed at.

MATERIAL AND EXPERIMENTAL METHODS

Material and Specimens

The welded pipe materials used for S-N fatigue testing were nominally API 5L X65 carbon steels procured from Tenaris. The pipe sizes were nominally 10.75 inch outside diameter (wall thickness of 1.300 inch, Phase I testing) and 9.625 inch outside diameter (wall thickness of 1.266 inch, Phase II-A testing).

A circumferential weld was axially positioned in the center of the pipe. This weld was fabricated from one-side (the outside diameter) in the 2G position using automatic welding equipment. Machining was performed on the inside diameter to improve alignment of the pipe ends before undertaking welding. Prior to delivery of the welded pipe samples to the testing laboratory, ultrasonic inspection of the girth welds was performed. Areas of suspected weld defects were marked on the pipe samples so that these areas could be avoided during extraction of the fatigue specimens. S-N test specimens were excised from the pipe blanks ensuring that the gage area of the specimen was not located in any of the areas with indications of any potential defects. The S-N test specimen is a typical reduced section “dog-bone” with the design shown in Figure 1.

Due to the specimens being extracted from pipe material and thus having a curved surface, special brass grip inserts were manufactured so as to conform to the pipe and also provide a flat grip area for clamping. A photograph of the concave and convex brass insert shown with a test specimen is provided in Figure 2. The weld cap of each S-N specimen was ground to ensure no preferential crack initiation on the OD of the pipe so as to avoid this non-representative failure mode.

Test Environment

Testing was performed in both laboratory air and a sour brine environment. The temperature and relative humidity for the fatigue tests in both conditions were between 70-75°F and 50-60%, respectively.

The corrosive environment used during testing consisted of a liquid and gaseous de-aerated environment. The gas mixture consisted of 6.8% H_2S, balance UHP N_2, by volume. The sour environment contained chloride salts, a mild acid, and the hydrogen sulfide/nitrogen gas mixture. This solution was a modified NACE TM0177, Solution B, with the initial pH of the test solution between 3.4 – 3.6, prior to the addition of the test gas. De-aeration of the test solution was performed prior to testing so as to produce a test solution with O_2 concentration less than 10 parts per billion (ppb). Introduction of the test gas mixture into the test chamber was undertaken after de-aerating the test solution, with the primary chamber charged at 100ml/min of test gas for four hours. The flowrate was then reduced to 20ml/min for a further 20 hours. Mechanical load cycling was then initiated and the test gas flow rate maintained at 20ml/min for the duration of the test.

Environmental Control System

Due to the harmful nature of the primary test gas (H_2S), and the corrosive test solution, the use of specially design environmental chambers is required. Also a gas delivery system is required to ensure delivery and extraction of the test gas mixture within the testing laboratory without undue risk to lab personnel. Similarly a robust, safety alarm system is required to provide automatic shutdown of the environmental system in the event of a test gas leak.

The environment enclosure for fatigue (S-N) testing consisted of a triple containment chamber design, comprising of a primary chamber, a shroud, and an exhaust enclosure. The inner most chamber, termed the primary chamber, contained the fatigue test specimen and the test environment (gas and solution). The primary chamber was constructed of a stainless steel body with elastomeric ends, which are sealed to the specimen with a non-corrosive sealant prior to testing. A photograph of the primary chamber is shown in Figure 3.

The second chamber, termed a shroud, is constructed of two aluminum flanges that are attached, and O-ring sealed, to the upper and lower specimen grips. A thin transparent polymeric tube is then connected and also O-ring sealed to each of the flange ends to provide a flexible gas chamber. Details of the shroud enclosure are shown in Figure 4. The shroud serves as a barrier to assist in the capturing of any sour gas that might escape from the primary chamber should the primary chamber seal system fail during testing. Also this chamber is filled with flowing N_2 gas to provide a further barrier to stop ingress of O_2 into the primary chamber during testing. The shroud also houses an H_2S detector, which is connected to an alarm/shutdown panel. The alarm/shutdown panel is used to stop test gas from flowing into the primary chamber in the event of a primary chamber leak and provides a visual and audible indication of an abnormal condition to test operators during normal business hours and institute emergency contact personnel after hours and on weekends/holidays.

The third chamber consisted of an acrylic and aluminum enclosure that sits on the cross-head of the test machine. This enclosure is attached to a snorkel-type ventilation and roof-mounted duct system for continuous evacuation of the enclosure space during sour gas testing operations. Also this enclosure is used to mount the hardware associated with the test gas and test solution delivery flowmeters and valves.

To ensure a continuous supply of test gas mixture to the environmental chambers, an external gas delivery system is required. This was positioned outside of the test laboratory, for safety reasons, with individual gas delivery and extraction pipelines entering the building through the external walls. The safety related equipment, employed to prevent hazardous conditions from the unintentional release of H_2S, consisted of H_2S monitoring and alarm systems, and emergency flow shutoff solenoid valves.

Fatigue test conditions

The fatigue testing was performed in the Solid and Fracture Mechanics Laboratory at Southwest Research Institute using three closed-loop, servo-hydraulic test frames, with previously described environmental chambers required for the sour brine tests. Photographs of the test set-up for both the lab air and environmental tests are shown in Figure 5. A pictorial description of the installation process for setting the specimen in the primary chamber is provided in Figure 6.

Although the testing was performed on what can best be termed non-standard specimens, the testing was conducted loosely in accordance with the relevant ASTM E466 [1] standard. Testing frequency for the lab air tests was in the range of 2-3Hz, with test frequency dependant primarily on the test load range. However, for all environmental tests the frequency was fixed at 0.01Hz. All specimens were tested until failure (two-pieces), at a maximum stress of 57.8 ksi. The applied stress levels were calculated based on the theoretical area of the curved test specimen in the gage length.

TEST RESULTS AND DISCUSSION

A summary of the fatigue tests performed in lab air and the modified NACE Solution B sour brine environment is given in Table 1. Data is presented in terms of environment, mean stress, stress range, and cycles to failure. The first phase of fatigue testing (Phase I), as shown in Table 1, involved a total of twelve specimens, six lab air tests and six sour/brine environmental tests. However, during the course of the project one test was inadvertently tested at the higher frequency of 0.33 Hz. The second phase of testing (Phase II-A) involved a total of nine specimens, three lab air tests, as shown in Table 1, and six sour/brine environmental tests (data not shown).

A summary graph for all lab air fatigue tests and for the modified NACE Solution B test environment is shown in Figure 7. Also shown in Figure 7 are the design curves derived from DOE [2] and API [3] documentation regarding design of offshore structure. It should be noted that the baseline DOE and API curves are shown in Figure 7 with no thickness adjustments made for the data. However, it should be stated that comparing the data obtained herein to the design curve is not the intent of the data shown in Figure 7. The focus of the work is to understand the corrosion fatigue performance of the welded pipes, so as to calculate the fatigue “knock-down” factor of sour/brine environments compared to that of laboratory air. The pipes tested during this program were carefully screened to be free from any weld defects. The design curves, on the other hand, encompass a level of conservatism suitable for a design approach. It should also be remembered that real structure may tend to have a shorter life than the S-N data since the S-N specimens sample only a small area of the weld, whereas in a full structure the fatigue process tends to find the worst case defect given the larger inherent weld in the structure.

As expected, there is a large effect on the fatigue life of the welded specimens when tested in the sour brine solution. Although the testing performed in this program was limited in nature, with only one to two specimens tested per stress range, the degree of scatter in fatigue results for each particular stress range and environment was found to be small. The results for the flowline Phase I testing indicate a large decrease, of between 8-110x, in fatigue properties when tested under sour brine environmental conditions (H_2S/N_2) compared to laboratory air.

As previously stated, one environmental test was inadvertently undertaken at a higher test frequency of 0.33 Hz, with the data point also shown in Figure 7. It is interesting to find that the result for this higher frequency test was an increase in life of approximately 3.5x when compared to the environmental tests performed at the lower frequency of 0.01 Hz. Although only one test was performed at this higher frequency, the level of repeatability within the other stress levels tested suggests that this difference may not be experimental scatter. Due to project constraints the effect of test frequency was not further examined during this phase of the test program. However, on-going testing is being performed to further elucidate the apparent frequency effect observed in this testing.

The work of Buitrago *et al* [4] studied the frequency effect on sour service fatigue crack growth (FCG) rates of a girth welded X-80 pipe material. The sour environment was very similar to the Phase I sour environment used in this program (modified NACE TM0177, Solution B). However, the gas mix consisted of 2.4% H_2S, balance UHP N_2. In general Buitrago *et al* [4] found the FCG rate trend was that da/dN (crack length increment as a function of cycles) increases with decreasing frequency. Buitrago *et al* measured actual increases in FCG rates of between 2-5x when changing frequencies from 0.33 Hz to 0.01 Hz.

As a further comparison of the S-N fatigue data generated during this program, the sour brine fatigue test results published by Buitrago and Weir [5] are shown together in Figure 8. Again this sour environment was the same used in the work of Buitrago *et al* (modified NACE TM0177, Solution B, 2.4% H_2S, balance UHP N_2). It is clear from Figure 8 that the testing carried out during this program was at a significantly higher stress range compared to that undertaken in previous studies. The sour environmental results from Buitrago and Weir [5] just exceed the X'/20 curve, which is similar to the sour environmental results from this program, performed under the same brine solution and a similar sour gas mixture.

Photographs of typical fracture surfaces for the lab air and sour brine environmental tests are shown in Figure 9. It is clear from the fracture surface macrographs that multiple site crack nucleation occurred along the weld root for both the lab air and environmental tests. For all specimen fracture surfaces there appeared to be no crack nucleation at the weld crown.

CONCLUDING REMARKS

The testing presented herein was successful in providing a measurement of the detrimental effect of a sour service environment on the candidate steel pipe material. Excellent test repeatability within each stress level and environment was obtained during this program. The measured fatigue life decrease in the curved pipe segments for all tests performed during this program was in the range of 8-110 times due to the combined effect of the material and fluid property variables examined.

Furthermore the experimental work presented herein clearly demonstrates the importance of performing environmental relevant fatigue testing when considering material and process selection for offshore applications that may contain a sour environment. Changes in environmental conditions as well as testing variables and manufacturing techniques can have a large impact on the subsequent corrosion fatigue behavior of the selected material and produced welds.

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Table 1
Fatigue (S-N) test results Phase I (H_2S/N_2, pH = 3.4 - 3.6, f = 0.01 Hz)

Environment	Temp. (ºF)	Max. Stress, σ_{max} (ksi)	Stress Range, $\Delta\sigma$ (ksi)	Load Ratio	Cycles, N	Comments
Lab Air	70-75	57.8	52.02	0.10	96,230	Weld failure
					79,049	Weld failure
					150,092	Base metal failure (Phase II-A)
		57.8	42.19	0.27	195,276	Weld failure
					166,390	Weld failure
					287,238	Grip/weld failure (Phase II-A)
		57.8	32.37	0.44	343,835	Weld failure
					445,648	Weld failure
					667,105	Weld failure (Phase II-A)
H_2S/N_2 (pH = 3.4 - 3.6)	70-75	57.8	52.02	0.10	8,460	Weld failure (0.33Hz)
					2,560	Weld failure
					2,248	Weld failure
		57.8	42.19	0.27	3,426	Weld failure
		57.8	32.37	0.44	4,212	Weld failure
					4,035	Weld failure

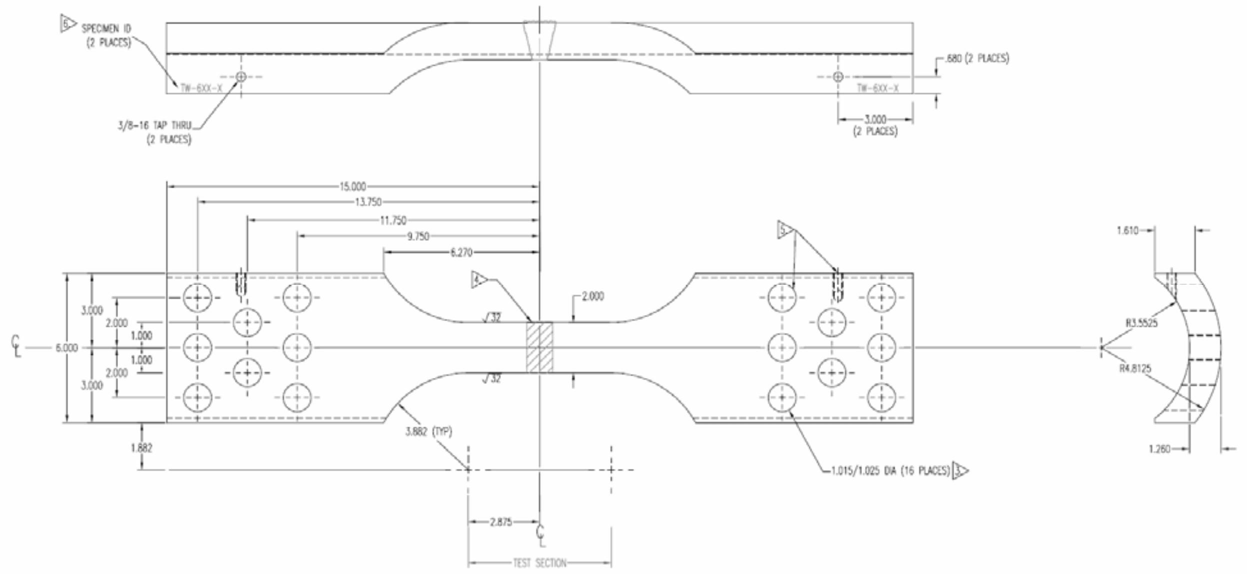


Figure 1
S-N test specimen used during all evaluations. Note that overall specimen length is 30 inch.

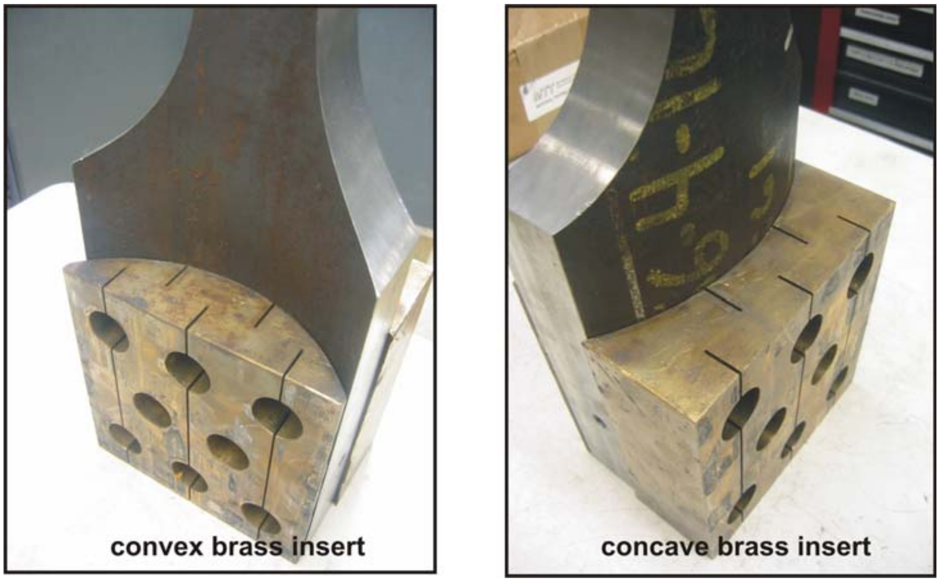


Figure 2
Photograph of convex and concave brass inserts used in the grips to apply a uniform clamping force across the pipe specimen.

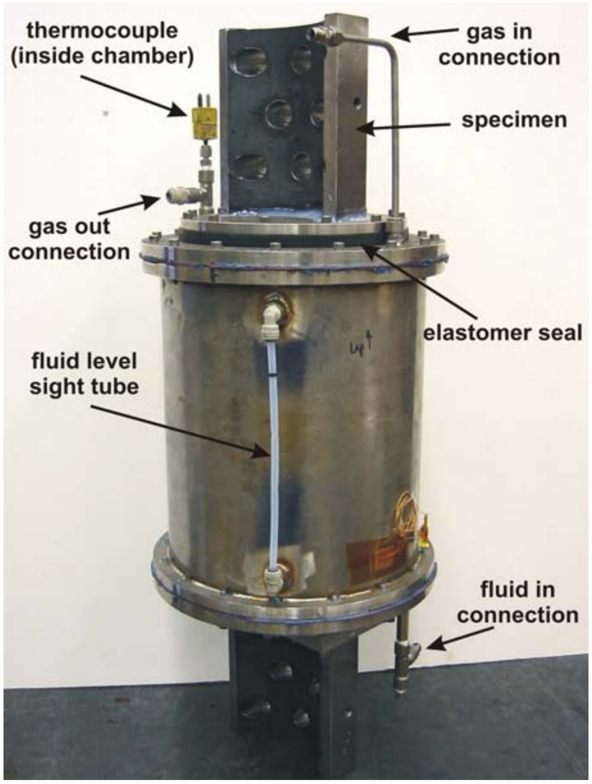


Figure 3
Photograph of the environmental primary chamber.

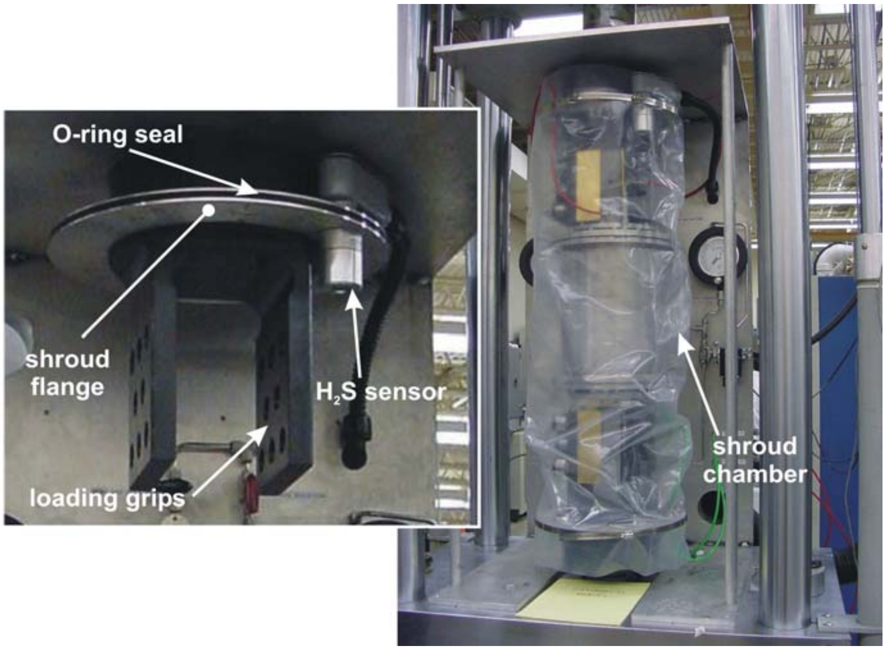
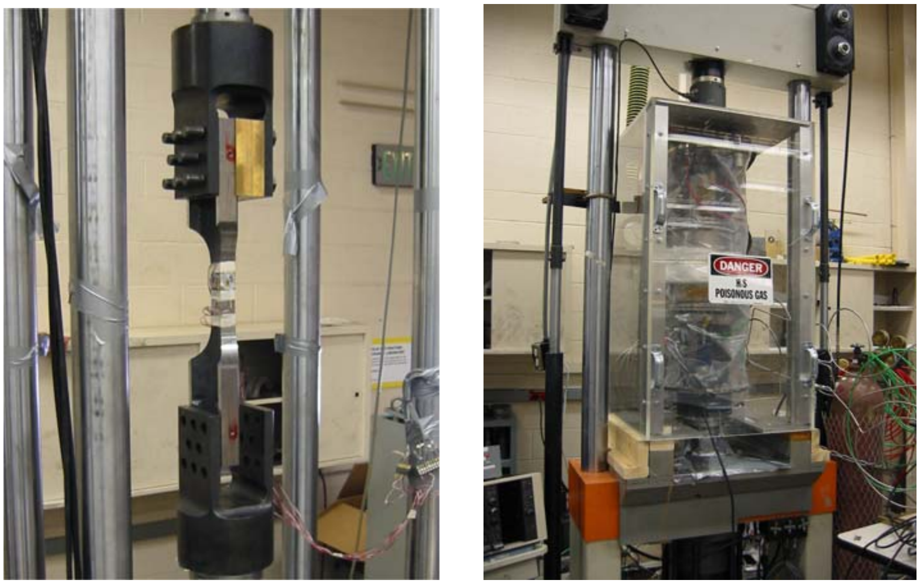


Figure 4
Photograph of the shroud enclosure containing the H_2S detector and flowing N_2 purge gas.



(a) (b)

Figure 5
Photographs of the test setup for (a) lab air testing, and (b) sour brine environmental testing.

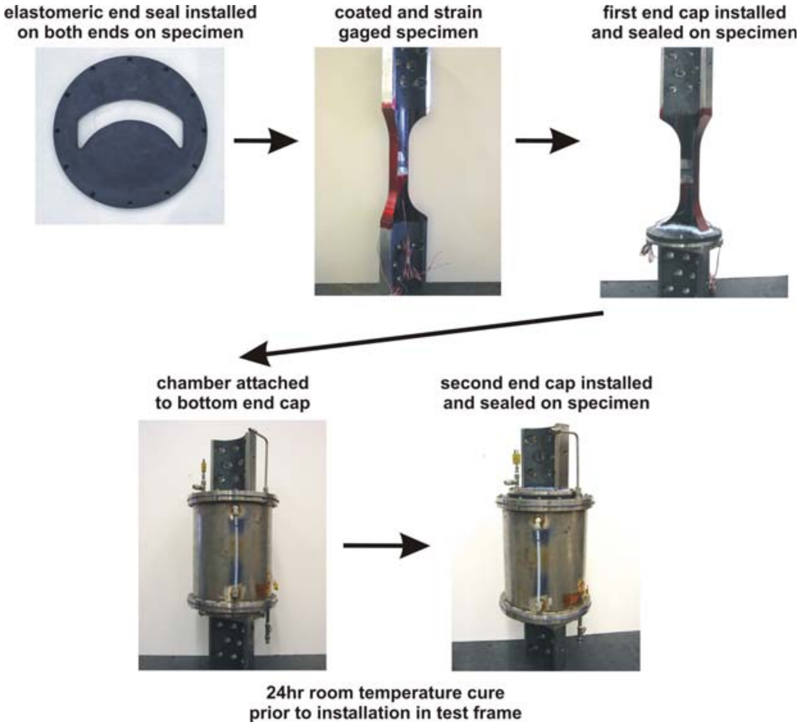


Figure 6
Pictorial description of the process required to install the specimens in the primary environmental chamber.

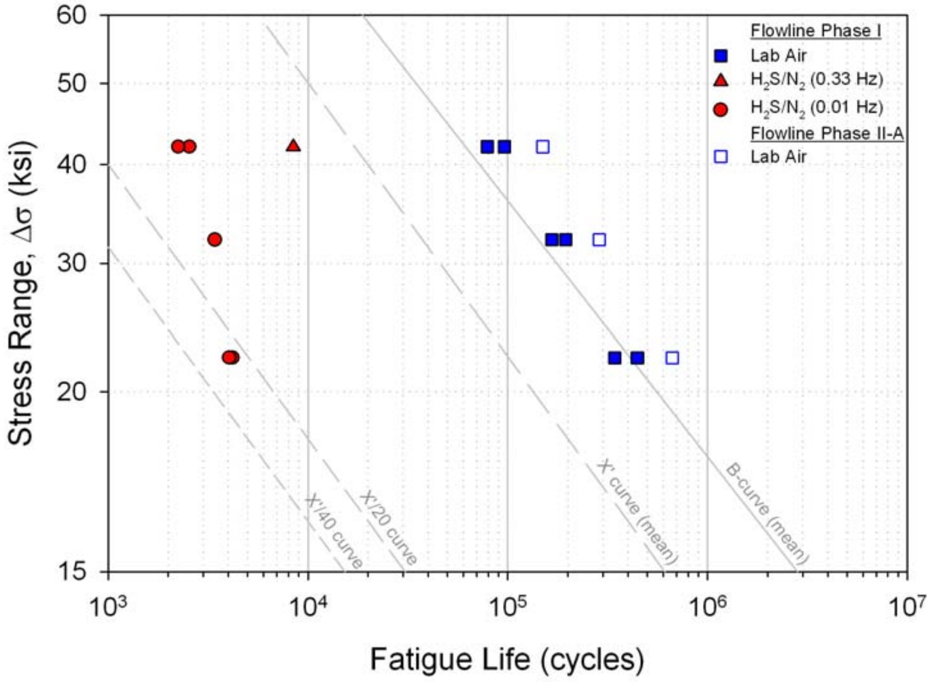


Figure 7
S-N fatigue data for both lab air and sour brine environments.

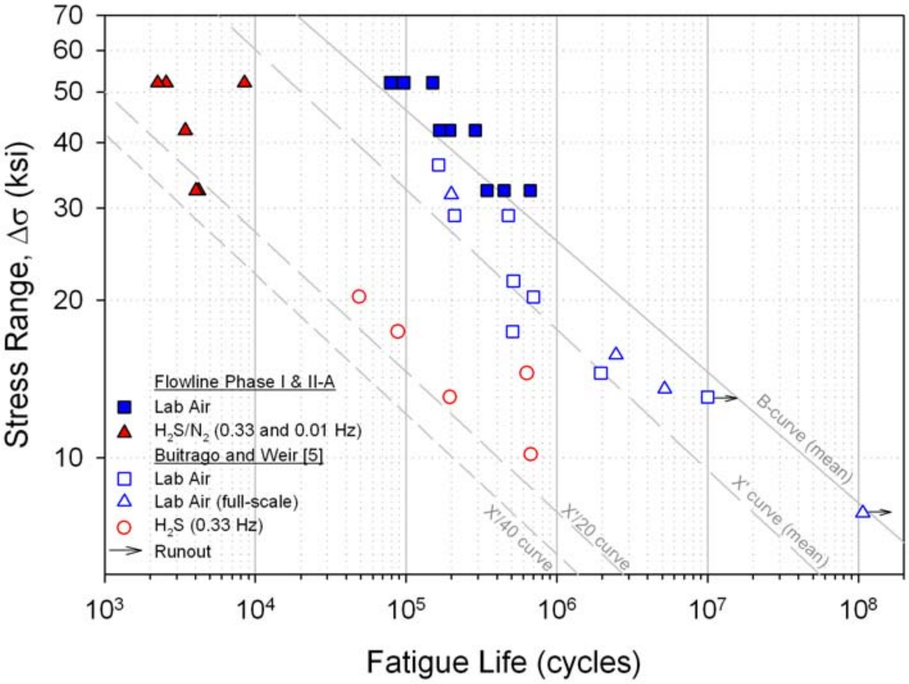


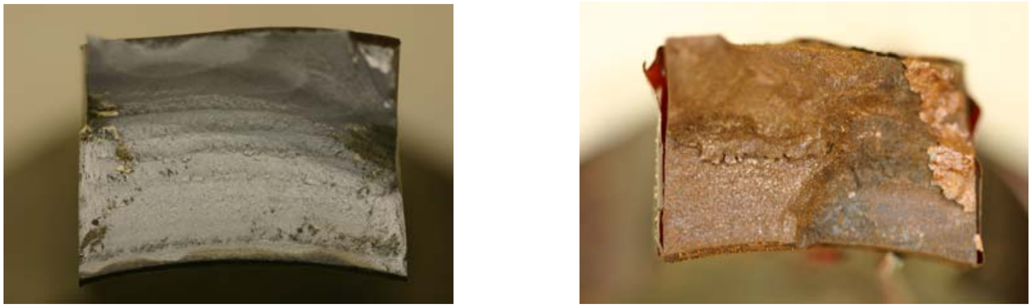
Figure 8

Comparison of S-N fatigue data for the current project and previously published sour service test results [5].

Lab Air

Sour Service

(a)



Lab Air

Sour Service

(b)

Figure 9

Laboratory air and sour service specimen fracture surfaces. (a) high stress range, (b) low stress range.