

Review of Techniques to Evaluate SCC Susceptibility of Carbon Steels Used in Construction of Hanford Nuclear Reservation Waste Tanks

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ABSTRACT

Stress corrosion cracking (SCC) is a documented threat to the integrity of carbon steel radioactive waste storage tanks at the Hanford Nuclear Reservation site. Presently, the slow strain rate (SSR) test is the workhorse test technique used for assessing SCC of carbon steels in nuclear waste simulants. The main advantages of the standard SSR technique are that it is relatively rapid, sensitive in detecting SCC, and relatively inexpensive. SSR test results are typically classified as “SCC” or “No SCC”, depending on the ductility parameters from the test and observations of crack features. Occasionally, tests are not easily classified, which results in a third category, “Inconclusive”. Inconclusive results are usually related to variations in ductility parameters compared to the control specimen, or the presence of atypical fracture facets or secondary features on the gage section. Regardless of the cause of the inconclusive result, these tests create uncertainty in assessing susceptibility to SCC. This paper describes the results of a preliminary study undertaken to develop an SCC testing protocol for evaluating inconclusive results. Three alternatives to the standard SSR technique, slower SSR (reduced extension rate), Ripple SSR, and notched SSR, were evaluated. Additionally, SCC evaluations from a crack growth technique using a compact tension specimen were compared to the results of the alternative SSR methods. The study showed that, regardless of the technique evaluated, there will be inconclusive results due to subjective aspects of the post-test evaluation. However, there appears to be a critical potential below which SCC is absent. The value of this potential varies with the test method.

Key words: Stress corrosion cracking, carbon steel, slow strain rate, crack growth rate, alternative SSR techniques, nuclear waste.

INTRODUCTION

The Hanford Nuclear Reservation contains radioactive and chemically hazardous wastes arising mostly from weapons production, beginning with World War II and continuing through the Cold War. The wastes are stored in 177 carbon steel underground storage tanks, of which 149 are single-shell tanks (SSTs) and the remaining are double-shell tanks (DSTs). The U.S. Department of Energy, Office of River Protection is responsible for retrieving the tank wastes, treating them in order to encapsulate them in glass logs, and then permanently closing the tanks and associated facilities. The most recent revision of the River Protection Project System Plan proposes, models (computer simulations), and reviews multiple scenarios for transferring the wastes from the SSTs into the DSTs, vitrifying the waste and closing the tanks.¹ The simulated scenarios have timelines between 30 and 50 years.¹ Such a timeline places a great emphasis on understanding and maintaining the integrity of both types of tanks.

The waste compositions in the storage tanks are grouped according to their main constituents, such as nitrite/nitrate-based and carbonate-based chemistries. Most of the wastes are highly alkaline in nature, typically with pH values between 12 and 14. Under alkaline conditions, carbon steels will tend to be passive and undergo relatively slow, uniform corrosion. However, carbon steels can be susceptible to localized corrosion (e.g., pitting) and stress corrosion cracking (SCC) in the presence of certain aggressive constituents, such as chloride and nitrate, even in these passive conditions². The original SSTs are thought to have experienced SCC failures because of high-residual stresses, high operating temperatures (near boiling in some cases), and the presence of high concentrations of nitrate in the waste.^{3,4} Research at Hanford and Savannah River Laboratories demonstrated that cracking could be prevented by maintaining the waste at a high pH (>12), with nitrite additions, and stress relieving the welds in the tanks. Accordingly, fabrication of the DSTs incorporated a post weld heat treatment step and chemistry controls were instituted during operation to maintain the pH of the waste above 12.

The extended waste transfer timeline requires on-going assessment of susceptibility of steels to SCC in simulated tank wastes. The slow strain rate (SSR) test technique is the workhorse method used for assessing SCC. The main advantages of the SSR test are that it is relatively rapid and inexpensive. The outcomes from the SSR test are typically classified as “SCC” or “No SCC”, based on ductility parameters and post-test observations of the fracture and secondary cracks. Occasionally, tests are not easily classified as “SCC” or “No SCC,” which results in a third category, “Inconclusive.” Inconclusive results are usually related to variations in ductility parameters compared to the control specimen, or the presence of atypical fracture facets or secondary features on the gage section. Regardless of the cause of the inconclusive result, these tests create uncertainty in assessing the susceptibility to SCC.

The focus of this work was to evaluate alternative SCC test techniques that could be used when the standard SSR technique produces a result categorized as “Inconclusive.” Several follow-on test options were assessed, including SSR testing at a slower strain rate, ripple/cyclic SSR testing, notched SSR testing, and crack-growth rate (CGR) testing. This paper presents the advantages and limitations of each technique in the context of SCC, the procedures used for each technique, and the testing results for all of the alternative techniques compared to the standard SSR technique.

Background on Alternative SCC Techniques

Prior to discussing the advantages and limitations of the alternative test methods, it is worth briefly discussing parameters that are associated with SCC and how the test method can affect those parameters. The chosen test method directly influences the stress state, but also indirectly influences the interaction of the environment with the material. Figure 1 is a schematic illustration of the crack-tip system.

The crack tip system can be thought of as the combined interaction of the crack tip chemistry, crack tip strain and strain rate with the material. The different follow-on techniques impact the crack tip system by varying the crack tip chemistry (primarily through bulk environment chemistry, applied or corrosion potential, and duration of test) and the strain and strain rate (primarily through specimen geometry and loading parameters).

Table 1 is a summary of the benefits, deficiencies, and effects on the crack tip system of the test techniques under consideration for follow-on testing after an “inconclusive” SSR result. The standard SSR test technique is the workhorse method used for good reason. It is easy, fast, relatively inexpensive, and generally provides conservative results. However, recent tests have produced some “Inconclusive” results. The “Slow” SSR method offers most of the advantages of the standard SSR technique, but the slower strain rate allows more time for an environmental affect. Notched SSR tests are generally more severe than the standard SSR technique. Additionally, the notch creates a different strain and strain rate at the crack tip during the test. The Ripple SSR technique introduces a cyclic loading component and allows for a longer test time, but it is not clear if this technique is applicable to the environments of interest. The effect on the crack tip system is to change the strain rate, allow additional time for corrosion mechanisms, and promote breakdown of passive films.

The CGR technique is viewed as the most realistic methodology; however, it is not practical to perform CGR testing for every inconclusive result due to the expense and test duration. As such, the test program focused on the notched, ripple, and slower SSR techniques. The procedures for all the SSR techniques assessed are discussed in the following sections.

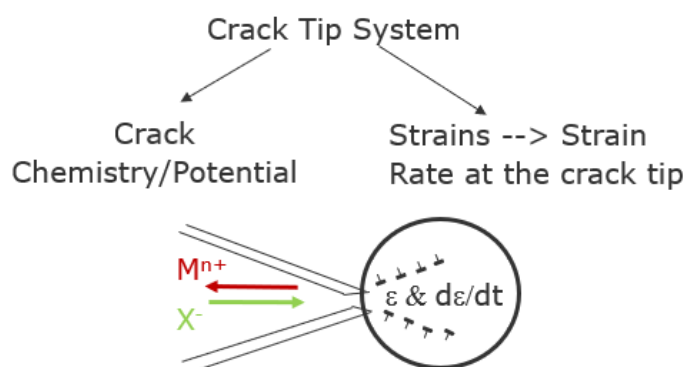


Figure 1: Schematic illustrating the crack tip system.

Table 1. Summary of the benefits and deficiencies of various techniques considered for follow-on testing after an “inconclusive” result.

Technique	Benefits	Deficiencies	Effect on Crack Tip System
Standard/Repeat SSR	• Easy, fast, relatively inexpensive	• Does not provide conclusive identification of SCC in some cases • Unrealistic loading condition	• Unknown because of unknown times for crack initiation and variable geometries of the cracks
“Slow” SSR	• Easy, relatively inexpensive, provides greater time for corrosion to occur	• Less rapid than the standard SSR, might not provide conclusive evidence of SCC • Unrealistic loading condition	• More time for exposure to corrosive environment
Notched SSR	• The ductility parameters may correlate better with SCC than smooth bar SCC tests. Can be used to study specific metallurgical features such as welds • Easy, fast, relatively inexpensive	• Evidence of SCC may be inconclusive • Because secondary cracking is not always present, this test requires SEM examination to verify SCC • Unrealistic loading condition	• Strain and strain-rate different than on standard un-notched gage section
Ripple SSR	• Provides the ability to simulate different strain rates while maintaining long exposure times • Simulates various strain rates of a structure • Can be combined with a notch	• Requires a more elaborate testing system • Evidence of SCC may be inconclusive • Unrealistic loading condition	• Change in strain-rate, more time for corrosion mechanism, promotes breakdown of passive film
Crack Growth Rate (CGR) with cyclic load	• Represents more realistic loading conditions, assuming that the crack represents undetected defects in the structure • Can be used to study specific metallurgical features such as welds • Can test multiple conditions on 1 sample • Crack growth rate can be compared to air fatigue limits to determine possible SCC	• Expensive and time consuming • Evidence of SCC may be inconclusive if using fracture mode as a decision factor	• Test Parameters can be adjusted to change strain and strain rate. • Can be a confirmatory test

EXPERIMENTAL PROCEDURES

Standard SSR Test Method

All standard SSR tests were performed according to the guidelines provided in ASTM G129-00⁵ using cylindrical tensile specimens at a constant extension rate of 10^{-6} in/s (2.54×10^{-5} mm/s), unless otherwise noted. For the 1-inch gage length specimen, this corresponds to an initial strain rate of 10^{-6} s⁻¹. For each test, the SSR specimen was placed in a polytetrafluoroethylene test cell equipped with polytetrafluoroethylene fittings. This assembly was then inserted into a load frame and connected to a load cell via pull rods and clevises. After the assembly was connected to the frame, the solution of interest was introduced and heated to the desired test temperature. All tests (except air tests) were conducted at applied potentials. The potentials were controlled and monitored with a saturated calomel electrode (SCE) reference electrode, which was maintained at room temperature using a Luggin probe/salt bridge filled with the test solution. A pure platinum wire was used as the counter electrode and a Gamry Reference 600™ potentiostat was used to maintain the desired test potential. All tests were performed under quiescent conditions.

An engineering drawing of the SSR test specimens is shown in Figure 2. The SSR specimens were fabricated such that the longitudinal axis was aligned with the plate rolling direction (i.e., longitudinal orientation). The specimens were 9 inches (22.9 cm) long and 0.25 inch (6.35 mm) in diameter with a centered gage section that was 1.0 inch (2.54 cm) long and 0.125 inch (3.175 mm) in diameter. All test

specimens were freshly polished before each test (within 30 minutes) using silicon carbide paper (600 grit). After polishing, the specimen was rinsed successively with acetone and deionized water and then immediately dried with compressed nitrogen.

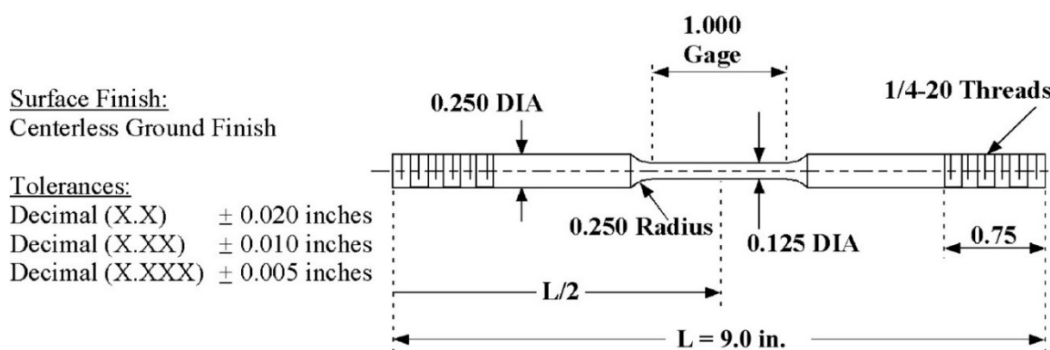


Figure 2: Engineering drawing of the SSR test specimen (units in inches)

All SSR test specimens were pulled to failure. Examination of the specimens after failure consisted of stereographic optical examination at 10 to 63 times magnification and imaging in a scanning electron microscope (SEM). Time-to-failure, elongation-at-failure, engineering tensile stress, and reduction-in-area were recorded for every test. The time-to-failure and the elongation-at-failure of the specimens were not used as the only SCC indicators because these parameters do not always clearly indicate the presence of SCC or its extent. Therefore, the occurrence of SCC was always confirmed by both visual inspection and SEM examination. However, these metrics were used to compare the relative aggressiveness of simulants.

Notched SSR Technique

There are two primary differences between the Notched SSR technique and the standard technique described previously. The first difference is the specimen geometry. A schematic showing a dimensionless notched SSR specimen is shown in Figure 3. The overall dimensions of the specimen are the same with the obvious exception that the gage is not smooth. The notch reduces the diameter and acts as a stress riser and concentrator in the gage, which necessitates the second difference from the standard SSR technique. The strain rate at the tip of the notch is higher than the strain rate in a smooth sample for the same nominal extension rate. Therefore, the extension rate in the tests was decreased from 1×10^{-6} in/s to 4×10^{-7} in/s (2.54×10^{-5} mm/s to 1.27×10^{-5} mm/s). The change in extension rate resulted in total test durations that were similar to the standard SSR test.