Project Number: **81898**

Project Title: **Increasing Safety and Reducing Environmental Damage Risk from Aging High-Level Radioactive Waste Tanks**

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Research Objective

The research activities of this EMSP project at the U. S. Department of Energy Savannah River Site (SRS) are developed for the site-specific needs in the area of high level nuclear waste tanks. Traditional and advanced fracture methodologies are assessed, the crack growth resistance properties for the material of construction (A285 carbon steel) are measured in terms of crack tip constraint, crack growth criteria based on crack opening displacement (CTOD) or angle (CTOA) are developed, and the relationship between stress corrosion cracking (SCC) and the weld residual stress is investigated. All these activities lead to the development of predictive tools for the structural integrity of the SRS waste tanks. The methodologies can be extended to commercial applications.

Research Progress and Implications

This report summarizes year 3 of a 3-year project. The activities include 1) Assessment of fracture methodologies; 2) Development of constraint-based crack growth resistance and CTOD/CTOA fracture criteria; and 3) Stress corrosion cracking and weld residual stress estimation.

1. Fracture methodology assessment

This subtask summaries previous research results on the detailed comparison of the available fracture methodologies (J-integral and various versions of the failure assessment diagrams or FAD). The results demonstrate that for typical applied stresses, the traditional approach for tank structural integrity, including the determination of tank fill limits, is equivalent to the national consensus code approach. A paper has been peer reviewed for 2004 ASME Pressure Vessels and Piping Conference and is published in ASME PVP Vol. 474, Fracture Methodologies and Manufacturing Processes [1].

2. Crack growth criteria development – CTOD/CTOA

The crack growth resistance (J-R) curves for A285 carbon steel (the material of construction for Type I and II waste tanks) were determined using bend specimens with various a/W (crack length to specimen width) ratios. These geometry dependent J-R curves can be expressed as a function of a crack tip constraint parameter [2]. In this subtask, the fracture testing in Ref. 2 is simulated with three-dimensional (3D) and two-dimensional (2D) finite element analyses (Fig. 1). Based on the flat crack front on the fracture surface and the finite element results, it can be concluded that the deformation is basically plane strain. The values of CTOD/CTOA are calculated first using the experimental crack length vs. load point displacement curve, then the calculated CTOD/CTOA is used as a fracture criterion to predict the crack growth. The key conclusions are listed:

(i) The values of CTOD/CTOA are initially high at the early stage of the crack growth, then progressively decreased to a relatively constant value (Fig. 2). *Post-test fractography shows that this phenomenon is not related to crack tunneling or surface measurement uncertainties of the crack growth.*

(ii) The initially higher values of CTOD/CTOA must be included in a fracture criterion so the experimental load vs. load-point displacement and J-R curves can be predicted accurately (Fig. 3).

(iii) The CTOD/CTOA can be related to the J-R curves. The initially higher values are a

natural consequence of crack growth resistance characterized by J-R curves. This trend can be qualitatively demonstrated. Since the J-R curves are crack-tip-constraint dependent [2], *the CTOD/CTOA fracture criteria must also be a function of constraint*. Without the initially higher values of CTOD/CTOA, the fracture testing data will be underestimated [3].

Figure 3 shows the J-R curves as predicted with a bilinear form of CTOD/CTOA fracture criterion, which takes the initially higher values of CTOD/CTOA into consideration. This work was carried out jointly with the University of South Carolina. A technical paper has been completed and ready to submit for peer-reviewed publication [3].

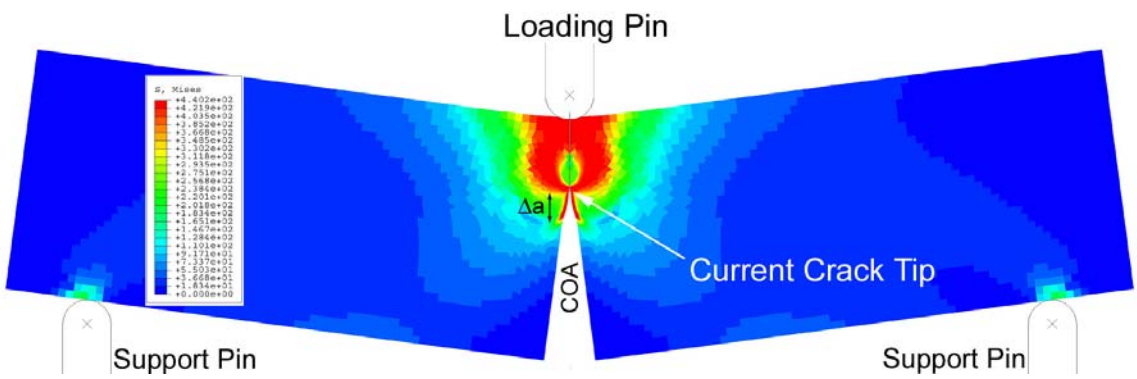

Figure 1 Finite element analysis of crack growth testing

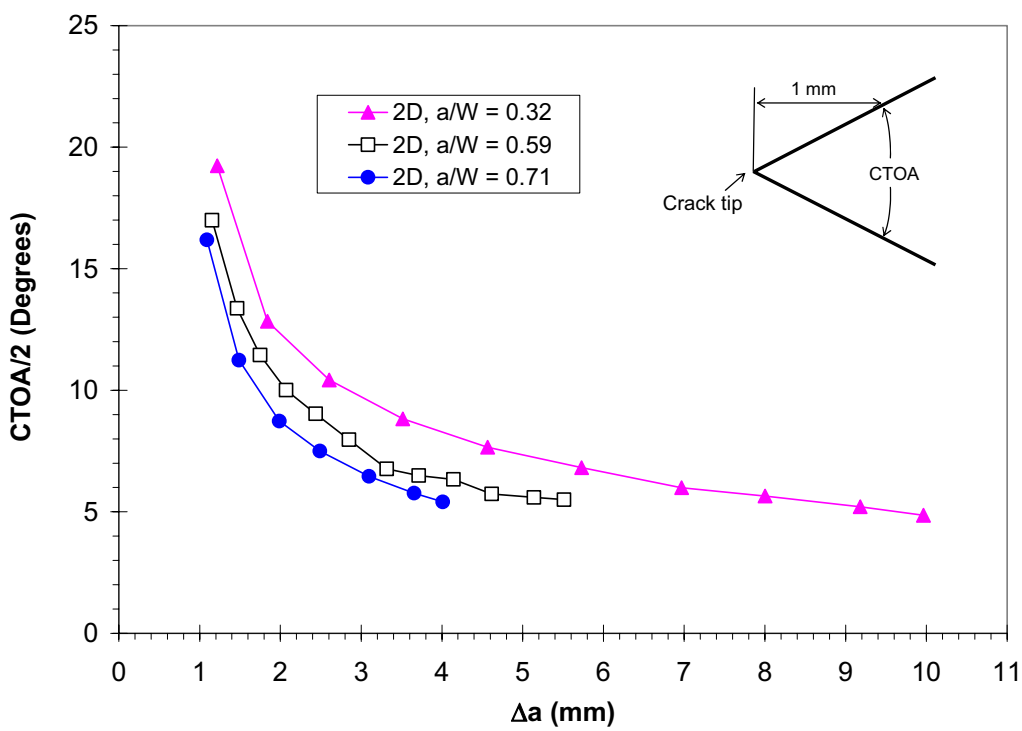

Figure 2 Specimen dependent crack tip opening angles (CTOA)

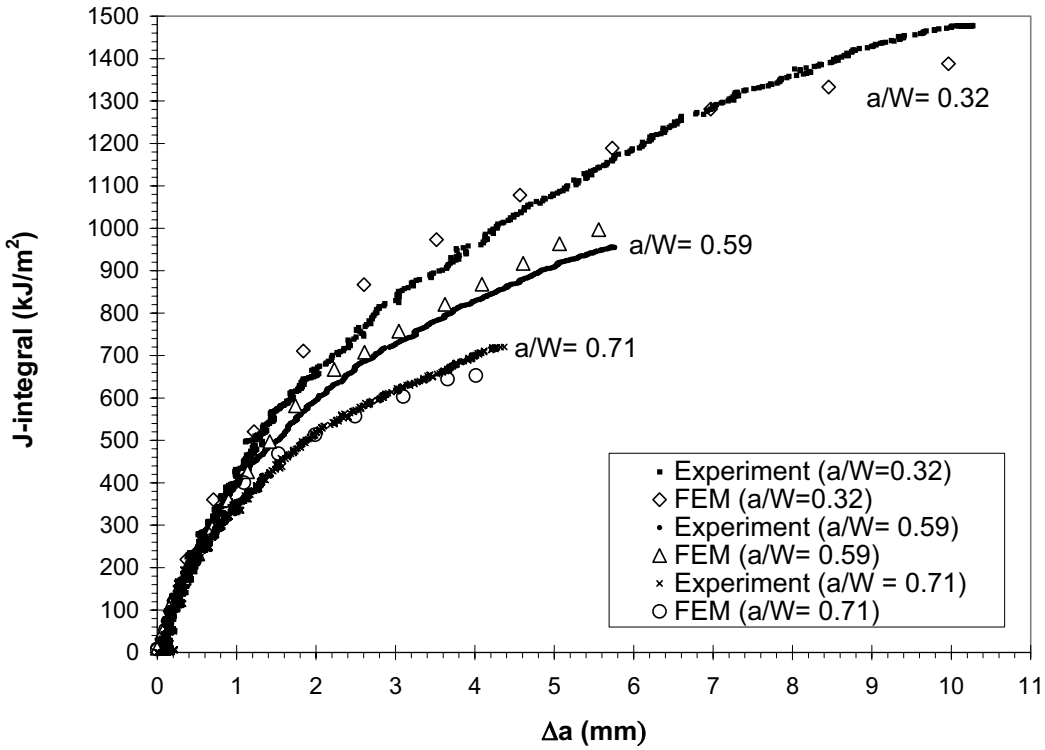

Figure 3 Prediction of J-R curves using a bilinear CTOD/CTOA fracture criterion

3. Stress corrosion cracking and weld residual stress

The materials of construction of the Type I, and II high level nuclear waste tanks at the SRS, and the single-shell tanks at the Hanford site, are susceptible to intergranular stress corrosion cracking (IGSCC) at the weld regions. The material of construction is A285 mild steel. The cause of cracking is attributed to nitrate stress corrosion cracking driven by the residual stress due to the welding of the large plates. The stress corrosion cracking (SCC) is observed in or near the weld of a vessel containing a corrosive chemistry. This degradation phenomenon has been investigated by experimentation to provide crack formation data. Coupled with previous published experimental data for K_{ISCC}, the resulting IGSCC lengths can be compared to the theoretical prediction from detailed analytical calculations for stress-intensity factors in a weld residual stress field.

Two laboratory specimens were prepared. Each 12”x12” specimen was made by joining two A285 plates with the SRS waste tank welding procedure used in 1950s. One of the specimens was stress-relieved based on SRS procedure and the other was as welded. Seed cracks were introduced by electrical discharge machining (Fig. 4). These specimens were submerged in five-molar (5M) sodium nitrate solution at about 90 °C to simulate an aggressive radioactive chemistry environment, without external loads.

As soon as two weeks after submergence the non-stress relieved plate began to develop stress corrosion cracking for the through-plate seed cracks perpendicular and across the weld. The cracks seemed to stop growing after the crack growth was confirmed soon after. The crack configurations and lengths are shown in Figure 5, which was obtained by magnetic particle testing (MT). The ultrasound nondestructive testing (UT) showed

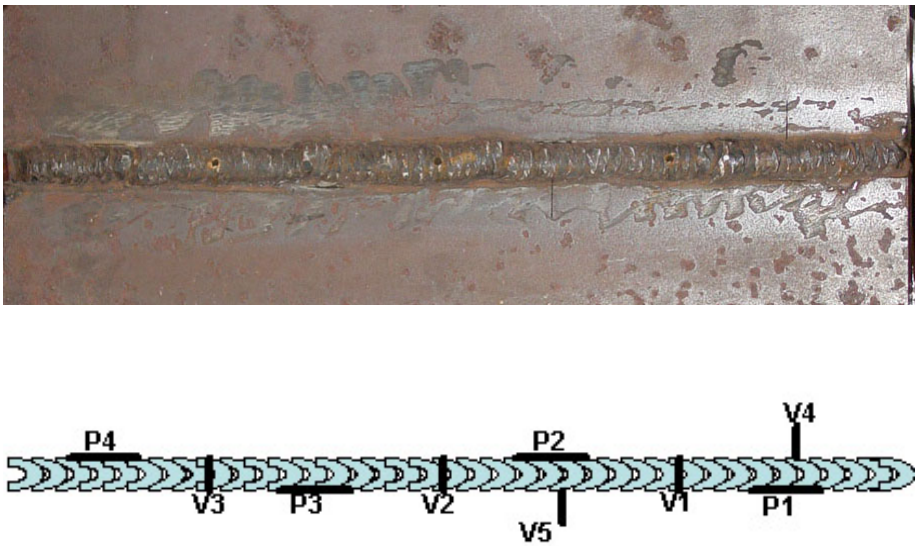

Figure 4 Welded plate and the machined cracks

Non-stress Relieved Plate (Front) Non-stress Relieved Plate (Back)

Figure 5 Stress corrosion cracking in non-stress relieved plate

that the subsurface configuration of one of the cracks in the through-thickness cross-section (Figs. 6). It can be seen that the crack length in the mid-thickness of the plate is shorter than the crack lengths on the surfaces. There is no indication of SCC in the part through-plate (thumbnail) cracks and no crack growth was detected in the stress-relieved specimen.

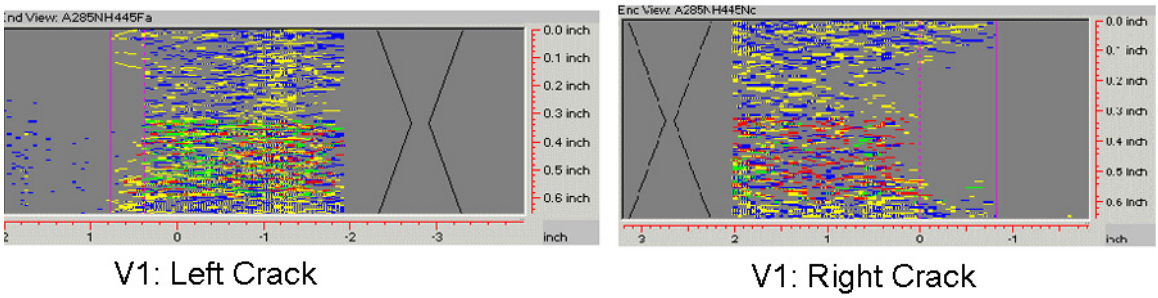

Figure 6 UT testing shows the subsurface crack configuration of V1 (see Fig.4)

A residual stress distribution was calculated with a finite element butt joint model by Battelle Memorial Institute [4]. The stress intensity factors for a vertical crack within the residual stress field can be calculated as a function of crack size (Figure 7). With a K_{ISCC} (32 ksi √in) obtained by SRNL [5], it can be seen in Figure 7 that the predicted IGSCC length is at most 2 inches, which qualitatively agrees with the final length of crack V2 in the center of the specimen (see crack designation in Fig. 4 and the crack lengths in Fig. 5). A recent finite element analysis was carried out at the University of South Carolina [6] to simulate the welding procedure of these specimen plates and then set the machine cracks traction free (a different numerical procedure from Ref. 4). Similar results were obtained and a technical paper is in progress.

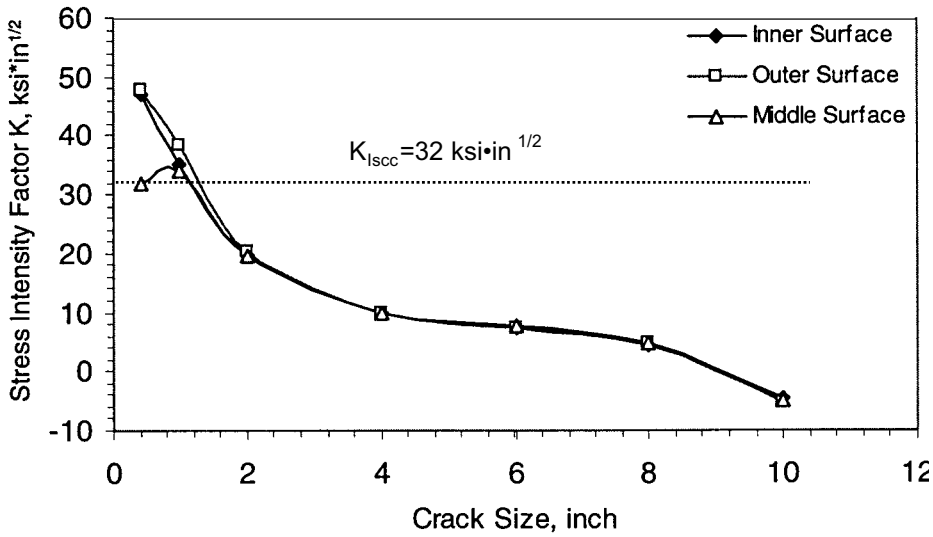

Figure 7 Stress intensity factor as a function of crack size in the residual stress field

The results indicate that SCC can indeed occur in a high level waste chemistry environment without external loading. In addition, the stress relief procedure adopted by SRS is adequate to eliminate SCC. The novel design of the experiment to prepare "seed" cracks from which to measure environmentally induced, subcritical crack extension was successful. This technique can be further developed along with refinements in computational models to determine the weld residual stress and the associated stress intensity factors of cracks.

Planned Activities

- Complete technical papers and submit to peer-reviewed journals.
- Design new SCC specimens and refine predictive modeling methodologies, if funding is available.
- Continue to refine CTOD/CTOA fracture criteria with crack tip constraint theories and publish the results in a peer-reviewed journal.

Information Access (References):

[1] Lam, P. S. and Sindelar, R. L., "Comparison of fracture methodologies for flaw stability analysis of storage tanks," ASME PVP Vol. 474, Fracture Methodologies and Manufacturing Processes, 2004.

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