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

There exists a paramount need for improved understanding the behavior of high-level nuclear waste containers and the impact on structural integrity in terms of leak tightness and mechanical stability. The current program, which at the time of this writing is in its early stages, aims to develop and verify models of crack growth in high level waste tanks under accidental overloads such as ground settlement, earthquakes and airplane crashes based on extending current fracture mechanics methods. While studies in fracture have advanced, the mechanics have not included extensive crack growth. For problems at the INEEL, Savannah River Site and Hanford there are serious limitations to current theories regarding growth of surface cracks through the thickness and the extension of through-thickness cracks. We propose to further develop and extend slip line fracture mechanics (SLFM, a ductile fracture modeling methodology) and, if need be, other ductile fracture characterizing approaches with the goal of predicting growth of surface cracks to the point of penetration of the opposing surface. We also aim to quantify the stress and displacement fields surrounding a growing crack front (slanted and tunneled) using generalized plane stress and fully plastic, three-dimensional finite element analyses. Finally, we will quantify the fracture processes associated with the previously observed transition of stable ductile crack growth to unstable cleavage fracture to include estimates of event probability. These objectives will build the groundwork for a reliable predictive model of fracture in the HLW storage tanks that will also be applicable to standardized spent nuclear fuel storage canisters. This predictive capability will not only reduce the potential for severe environmental damage, but will also serve to justify life extension through retrieval of waste. This program was initiated in November of 2001.

Research Progress and Implications

This report summarizes work after 6 months of a 3-year project. The following three subsections describe current activities of experimental, analytical and numerical portions of this program.

Experimental Activities

INEEL, SRTC

The design and specification of the experimental testing program for the first project phase is completed. A number of specimen types, including round tension specimens, standard fracture toughness test specimens, plate-type surface crack specimens, through-cracked plate specimens, and a new face-groove tension specimen have been fabricated or are currently queued for final machining. The test program will fully characterize the mechanical response of both waste tank steels in addition to newly purchased materials with analogous mechanical characteristics. The plate-type specimens and the face-grooved tension specimens will simulate the behavior of various part through tank wall crack geometries at various stages of crack growth.

The designs for the plate-type specimens (for testing 304L material) and the face-groove specimens are completed. Finite element analysis was used in the specimen design to ensure that uniform tension be maintained in the ligament so the test result can be adequately compared with the analytical solution (Slip Line Fracture Mechanics). Standard ASTM configurations will be used where appropriate for mechanical behavior determinations. A preliminary design for the plate specimen to be used with the carbon steel materials (A285, A516, and A537) has been developed. The A285 plates have been received; the A516 and A537 material plates are being procured. Mechanical testing of standard ASTM specimens of A285 material has been completed under a previous SRTC test program. The microstructure and fracture surface of these specimens are being characterized to establish the opening angles during crack extension, and microstructural features that control the strong effect of crack extension with respect to plate rolling direction. The plate specimen testing of the carbon steel materials will follow the optimized design of the 304L material. Modifications to machine fixtures to allow testing of large plate specimens are under way.

The 304L test specimen blanks have been cut out of the ½ inch plate stock. All smaller specimen blanks have been machined to final dimension and are ready for insertion of cracks or grooves. The first lot of 23 plate specimens has been finish machined, except for insertion of the cracks/grooves. A vendor has been selected for the final EDM machining (groove insertion). The first stage of the testing program must be completed to establish groove sizes for the remaining specimens.

The first stage of the testing program is an investigation of the material fracture response sensitivity to initial groove/crack tip radius. The project will benefit (cost and time) if thin EDM grooves can be substituted for sharp-tipped fatigue precracks. Specimen-to-specimen consistency will be better, and specimens will take less time to produce. Precise groove/crack geometries can be specified and created for particular data requirements, whereas only approximate "target" geometries can be specified if precracking is needed. The first stage testing will begin in early June. Once results are obtained and analyzed, the remaining specimens can receive final preparation.

Analytical Activities: Slip Line Fracture Mechanics Development
MIT

There exists a need to estimate the likelihood of brittle cleavage cracking in normally tough storage tanks for high level waste. For tough steels, slip line fracture mechanics (SLFM) has just been developed to predict the force-deformation curve in a quasi-static Charpy test from the crack tip opening displacement (CTOD) to initiate dimple crack growth, and the crack tip opening angle (CTOA) for continued growth. The analysis pictured in Figure 2 is for a 0.25 mm CTOD and shows dimple crack growth at CTOA = 30° for 1 mm, when the maximum normal stress reaches a critical value for cleavage. After 3 mm of cleavage, slip by pivoting around the outer contact points reduces the normal stress below that for cleavage, and the cracking reverts to the dimple mode, as observed in Charpy tests.

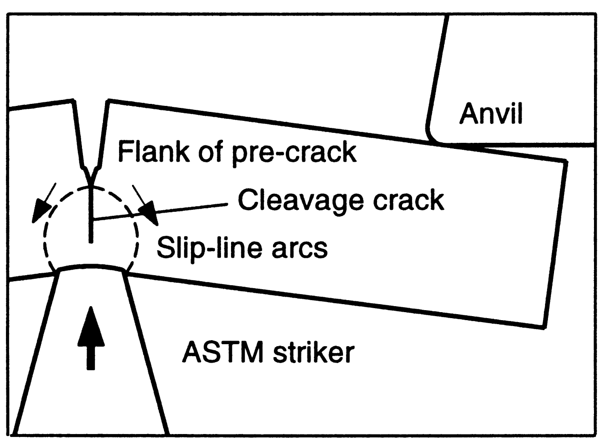

Figure 2. Transition from dimple fracture by slip line fracture mechanics to cleavage in a Charpy specimen.

For extensive crack growth, the statistics of rare cleavage are considered. Means are outlined to extrapolate low temperature results to the higher temperatures required in service.

Numerical Modeling
SRS, INEEL

Several possible displacement based crack growth-modeling criteria exist. Most rely on some form of nodal release formulation or element annihilation. Displacement based criteria (Crack Opening Displacement (COD), Crack Tip Opening Displacement (CTOD) and Crack Opening Angle (COA)), can be related to the proposed use of slip line method associated with strain fields in front of the crack tip. The use of an energetic criterion such as J could additionally be used to either supplement or in combine with the slip-line fracture mechanics theory.

The ABAQUS finite element code has been evaluated for modeling full crack extension. Using plane strain element and the build-in nodal release technique, a two-dimensional analysis methodology is being developed with a crack growth criterion specified by SLFM.

Planned Activities

Currently planned activities include the following with associated approximate near term time lines.

❑ Initial crack tip radius requirements for current materials (EDM or fatigue crack)	July 2002
❑ Investigation of sudden ductile-cleavage transition	Ongoing
❑ General mechanical properties determinations	September 2002
❑ Full plate testing (initiate)	August 2002
❑ ABAQUS based modeling (crack growth) (To be completed)	October 2002
❑ Model migration to research code to include 3-D fully plastic crack growth. (initiate)	September 2002

Longer term planned activities include but are not limited to the following list and timeline.

❑ Inclusion of SLFM fracture criterion into numerical models.	2003-2004
❑ Ductile-cleavage transition mechanism identification to include in numerical models.	2004
❑ Plane Strain, Hardening Steel Crack Penetration Tests.	2003-2004
❑ Plane Stress, Hardening Steel (Catastrophic Failure)	2003-2004
❑ Adequacy of analytical/numerical approaches for Explaining observed experimental results.	2003-2004