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 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. Ultimately we aim to also 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 investigate 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 guide safe retrieval of waste. This program was initiated in November of 2001.

Research Progress and Implications

This report summarizes year 2 of a 3-year project. The following three subsections describe current activities of experimental, analytical and numerical portions of this program.

Experimental Activities

INEEL: ***304L Surface Crack Experiments and Post Fracture Analysis***

Microtopography is a new method, developed at INEEL, for analyzing ductile fracture processes. This technique provides a four-dimensional view (spatial, and time varying) into the interior of a cracked specimen or structure throughout the ductile crack growth process. Microtopography provides physical data from an individual specimen or structure that is unavailable through any other means. This capability offers unique perspectives on ductile crack growth, especially in the three-dimensional fracture process of part-through surface cracks. Understanding this three-dimensional ductile surface crack growth is of critical importance to the overall goal of this project – predicting the behavior and/or structural integrity of high-level waste storage tanks that contain such cracks, when those tanks are subjected to abnormal stress conditions.

This recently enhanced microtopography system has analyzed several of the 304L stainless steel part-through surface cracked plate specimens and has produced outstanding results. An incremental crack growth analysis, only one of a number of possible analyses, is shown graphically in Figure 1. This data format provides important crack position information, but also allows the local crack tip opening angle to be extracted at every position and at any time throughout the fracture process. The resultant data provides critical experimental points of comparison for the finite element crack growth models being developed as part of this program. These experimental data extracted from actual test specimens by the microtopography method are unique in their accuracy, completeness, and availability. As finite element models are further developed, these data will provide experimental verification points to assure the correctness of the numerical solutions.

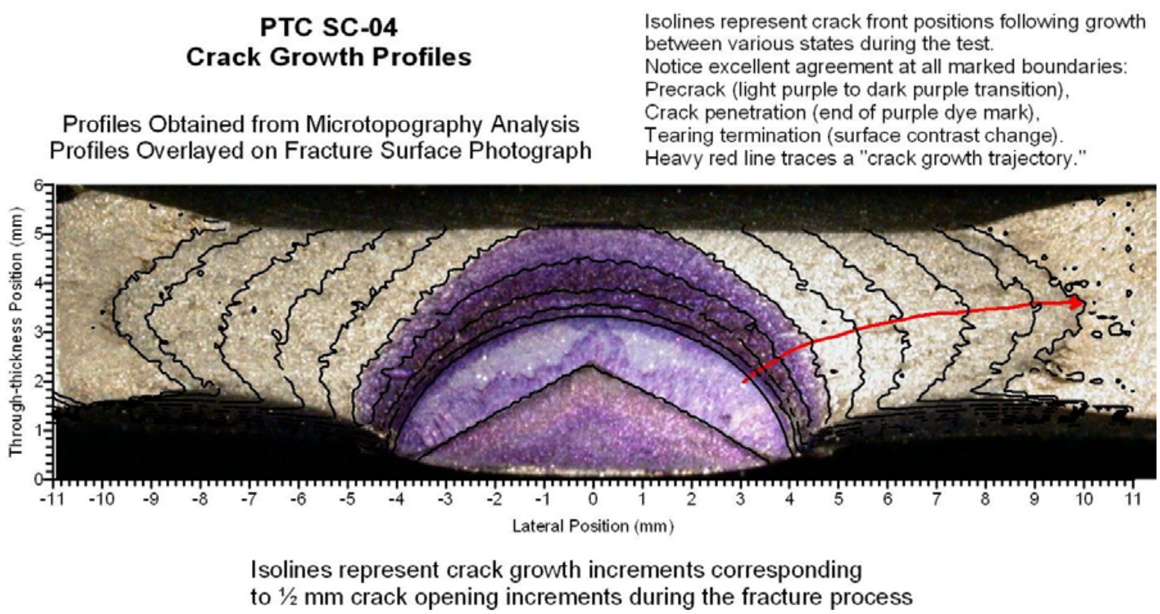


Figure 1. A stainless steel (304L) part-through surface cracked plate specimen fracture surface. This image overlay demonstrates an incremental crack growth analysis and is one example of many possible fracture surface analyses. This type of analysis provides important crack position information in addition to measuring the local crack tip opening angle, which is another important fracture process parameter. All of these data can be extracted at any position and time step throughout the fracture process.

Collaboration Type: Program interaction
Collaborator: Mr. Randy Lloyd and Dr. John H. Jackson
Collaborating Organization: INEEL

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 normally tough steels, two-slip-line fracture mechanics (SLFM2) and a cleavage criterion have been extended to provide the transition with temperature in the dimple area swept out before cleavage in Charpy-type specimens. This information is needed to estimate the statistics of rare cleavage transitions in storage tanks under accidental overloads. The parameters needed for SLFM2 are being sought from load-displacement data in quasi-static Charpy tests. It appears that three of the parameters can be combined into a single effective one. To study the effects of discretization in finite element analysis, continuum SLFM2 solutions have been obtained for mesh shapes, average element strains and stresses, and nodal forces as a slip line sweeps past an element. Finally, for finite element calculations of crack growth in a structure using Rashid's Migrating Tip Mesh, the crack tip driving parameters imposed on SLFM2 exclusion region are available. It remains to formulate the crack growth from SLFM2 for embedding into the exclusion region tools.

A jig for plane stress testing of the growth of through-cracks has been designed for either single or twin oblique necks in front of the growing crack. It appears that transient, inhomogeneous thinning limits the use of fracture mechanics to the decohering zone that represents the necking between rigid shoulders, and that the necessary traction-displacement relation and any sensitivity of it to displacement gradients along the neck, can be estimated from tests using this jig.

Collaboration Type: Program interaction
Collaborator: Prof. Frank McClintock
Collaborating Organization: MIT

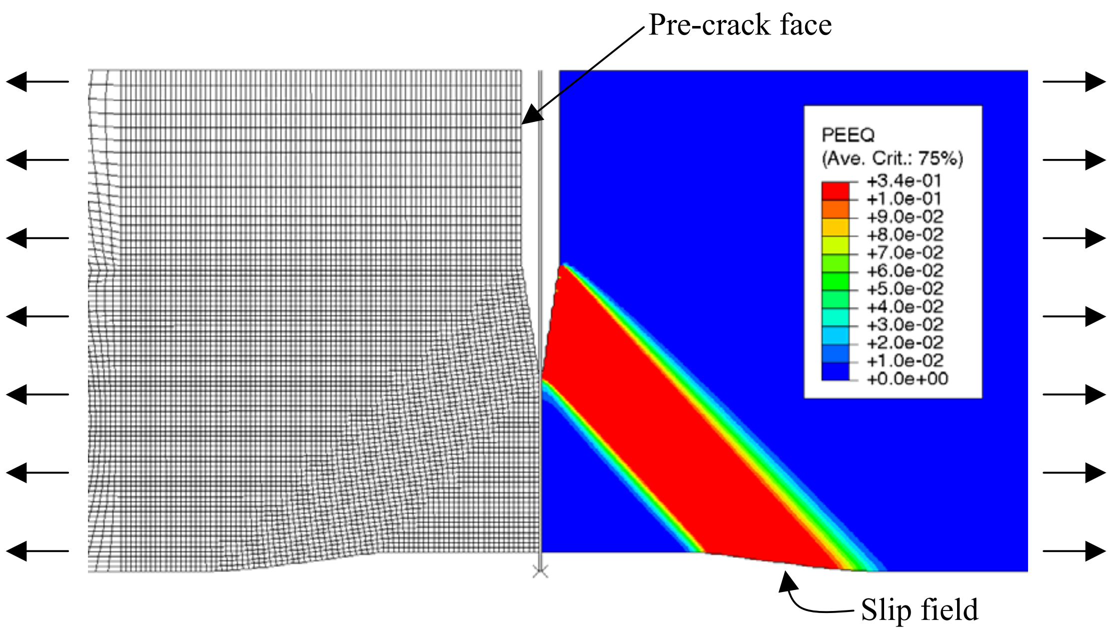
Numerical Modeling
INEEL, UC Davis

Numerical Activities A: Node Release Calculations

A finite element model has been developed to simulate propagating fractures in ductile materials using node-release techniques. For a rigid, perfectly-plastic material, computational results have been compared to an analytical solution based on slip line fracture mechanics, with very good agreement observed. A series of parametric simulations have been performed to investigate and quantify the effects of various numerical parameters (e.g., mesh size, node release criteria, debonding rates) on solution quality.

Following these development and verification efforts, the model was then modified to include more realistic elastic-plastic material response. INEEL measured tensile data for a candidate material was used for this calculation. Currently, the model is being enhanced such that the important variables governing crack propagation can be influenced by solution dependent parameters, which is the case in the real world.

This effort has been conducted in close collaboration with Professor Frank McClintock of MIT.



The above figure is a finite element numerical simulation of ductile crack growth using a node-release technique. The deformed computational mesh is shown on the left with contours of equivalent plastic strain on the right. The Crack Tip Opening Angle (CTOA), set at 20 degrees for this simulation, is used to govern crack extension. The calculation assumes a rigid perfectly-plastic material, permitting comparison to analytical results from slip line fracture mechanics. Very good comparisons to the analytical solution provide confidence in the modeling approach.

Collaboration Type: Program interaction
Collaborator: Dr. Richard Williamson
Collaborating Organization: INEEL

Numerical Activities B: 3-D Crack Extension Model Development

A surface crack feature extending through the tank wall thickness and then transitioning to a running through-crack involves at least three crack growth processes with transitory behavior between: crack initiation, crack growth in the thickness direction (plane strain) and through-thickness crack extension (plane stress). Commercial finite element software (ABAQUS) can address significant portions of the plane strain through-thickness crack growth for direct comparison to SLFM analytical solutions (see above section). However, the complex 3-D nature of the problem requires more sophisticated modeling tools. In order to respond to this numerical need, collaborative arrangements have been established between the INEEL and researchers at U.C. Davis. This research group has already envisioned the fundamental, prerequisite tools necessary to extend current 2-D capabilities into a 3-D setting.

The UC Davis team will begin work (April, 2003) on synthesizing a comprehensive computer-based simulation method for crack growth in ductile structures. A unique aspect of this methodology is its potential for modeling realistic three-dimensional structures and crack configurations. The UC Davis work will draw upon the ongoing theoretical and experimental work pursued at the INEEL and MIT under this project, as well as the idealized two-dimensional computer analyses carried out to date at the INEEL by Dr. Williamson. The UC Davis team will also draw upon their significant background in fracture modeling and in computer-based methodology development that is highly relevant to the project's objectives.

Collaboration Type: Program interaction
Collaborators: Prof. Mark Rashid,
Mr. Mili Selimotic (Ph.D. Candidate: U.C. Davis)
Collaborating Organization: University of California at Davis

Planned Activities

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

- Field variable control of crack extension in ABAQUS models. Both perfectly plastic and strain hardening. 7-03
- Completion of plane stress MIT test fixture design for specialized experiments. 7-03
- Fabricate specimens from SRTC provided A285 plate and conduct surface crack experiments to obtain additional fracture process data. 9-03
- Use latest 2-D version of UC Davis code to model and predict fracture path using both perfectly plastic and strain hardening material definitions. 9-03.

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

- Invited to present latest program results at ACS meeting in New York, NY. Sept. 7-11, 2003.
- Conduct specialized experiments using plane stress MIT test fixture. 11-03
- Peer reviewed publication of results. 1-04
- Investigate follow-on funding opportunities to leverage work to date. 4-04

Information Access

Select publications:

F. A. McClintock and R. L. Speth, “Dimple-Cleavage Transitions in Crack Growth: Deterministic in Charpy Tests from Slip Line Fracture Mechanics, and Statistical in Structures.” Proceedings of Mechanisms and Mechanics of Fracture: The John Knott Symposium, Structural Materials Division of TMS, Crown Plaza Hotel in Columbus, OH, Oct. 7-10, 2002, pp. 23-30.

Lloyd, W.R., “Microtopography for ductile fracture process characterization – Part 1: Theory and methodology,” **Engrg. Frac. Mech. 70**, pp.387-401, 2003.

Lloyd, W.R. and McClintock, F.A., “Microtopography for ductile fracture process characterization – Part 2: Application for CTOA analysis,” **Engrg. Frac. Mech. 70**, pp.403-415, 2003.

Lloyd, W.R. et al., Microtopographic Analysis of Part-Through Crack Growth in Alloy 304L Plate-type Tension Specimens, **INEEL/EXT-03-00495**, 2003.

Website: General group information www.inel.gov