Presentation of the Final Report

STRESS CORROSION CRACKING

Presented by

Peer Panel on Waste Package Materials Performance

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Presented to

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Main - no

Findings

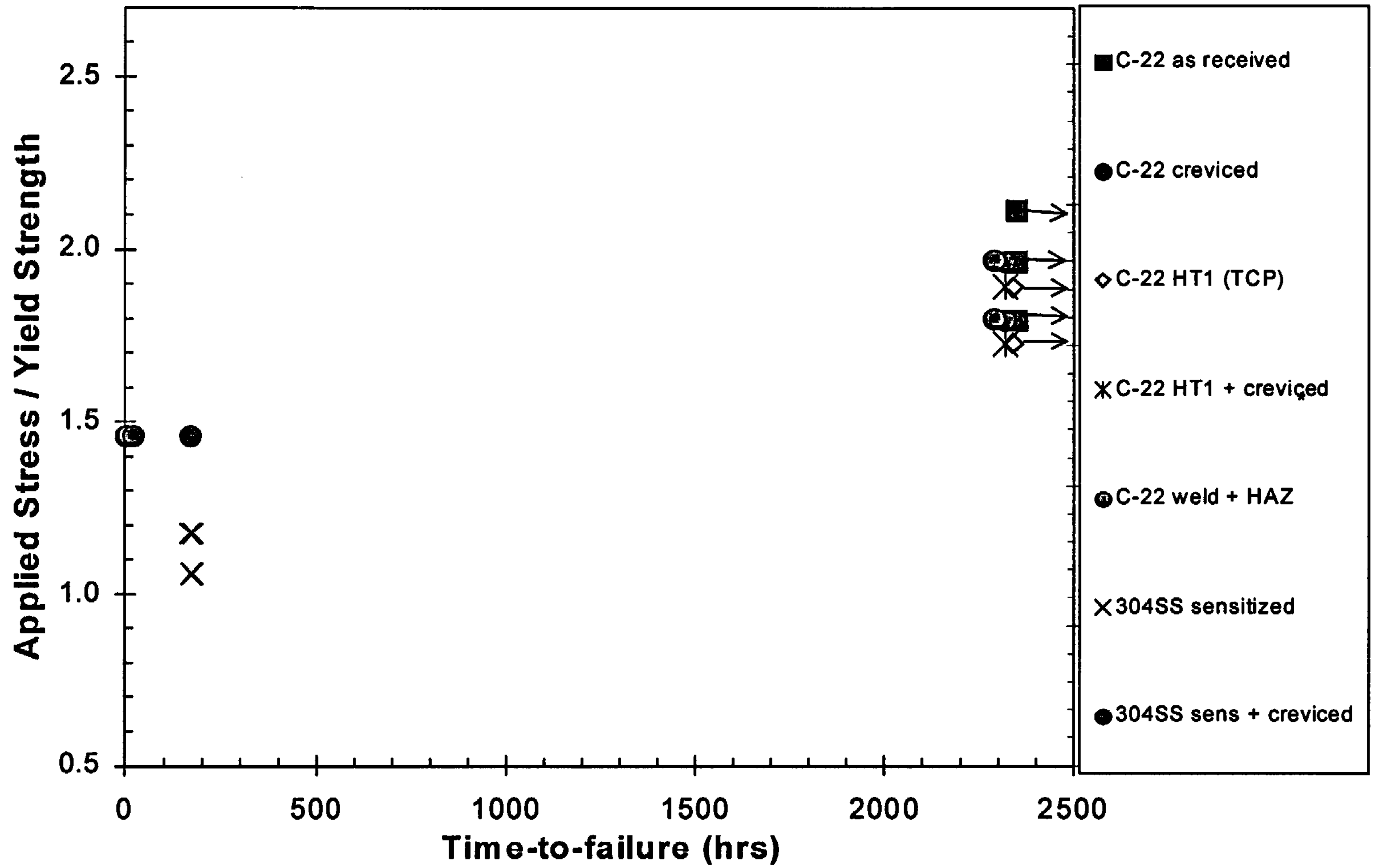
Stress Corrosion Cracking

Stress Corrosion Cracking – Slow crack growth in a metal produced by the combined action of corrosion and tensile stresses (residual or applied)

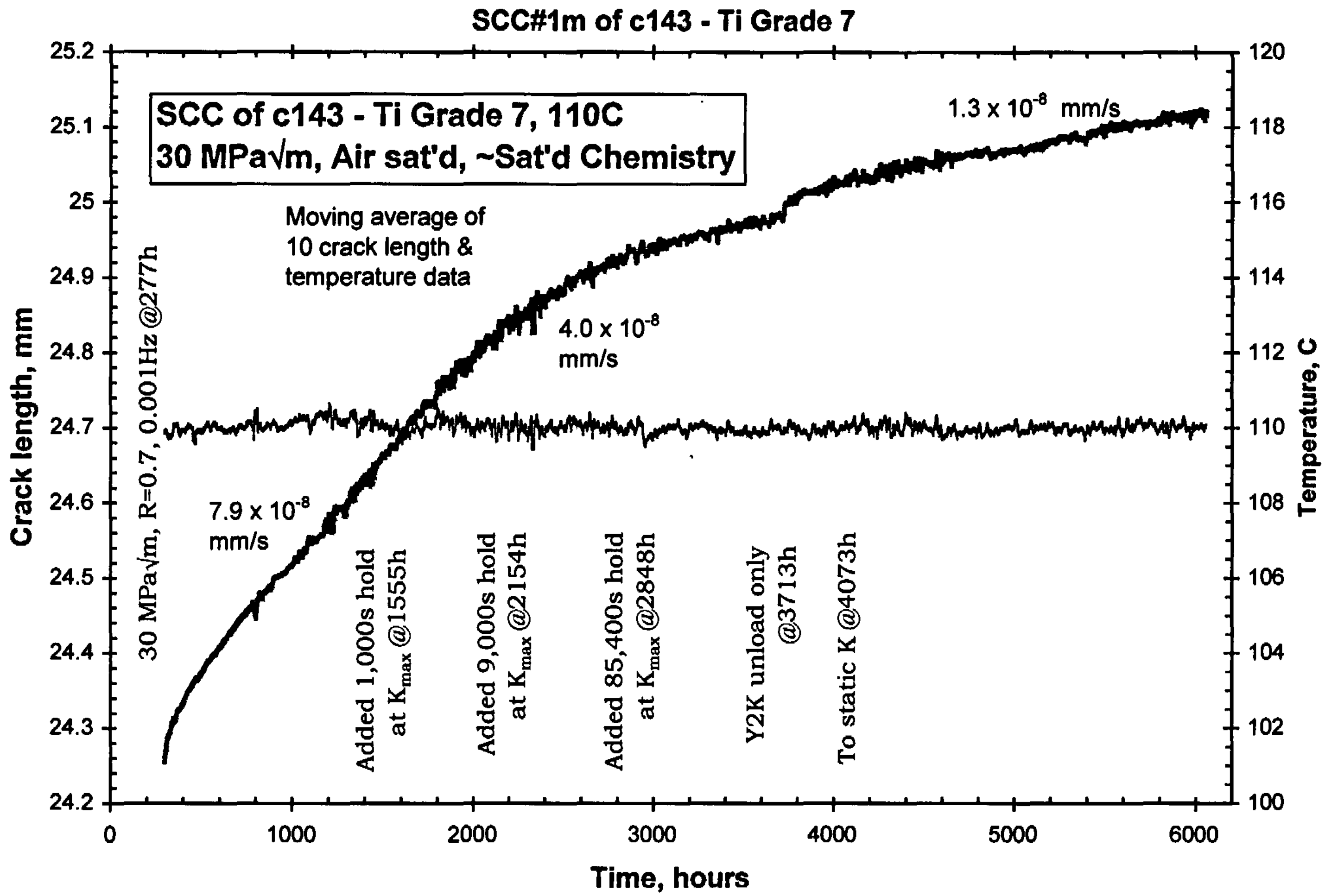
Alloy 22 is very resistant to SCC but might crack under extreme conditions

- High temperatures
- Concentrated, low pH chloride solutions
- Oxidizing potentials
- Aged microstructures

Ti Grade 7 has been shown to undergo SCC in some relevant repository environments



Alloy 22 Stress Corrosion Cracking Test Results
(Constant Load Tests at 105°C in 7500X J-13, pH 12.4)



Crack Growth of Titanium Grade 7 in Basic Saturated Water at 110°C

Findings
Stress Corrosion Cracking

Project Approach to SCC Mitigation

- Use of a highly SCC resistant alloy (Alloy 22) for the waste package
- Control of residual tensile stresses in waste package

Findings
Stress Corrosion Cracking

Technical Issues

SCC life prediction models

Waste package environment

Control of residual tensile stresses

Metallurgical stability

Titanium drip shield performance

Findings
Stress Corrosion Cracking

Life Prediction Models for SCC

Essential component of SCC program

- Laboratory test techniques have inadequate sensitivity to crack growth for prediction of acceptable performance of the waste package

Findings
Stress Corrosion Cracking

Project Life Prediction Models

Two SCC models for life prediction

- ❑ Threshold stress intensity factor model
- ❑ Slip dissolution/film rupture model
  - ◆ Threshold stress component for crack initiation

Findings

Stress Corrosion Cracking

Threshold Stress Intensity Factor Model

- Threshold stress intensity factor (K_{ISCC}) considered to be a material property
  - Function of the exposure environment
- Applied stress intensity factor (K_I) is a crack driving force parameter
  - Function of flaw orientation, flaw size, and stress
- At K_I values below K_{ISCC}, cracking will not occur even in the presence of a potent cracking environment and an SCC susceptible metal

Findings

Stress Corrosion Cracking

Threshold Stress Intensity Factor Model

Project Data and Model Application

- Project has done a thorough job of evaluating the likely range in stress intensity factors for Alloy 22 outer barrier
  - Expected residual stresses
  - Range of flaws present in the package
- K_{ISCC} values measured from tests in simulated repository environments
  - Tests with pre-cracked wedge loaded double cantilever beam specimens (crack extension measured by compliance)
  - Crack growth tests performed with pre-cracked compact types specimens (crack extension measured by reversing DC potential drop)

Findings
Stress Corrosion Cracking

Threshold Stress Intensity Factor Model

Technical Issues

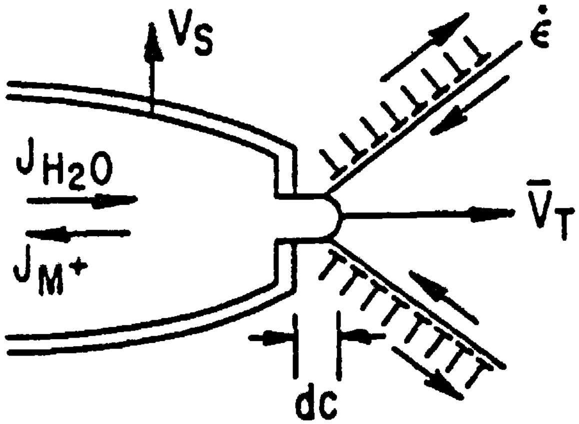
- Sensitivity to crack growth not addressed in DOE work
- Some scientists have speculated that K_{ISCC} does not exist
  - Lower limit of sensitivity to crack growth
- CNWRA estimates maximum sensitivity of 10 μm based on fractography
  - For a one year test, this sensitivity would correspond to through wall penetration for 25 mm waste package with a 5 mm deep preexisting flaw in 2000 years

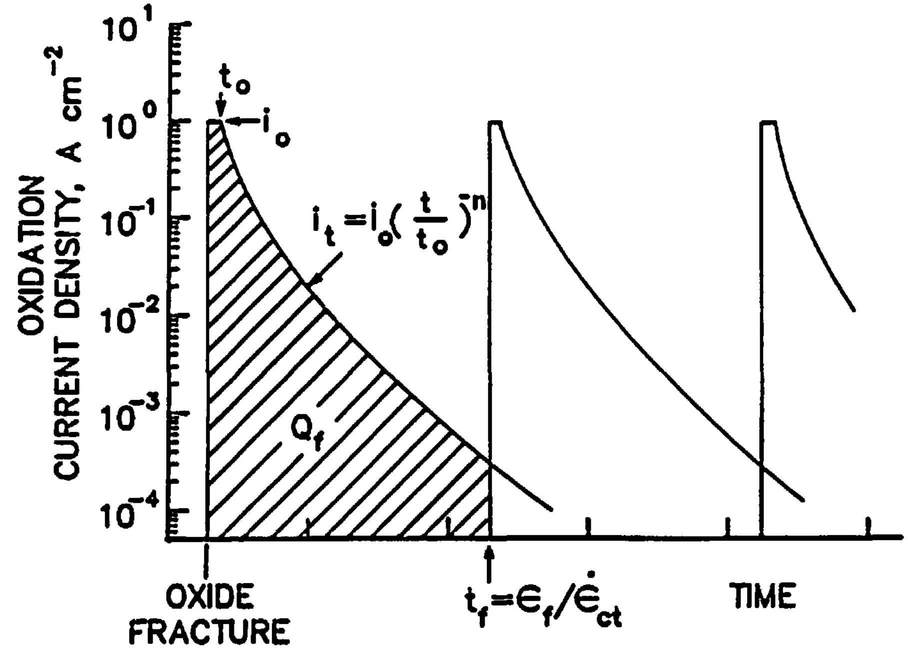
Findings

Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

- Deformation at crack tip ruptures passive film
- Crack advance by anodic dissolution (corrosion) at the film free crack tip
- Crack walls and free surfaces are protected from corrosion by the passive film
- Rate of crack propagation a function of
  - Kinetics of corrosion reactions
  - Mechanical properties of film
  - Rate of repassivation of film
  - Creep rate of metal





$$V = \frac{dq}{dt}; \quad \overline{V}_{av} = \frac{M}{Z\zeta F}\cdot\frac{Q_f}{t_f}$$

FOR HIGH $\dot{\epsilon}_{ct}$ AND/OR LONG t_o :

$$\overline{V}_{av} = \frac{M}{Z\zeta F}\cdot i_o$$

FOR LOW $\dot{\epsilon}_{ct}$ AND/OR SHORT t_o :

$$\overline{V}_{av} = \frac{M}{Z\zeta F}\,\frac{i_o t_o^n}{(1-n)\epsilon_f^n}\,\dot{\epsilon}_{ct}^n$$

$$= f(n)\,\dot{\epsilon}_{ct}^n$$

Findings
Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

- Slip dissolution model is turned on when stress in outer surface of waste package exceeds a threshold value
  - Residual stresses from fabrication are the primary sources of stresses assumed in the evaluation

Findings
Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

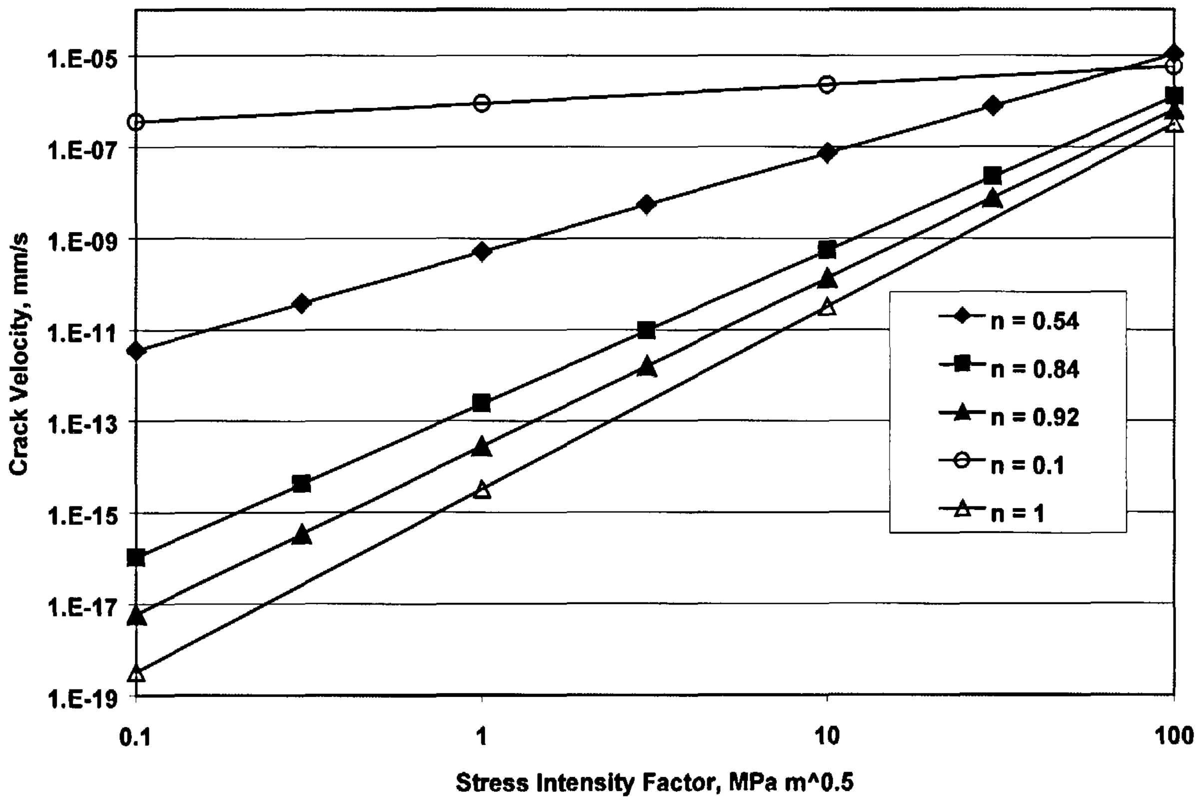
- Crack velocity under constant load conditions is proportional to stress intensity factor raised to a power

$$v = \overline{A}(K_I)^{\overline{n}}$$

- SCC susceptibility decreases with increasing $\overline{n}$
- Sensitivity of crack velocity to changes in K_I increases with increasing $\overline{n}$

Findings
Stress Corrosion Cracking

Alloy 22, Slip Dissolution Model



Findings

Stress Corrosion Cracking

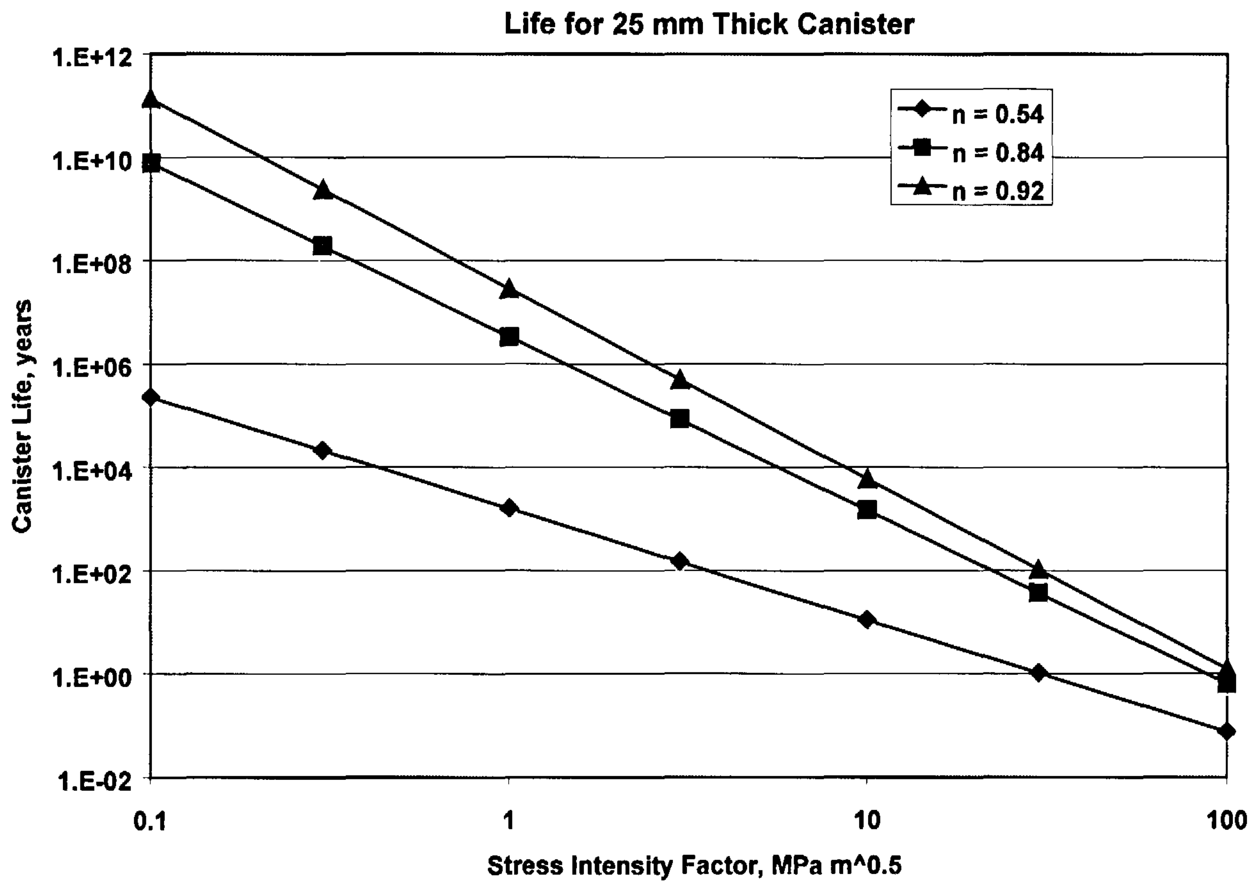
Slip Dissolution/Film Rupture Model

For n = 0.92 ($\bar{n} = 3.68$)

Stress intensity factor must be less than about 10 MPa(m)$^{0.5}$ to obtain a 10,000 year life

- **Assumes a constant crack growth rate with time and decreasing temperature**

Findings
Stress Corrosion Cracking



Findings

Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

Project Data and Model Application

- Initially, lower bound threshold stress was estimated to be 10 to 40% of the yield strength
  - Based on data for 304 and 316 stainless steel and other Fe-Cr-Ni alloys
- Threshold stress has been increased to 80 to 90% of the yield strength
  - Based on U-bend and slow strain rate test data for Alloy 22 in relevant simulated and bounding repository environments
- In simulations, model is rarely turned on because the stress rarely exceeds the high threshold stress

Findings

Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

Project Data and Model Application

- Current estimates of n for Alloy 22 range between 0.84 and 0.92
  - based on crack growth tests under cyclically loaded conditions in concentrated mixed salt solution
- Compares with an n value of 0.54 for 304 SS in high temperature water

Findings

Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

Technical Issues

- Original slip dissolution model (developed for nuclear industry) did not contain a threshold stress or stress intensity factor
  - Assumed that crack propagation would occur in the presence of a potent environment if a crack like defect is present and there is dynamic strain at the crack tip
- The use of a threshold stress for SCC initiation is non conservative
  - SCC typically initiates at defects except where the environment is very potent

Findings

Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

Technical Issues

- Calculations of A and the conversion of n to $\bar{n}$ and A to $\bar{A}$ are based on empirical relationships developed for 304 stainless steel in 288 C water
- Not obvious that these conversions should be applicable
  - Differences in deformation behavior between 304 SS and Alloy 22

Findings
Stress Corrosion Cracking

Slip Dissolution/Film Rupture Model

Technical Issues

- Current claimed sensitivity to crack growth using the reversing DC electric potential drop technique is inadequate to establish the magnitude and variability of the constants in the model
  - Sensitivity of 5×10^{-10} mm/s
  - Corresponds to 158 mm of crack growth in 10,000 years

Findings
Stress Corrosion Cracking

Waste Package Environment

Technical Issues

- Alloy 22 is highly corrosion resistant but might crack at the extremes of the environmental boundaries
  - Concentrated low pH chloride solutions
  - In the presence of minor environmental constituents, such as Pb
    - Based on experience in pressurized water reactors in Nuclear Power Industry

Findings
Stress Corrosion Cracking

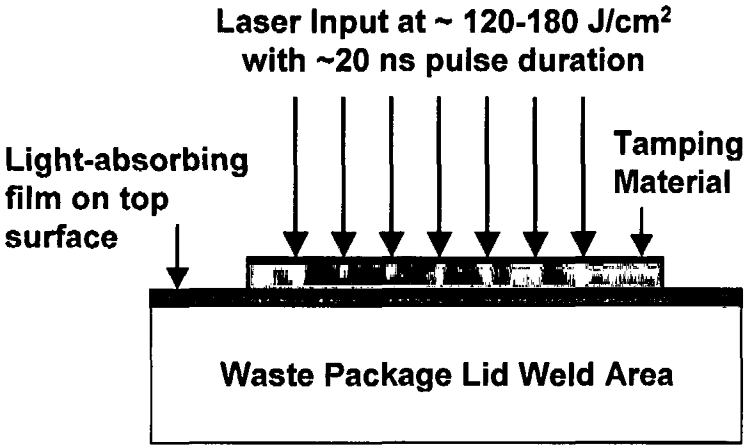
Control of Residual Tensile Stresses

Project Approach

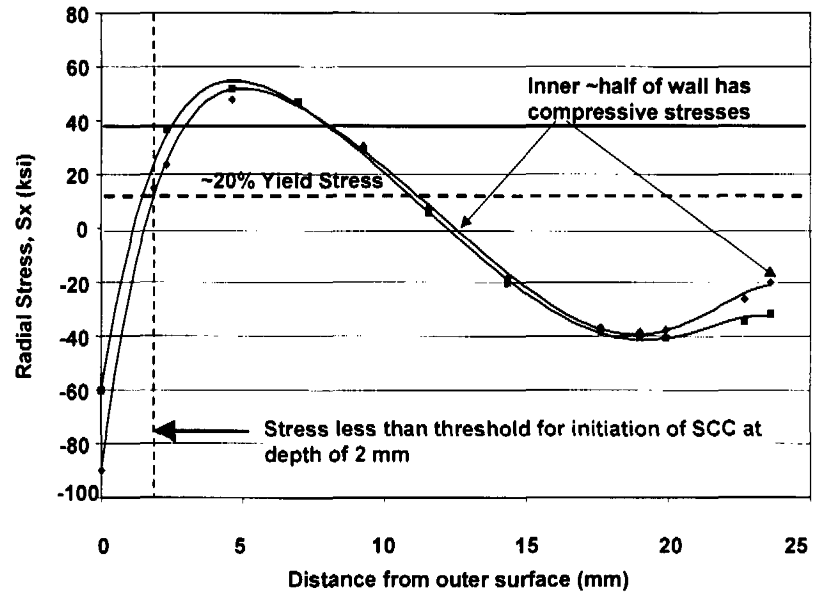
- Stress anneal and water quench of canister before loading of waste and closure weld
- Laser peening and local induction annealing treatments of closure welds

Stress Mitigation with Laser Peening Process

Laser Peening Concept



Through-Wall Stress in Laser Peened Areas



Findings
Stress Corrosion Cracking

Control of Residual Tensile Stresses

Technical Issues

- Difficult to obtain uniform compressive residual stresses by stress anneal and water quench
  - Experience in pulp and paper industry
  - Closed end of canister might exacerbate problem
- Slow cooling to minimize tensile residual stresses might promote deleterious metallurgical changes

Findings
Stress Corrosion Cracking

Control of Residual Tensile Stresses

Technical Issues

- ❑ **Residual tensile stresses also might exist in transition zones for laser peening and local induction annealing treatments**

Findings

Stress Corrosion Cracking

Metallurgical Stability

Project Approach

- Plan to evaluate SCC behavior of Alloy 22 with aged and welded and aged microstructures
- No plans to evaluate different stages of aging

Findings

Stress Corrosion Cracking

Metallurgical Stability

Technical Issues

- Early stages of aging might be more deleterious to SCC resistance than later stages of aging
  - Potential for Cr and Mo depletion near precipitates might be greater early in aging process
  - Depletion might be healed later in process
- Metallurgical stability (and SCC susceptibility) might be a function of alloy composition within the specifications for Alloy 22

Findings
Stress Corrosion Cracking

Titanium Drip Shield Performance

Project Approach

- Cracking of the drip shield is possible under applied stresses resulting from rock fall
  - SCC of Titanium Grade 7 was observed in tests of precracked specimens in simulated repository environments under constant load conditions
- SCC failure is of low consequence to drip shield performance
  - Plugging of cracks by mineral scales

Findings

Stress Corrosion Cracking

Titanium Drip Shield Performance

Technical Issue

- Is there a benefit in the use of an alloy that is expected to experience through wall cracking under the anticipated repository conditions?
- Is there a possibility of complete local loss of integrity at a rock dent?

Findings
Stress Corrosion Cracking

Panel Recommendations

SCC Modeling

- The maximum sensitivity to crack growth be established and improved
  - Threshold stress intensity factor tests
  - Crack propagation tests
- Slip dissolution/film rupture model
  - Threshold stress component be replaced with the threshold stress intensity factor model
  - Develop model constants specific to Alloy 22

Findings

Stress Corrosion Cracking

Panel Recommendations

SCC Modeling

- Alternative models for SCC be considered by the Project
  - Provide validation and support for current Project approach
  - Required if current models are found to be deficient

Findings
Stress Corrosion Cracking

Panel Recommendations

Waste Package Environment

- Project evaluate SCC performance of Alloy 22 within and beyond the expected environmental bounds
- Project evaluate the role of minor constituents in the repository, such as Pb, on cracking behavior

Findings
Stress Corrosion Cracking

Panel Recommendations

Control of Residual Tensile Stresses

- Project thoroughly evaluate heat treatment procedures for stress mitigation
  - Modeling
  - Measurements on prototype containers

Findings
Stress Corrosion Cracking

Panel Recommendations

Metallurgical Stability

- The project evaluate effects on SCC of early stages of
  - Ordering
  - Grain boundary depletion of passive-film forming elements
  - Impurity enrichment at grain boundaries
- The project evaluate effect of heat-to-heat variation on metallurgical stability and SCC susceptibility

Findings

Stress Corrosion Cracking

Panel Recommendations

Titanium Drip Shield Performance

- Project select an alternative material for the drip shield if it is confirmed that Titanium Grade 7 undergoes SCC under realistic repository conditions