Waste Package: Corrosion Testing and Model Development

Presentation to:
Nuclear Waste Technical Review Board (NWTRB)

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U.S. Department of Energy
Office of Civilian Radioactive
Waste Management

Yucca Mountain Project

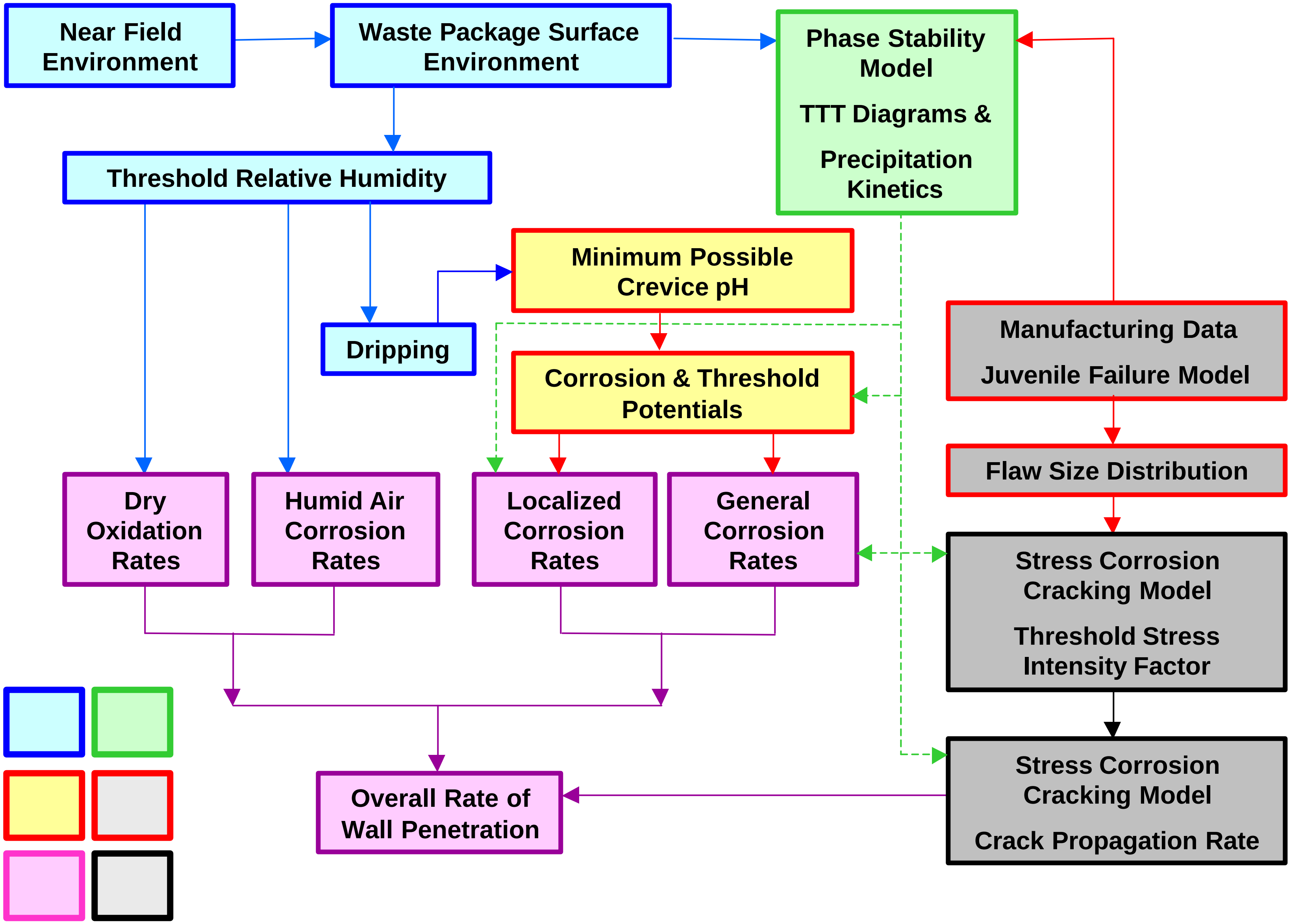
Introduction

- Long-term containment (10,000 years) requires materials with exceptional corrosion resistance
  - Very small penetration rates must be measured
  - Measurement error must be minimized to the extent possible
- Site Recommendation (SR) & License Application (LA) require credible predictive models based on sound understanding
- Such models have been developed for relevant degradation modes
  - General & Localized Corrosion
  - Stress Corrosion Cracking
  - Juvenile Failure
  - Phase Stability

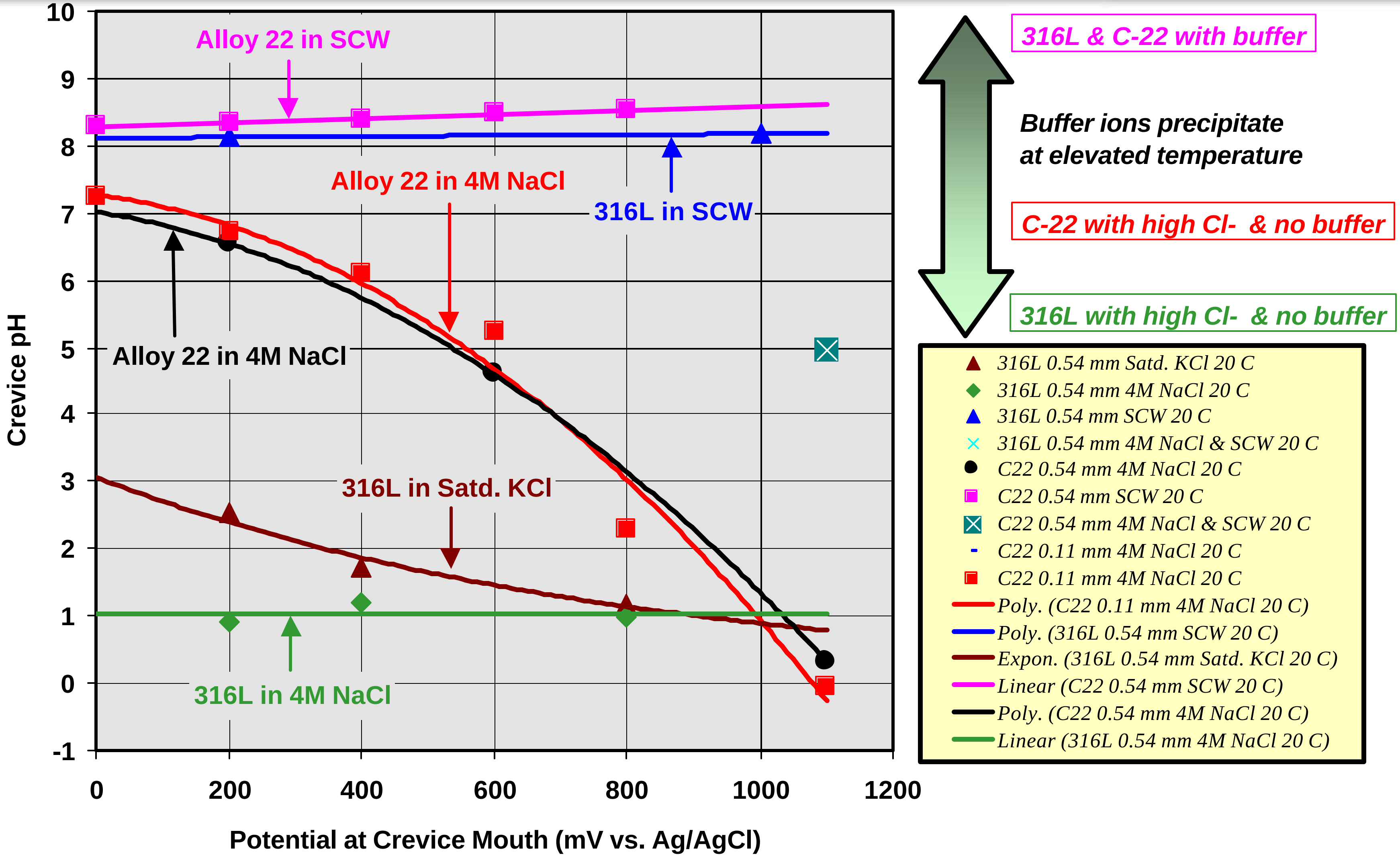
Introduction
(continued)

- **Preliminary conclusions**
  - No significant localized corrosion expected
  - Life not limited by general corrosion
  - Phase stability appears to be acceptable
  - Focus on SCC at final closure weld

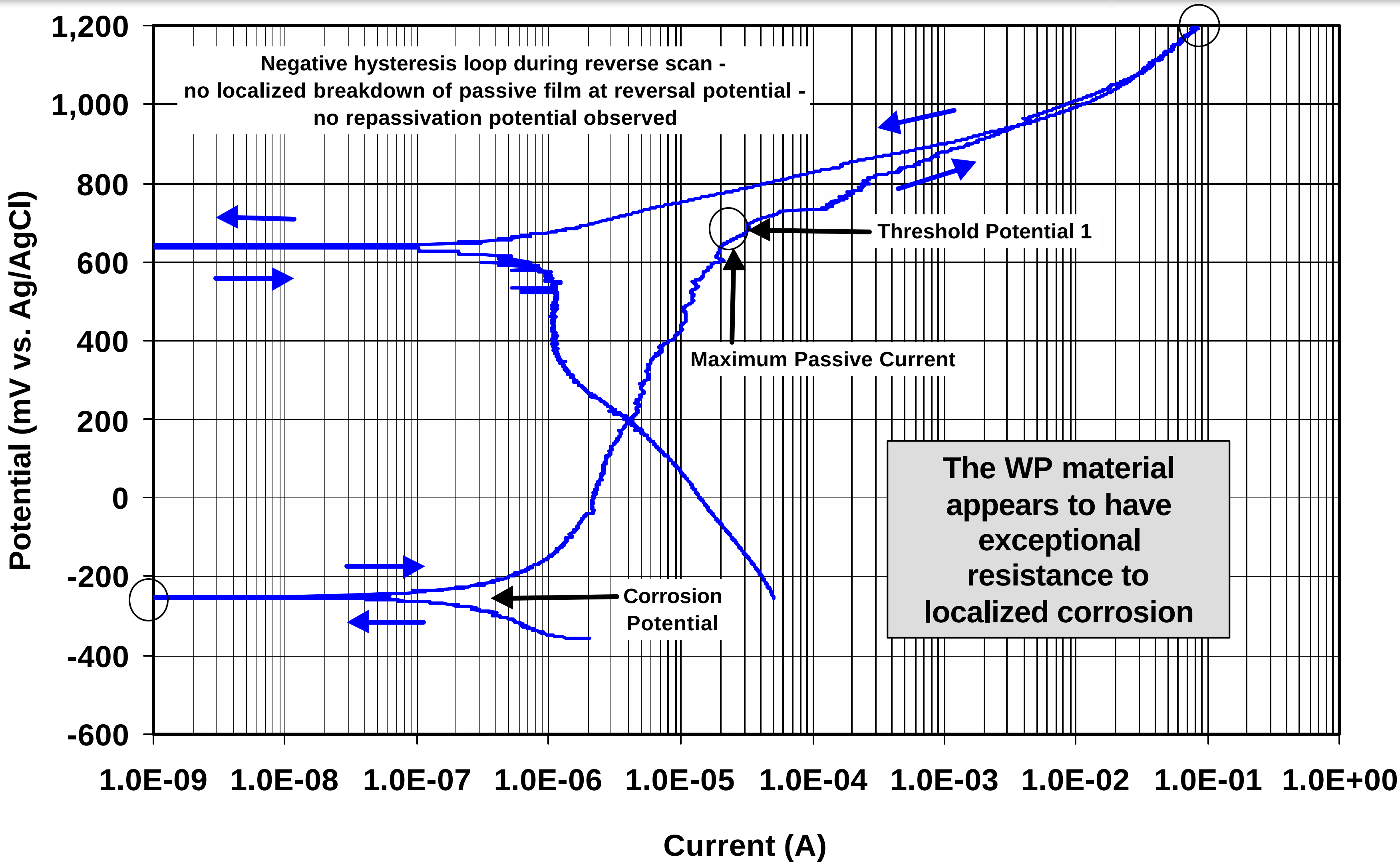
Abstracted Model for Waste Package Degradation



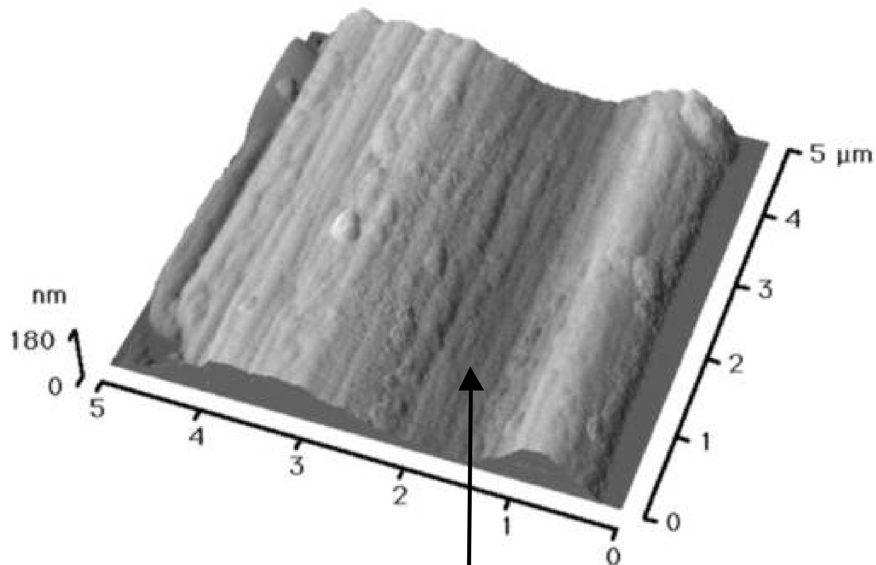
Determination of Crevice pH for Waste Package Materials



Type 1: Alloy 22 in SSW at 120° C (DEA033)



Atomic Force Microscopy of Alloy 22 surface exposed to vapor phase SAW for 1 year at 90°C



Scratch from surface finishing

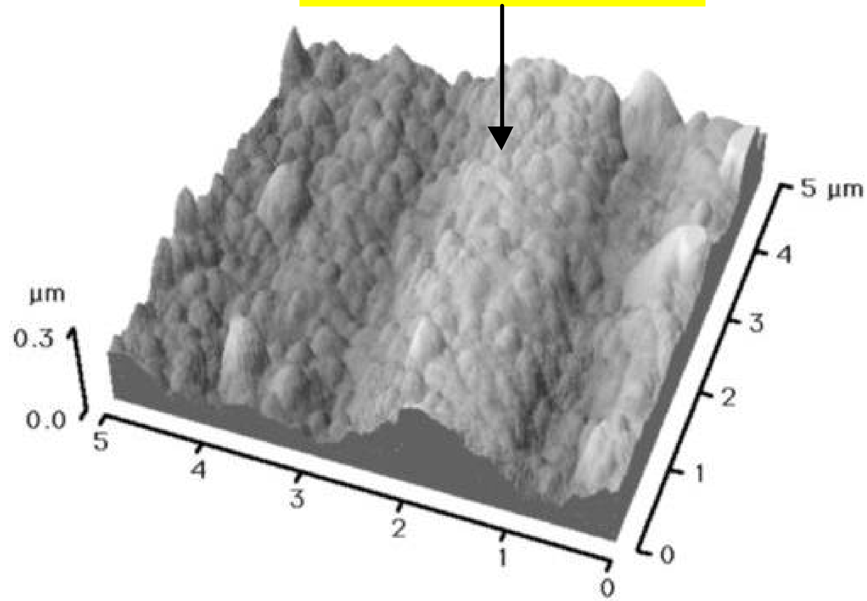
No Exposure (control sample)

The thickness of the oxide grown in one year is consistent with the nominal corrosion rate of 0.05 to 1 micron per year.

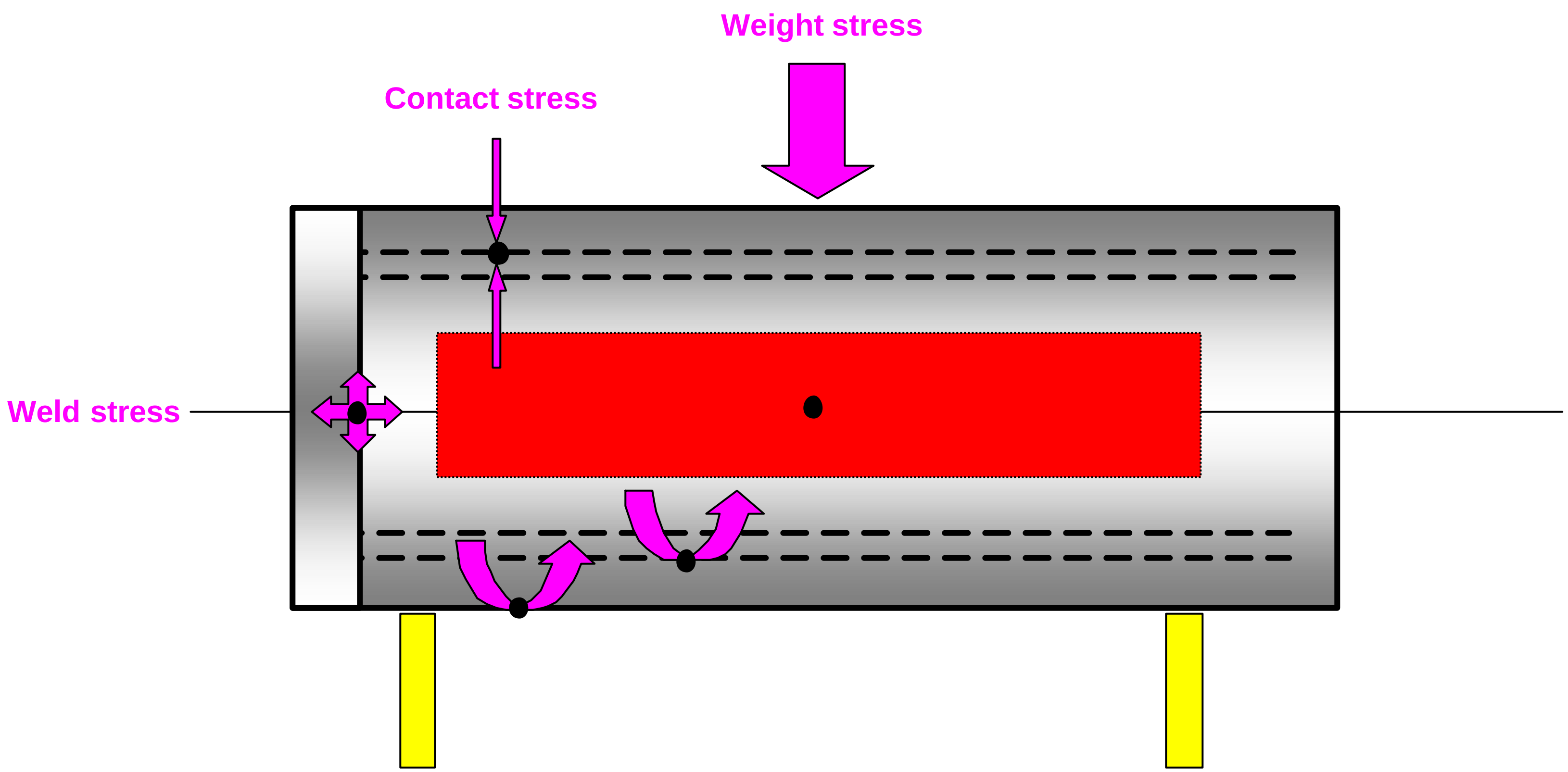
Long Term Corrosion Test Facility at LLNL

Vapor-Phase Exposure (above water line)

General corrosion



SCC Model
Three Primary Contributions to Stress



SCC Model - Critical Stress & Flaw Size

- **Criteria for stress corrosion cracking**

$$K \geq K_{ISCC}$$

- **Stress intensity factor for ideal crack**

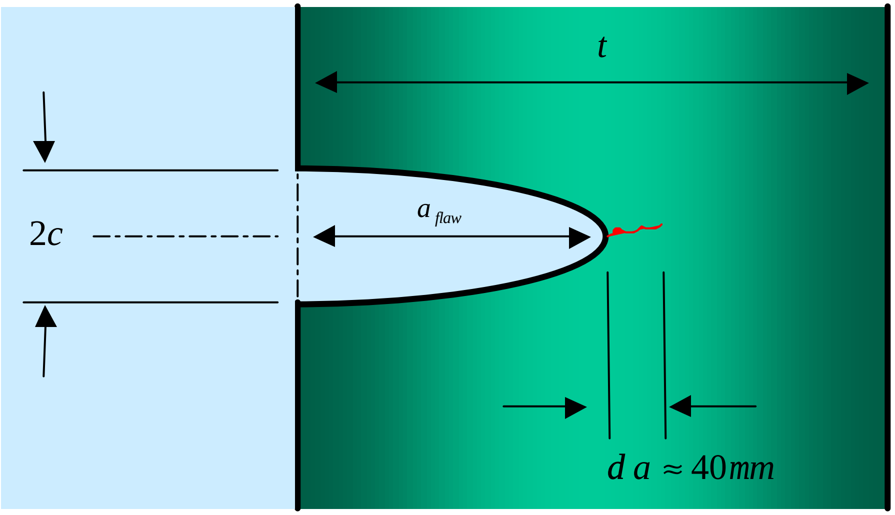
$$K = b s \left(p a\right)^{1/2}$$

- **Stress intensity factor for crack at base of elliptical flaw (or pit)**

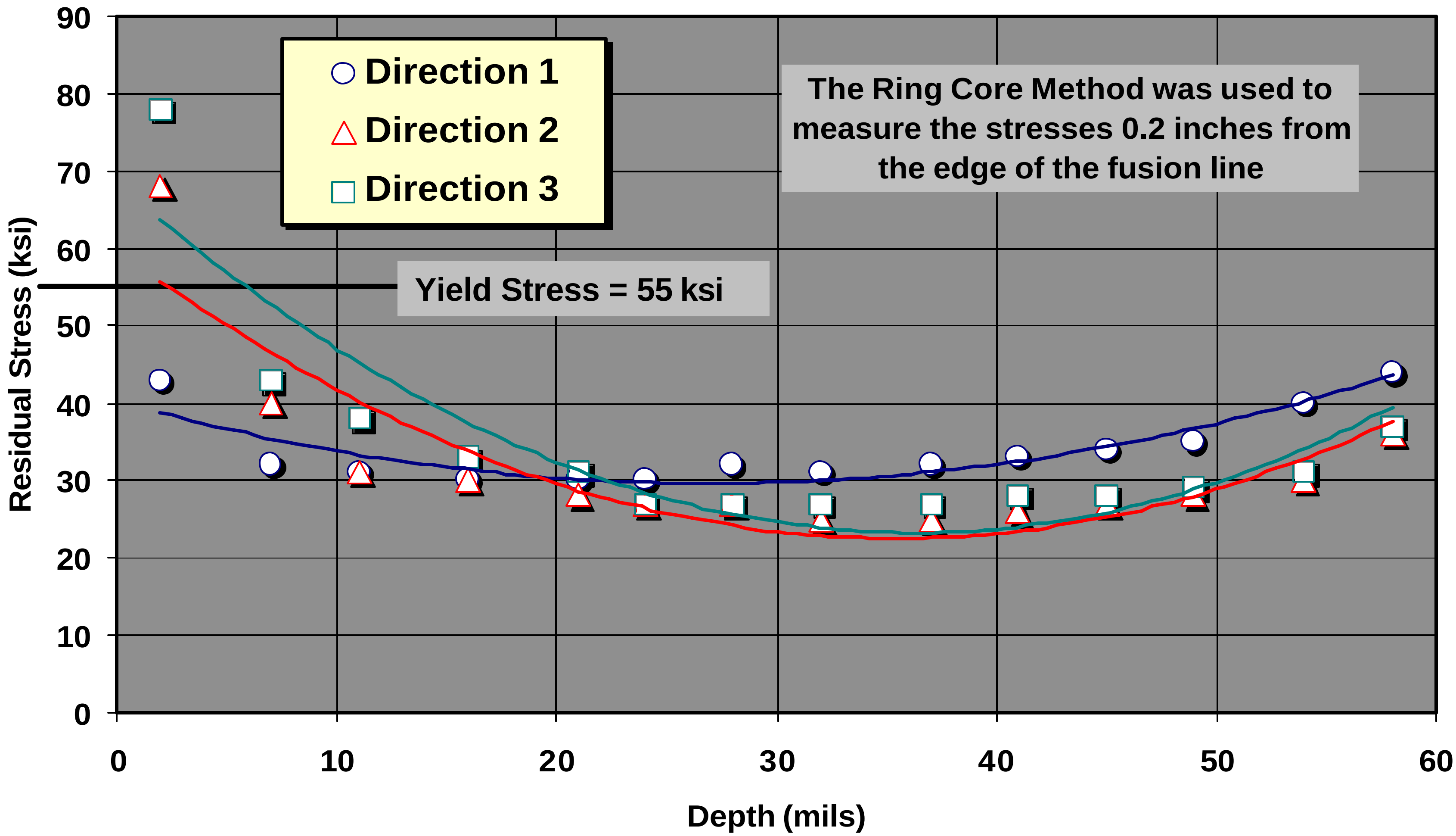
$$K = a b s \left[p\left(a_{flaw} + d a\right)\right]^{1/2}$$

$$K = b K_t s \left(d a\right)^{1/2}$$

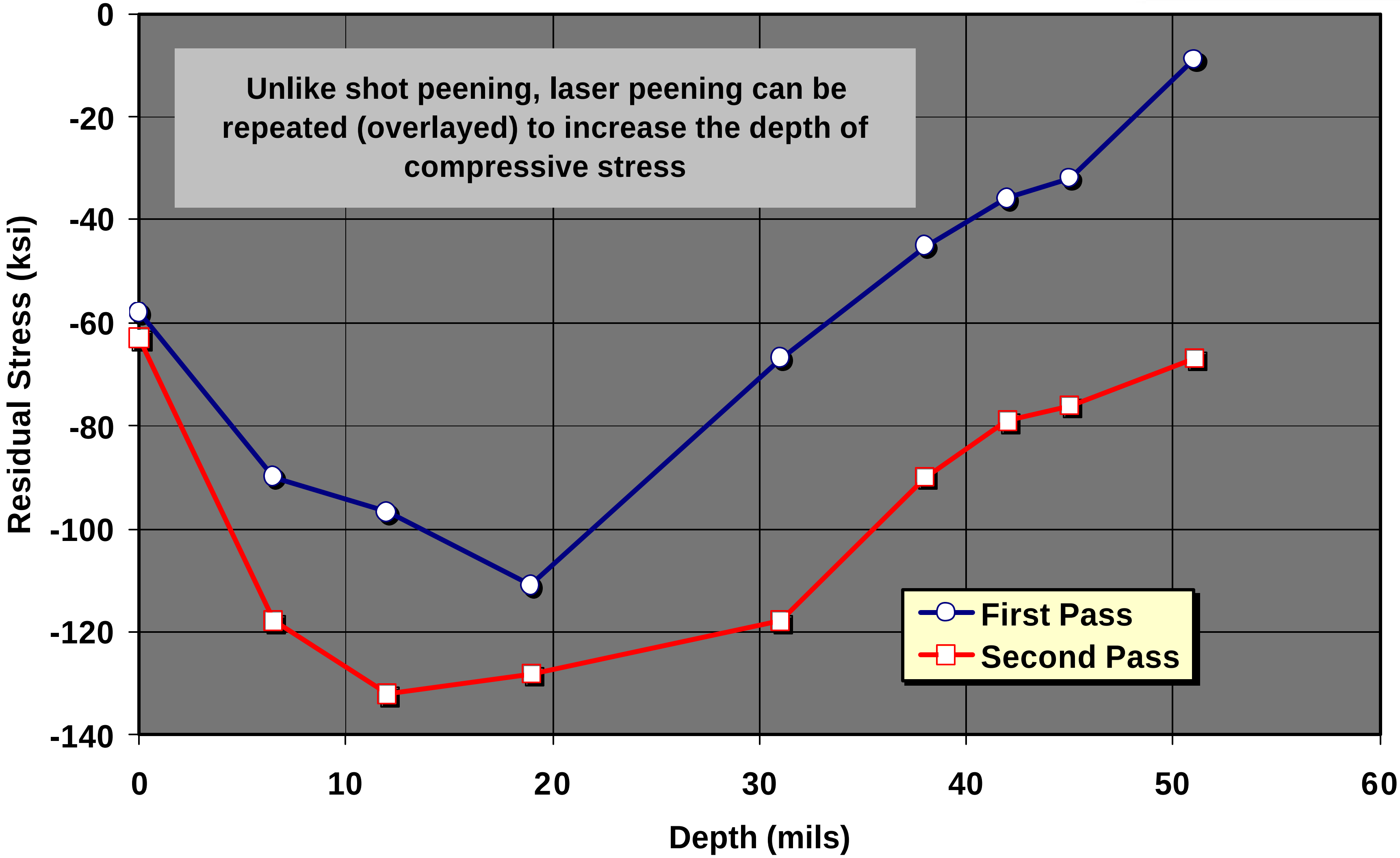
$$K_t = 1 + \frac{2a}{c}$$



Measurement of Residual Weld Stress in a Prototypical Closure Weld of Waste Package



Double-Pass Laser Peening (4340 Steel)



Mechanisms for WP Juvenile Failure

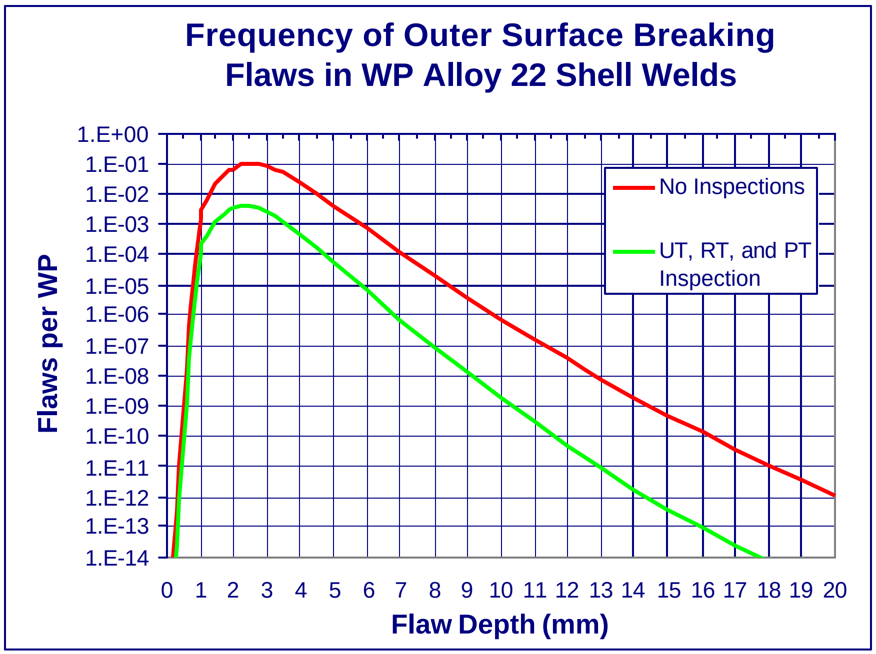
- **Types of generic flaws applicable to waste packages**
  - Weld or base metal flaws
  - Out-of-spec material in weld or base metal
  - Improper heat treatment
  - Surface contamination
  - Handling damage
  - Administrative error leading to unanticipated environment
- **Generic flaws not considered applicable to waste packages include**
  - Improper weld flux
  - Poor weld joint design
  - Missing welds
  - Mislocated welds

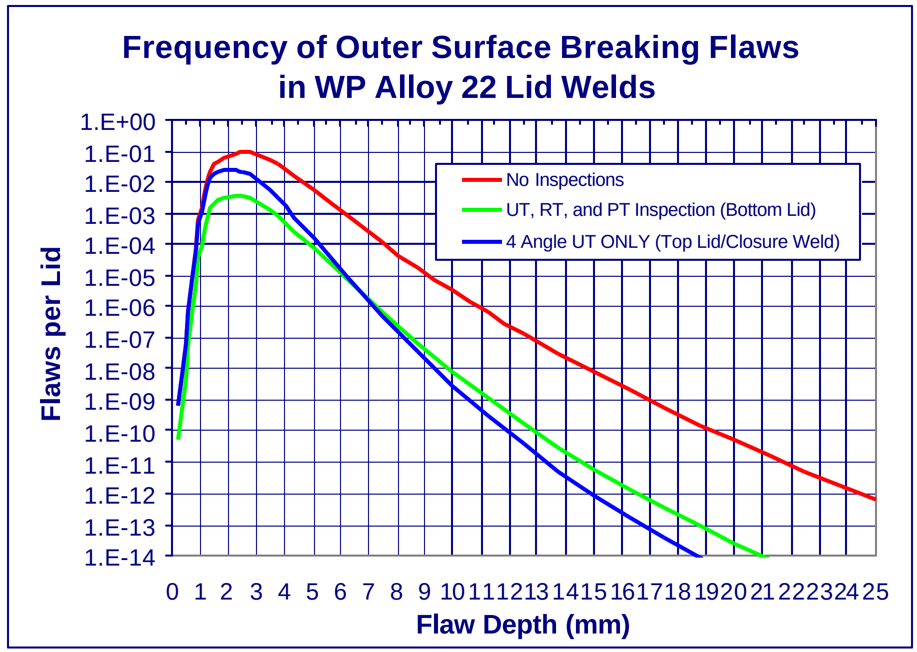
Review of Early Failures in Various Containers

- **Types of containers include:**
  - **Boilers and Pressure Vessels**
  - **Nuclear Fuel Rods**
  - **Radioactive Cesium Capsules**
  - **Dry Storage Casks for SNF**
  - **Food Storage Cans**
- **Manufacturing defect related failure rates in the range of 10^{-4} to 10^{-6} per container**
- **Review identified eleven generic types of flaws that can affect welded metallic containers**

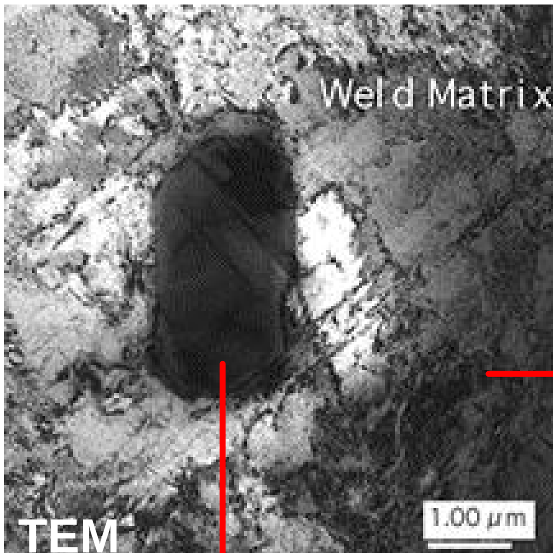
Alloy 22 Weld Flaw Distributions

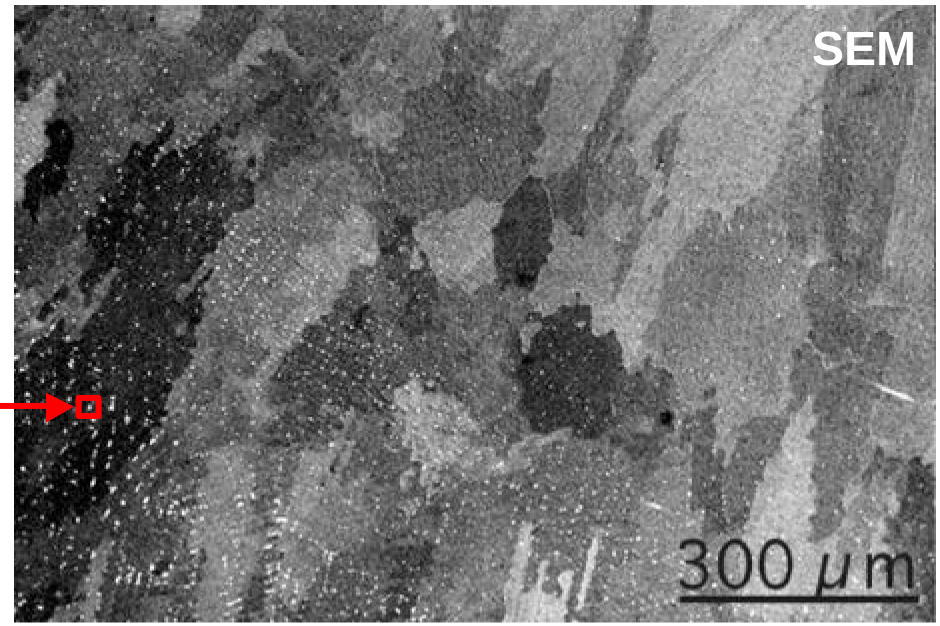
- **Preliminary flaw distributions developed based on data from recent NRC sponsored modeling of nuclear piping welds**
  - **20 mm and 25 mm thick, Stainless Steel, TIG welds**
  - **Includes reliability of UT, PT, and RT inspections as appropriate**





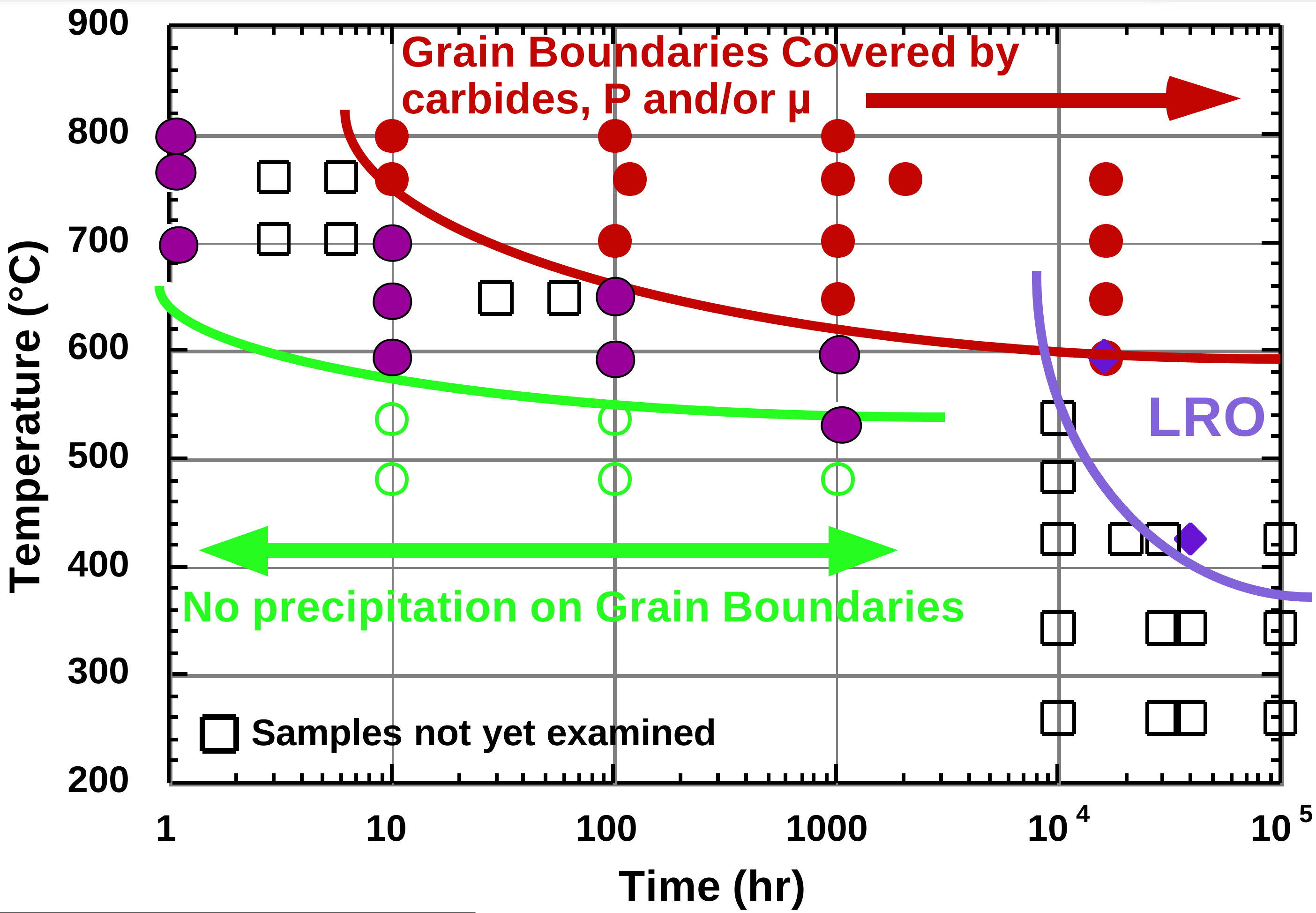
Precipitated μ Phase Observed in Welded Alloy 22 Aged for 40,000 hr at 427°C





Work is now underway at LLNL to better understand formation of intermetallic phases that may form in Alloy 22 welds.

Time Temperature Transformation (TTT) Diagram for Alloy C-22



Applicable to Base Metal

Inputs to Waste Package Degradation Process Model Report

- Environment on Drip Shield & Waste Package Surface (July 99)
- Juvenile Failures (July 99)
- Phase Stability & Aging (July 99)
- Mechanical Failure Due to Rockfall (August 99)
- General Corrosion of Waste Package (July 99)
- Localized Corrosion of Waste Package (July 99)
- General Corrosion of Drip Shield (August 99)
- Localized Corrosion of Drip Shield (August 99)
- Stress Corrosion Cracking of Waste Package (September 99)
- Stress Corrosion Cracking of Drip Shield (September 99)
- Hydrogen Induced Cracking of Drip Shield (September 99)
- Degradation of Stainless Steel Structural Material (September 99)
- Abstractions for WAPDEG (August 99 to October 99)

Important Issues

- **Updated design**
  - **Stainless steel & titanium were not used in TSPA-VA design**
  - **Tests on these materials have just started**
  - **Limited availability of qualified data**
  - **Increased gamma radiolysis**
- **Fabrication processes**
  - **Shrink fitting with outer barrier of Alloy 22**
    - » Precipitation of undesirable phases during heating
    - » Development of excessive tensile stress during cooling
  - **Unannealed closure welds**
    - » Initiation of SCC at weld defects
    - » Possible mitigation of residual weld stress with laser peening

Important Issues
(continued)

- **Competing models for Stress Corrosion Cracking (SCC)**
  - **Initiation based upon threshold stress intensity factor**
    - » Method employed by Yucca Mountain Project
    - » Double Cantilever Beam Method (Ajit Roy)
    - » Data have been obtained for Alloy 22 in NaCl solutions
  - **Finite propagation rate based upon film-rupture model**
    - » Method employed by General Electric Corporation
    - » Reverse DC Method (Peter Andresen)
    - » No data have been generated for Alloy 22

Important Issues
(continued)

- **Microbial Influenced Corrosion (MIC)**
  - **Microbes may pose unique threats**
    - » Sulfate reducing bacteria could produce sulfide, a species known to promote SCC of Alloy 22
    - » Iron oxidizing bacteria could convert Fe(II) to Fe(III), thereby pushing the corrosion potential closer to threshold for localized attack
  - **Quantitative models have not yet been developed**

Important Issues

(continued)

- **Effects of increased radiation field on corrosion processes**
  - Gamma radiolysis can produce hydrogen peroxide
  - Hydrogen peroxide can shift the corrosion potential in anodic direction closer to thresholds for localized attack
- **A strategy has been formulated for addressing any enhanced radiolysis effects in the EDA II design**
  - Re-examination stainless steel corrosion data from gamma pit that was produced by Yucca Mountain Project in the mid 1980's
  - Discussion & collaboration with investigators at General Electric Corporation
  - In the absence of gamma radiation, investigate the effect of hydrogen peroxide concentration on the corrosion potential (and other electrochemical responses) of WP materials
  - Repeat gamma pit studies with Alloy 22 and Ti Gr 7, thereby augmenting early Project data for stainless steels

Summary

- **Long-term containment (10,000 years) requires materials with exceptional corrosion resistance**
  - **Very small penetration rates must be measured**
  - **Measurement error must be minimized to the extent possible**
- **Site Recommendation (SR) & License Application (LA) require credible predictive models based on sound understanding**
- **Such models have been developed for relevant degradation modes**
  - **General & Localized Corrosion**
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Summary
(continued)

- **Preliminary conclusions**
  - No significant localized corrosion expected
  - Life not limited by general corrosion
  - Phase stability appears to be acceptable
  - Focus on SCC at final closure weld

Scientific & Technical Contributions

- **Definition of Interfacial Waste Package Environment**
  —Greg Gdowski & Francis Wang
- **Long Term Corrosion Testing**
  —Dan McCright, John Estill, Ken King, Steve Gordon & Larry Logotetta
- **Electrochemical Studies & Surface Physics**
  —Joe Farmer, John Estill, Ken King, Steve Gordon & Larry Logotetta
  —Peter Bedrossian & David Fix
- **Phase Stability**
  —Tammy Summers, Patrice Turchi & Larry Kaufman
- **Stress Corrosion Cracking Studies**
  —Ajit Roy, John Estill, Maura Spragge, Dennis Fleming & Beverly Lum
- **Microbial Influenced Corrosion**
  —JoAnn Horn, Denny Jones, Tiangan Lian,
- **Welding Processes, Residual Stress Analysis & Laser Peening**
  —Don Stevens, Lloyd Hackel, Fritz Harris (MIC) & Al Lingenfelter
- **Waste Package Modeling**
  —Joe Farmer, Stephen Lu, Bob Riddle & Jia-Song Huang

Additional Supporting Data

- **Cyclic Polarization**
  - Pt baseline
  - Type 1: Alloy 22 in SAW
  - Type 2: Alloy 22 in SCW
  - Type 3: 316L in SSW
  - Type 4: Ti Gr 7 in SSW
- **Crevice pH & Current**
  - Stainless Steel 316L: 4M NaCl, 200 mV, 23 Centigrade - pH
  - Alloy 22 in 4M NaCl at 23 Centigrade - pH
  - Alloy 22 in 4M NaCl at 23 Centigrade - Current
  - Alloy 22 in SCW at 23 Centigrade - pH
  - Determination of Crevice pH for WP Materials

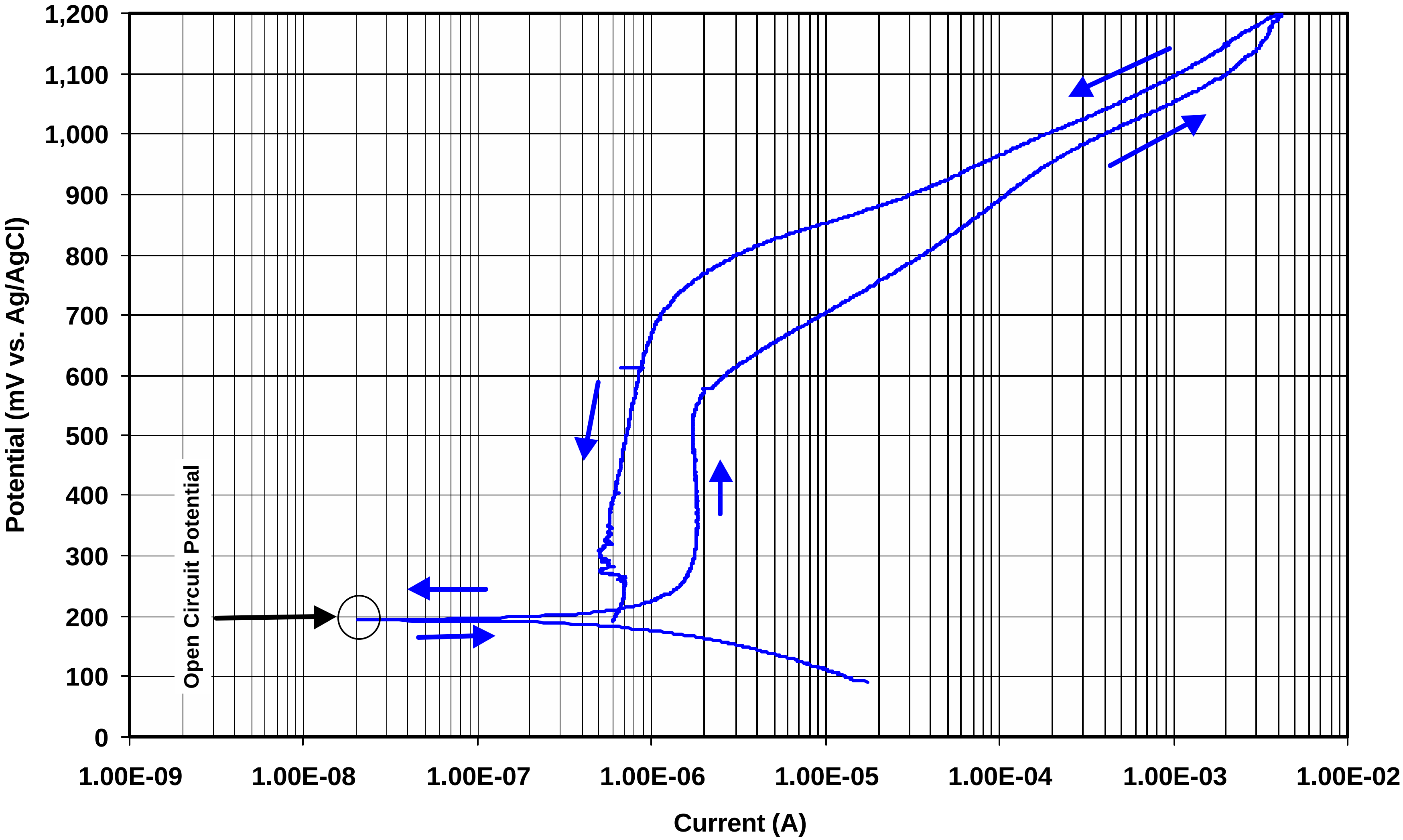
Additional Supporting Data

- **Long Term Corrosion Testing Facility Data**
  - Dissolved Oxygen in LTCTF
  - General Corrosion of Alloy 22: Weight Loss Samples
  - General Corrosion of Ti Gr 16: Crevice Corrosion Samples
  - Analysis of Error in Corrosion Rate Measurements
  - AFM of Alloy 22 Samples from LTCTF
  - AFM of Patterned Samples
- **Weld & Stress Corrosion Cracking**
  - Residual Stress in Prototypical Welds of Alloy 22
  - SSRT of Alloy 22
  - SSRT of Ti Gr 12 (Ti Gr 7 analog)

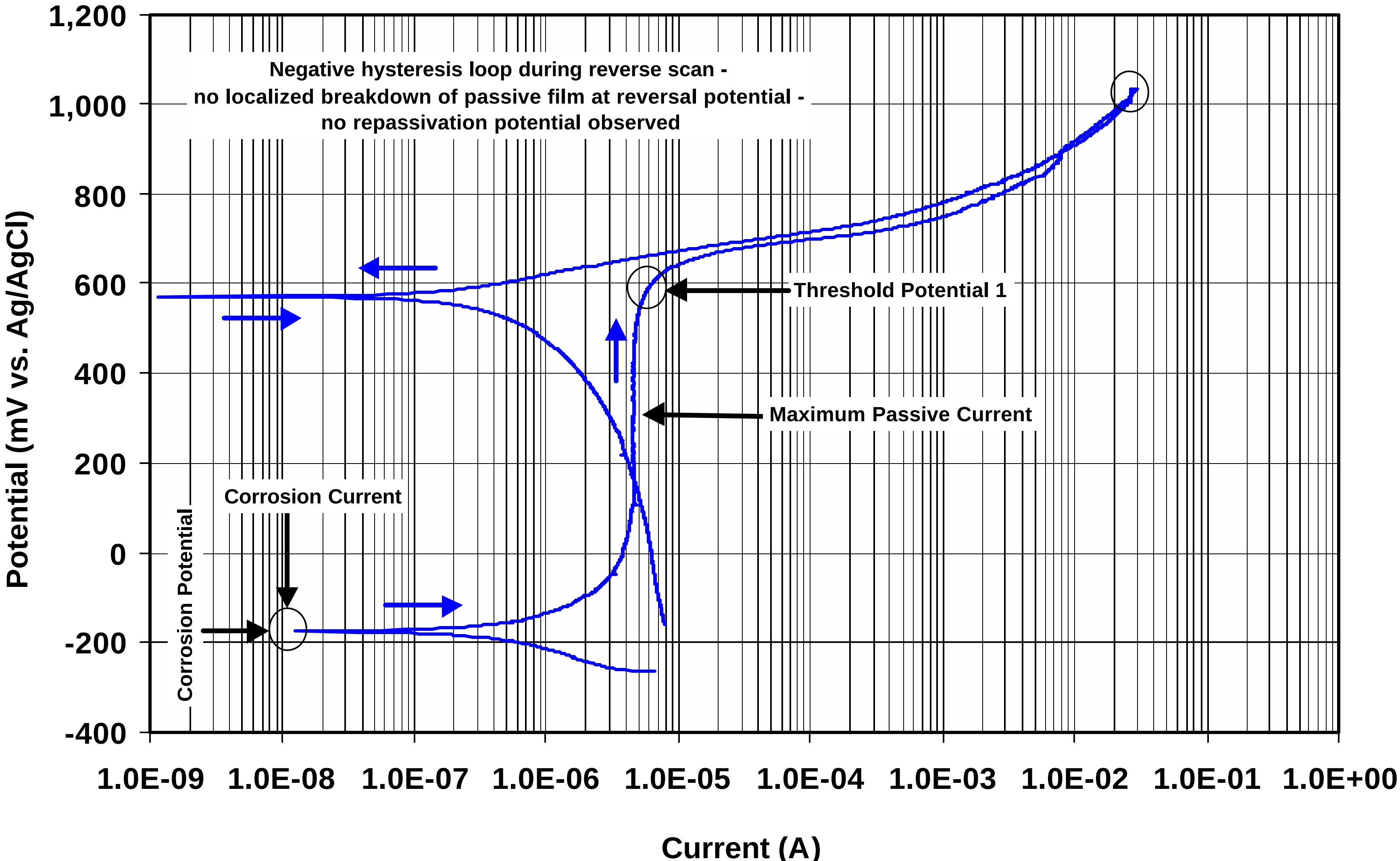
Additional Supporting Data
(continued)

- **Phase Stability**
  - **Complete Coverage of Alloy 22 GBs at High Temperature**
  - **88,000 Years Required**
- **Juvenile Failure Model**

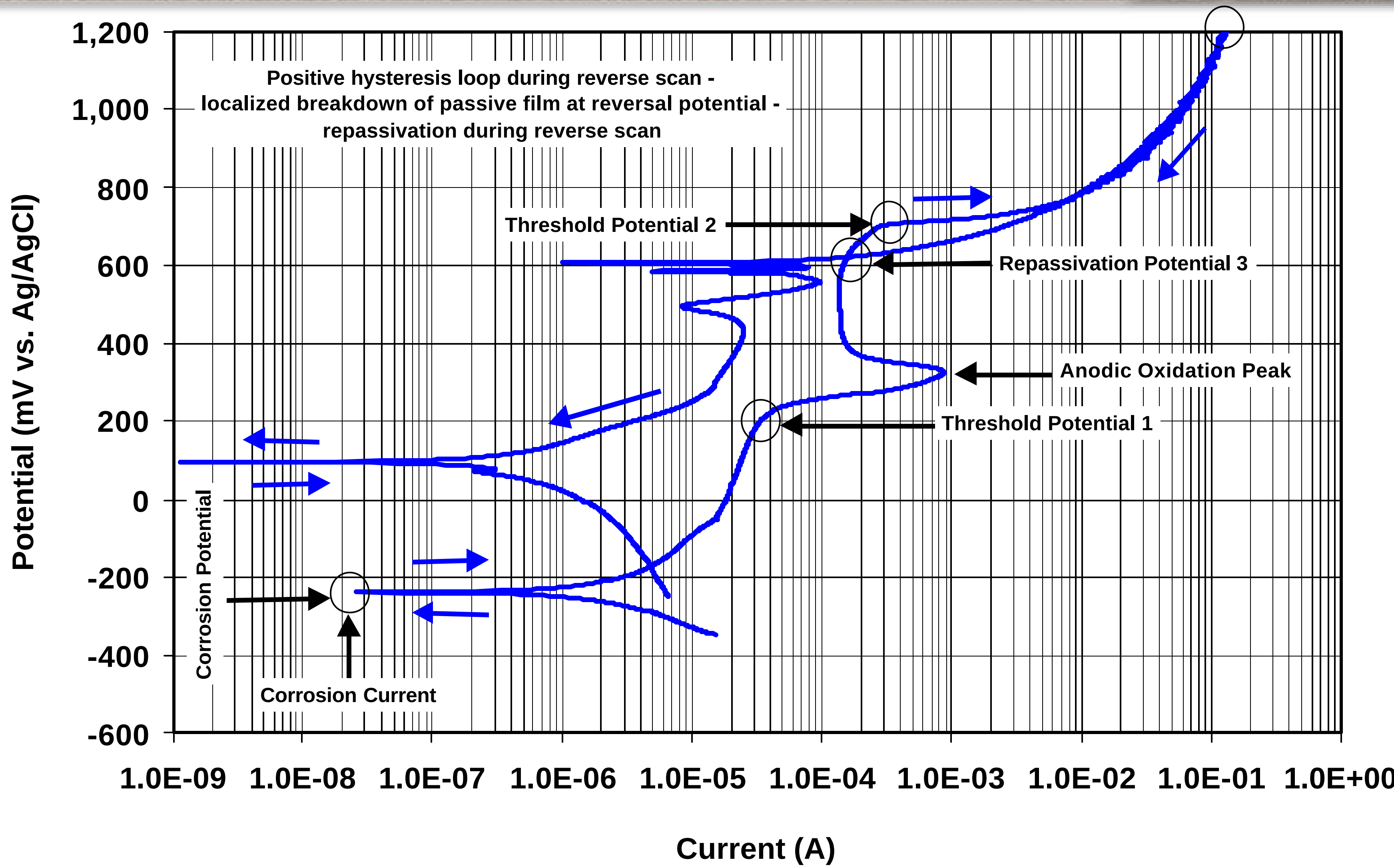
Baseline: Pt in SCW at 90° C (PT001)



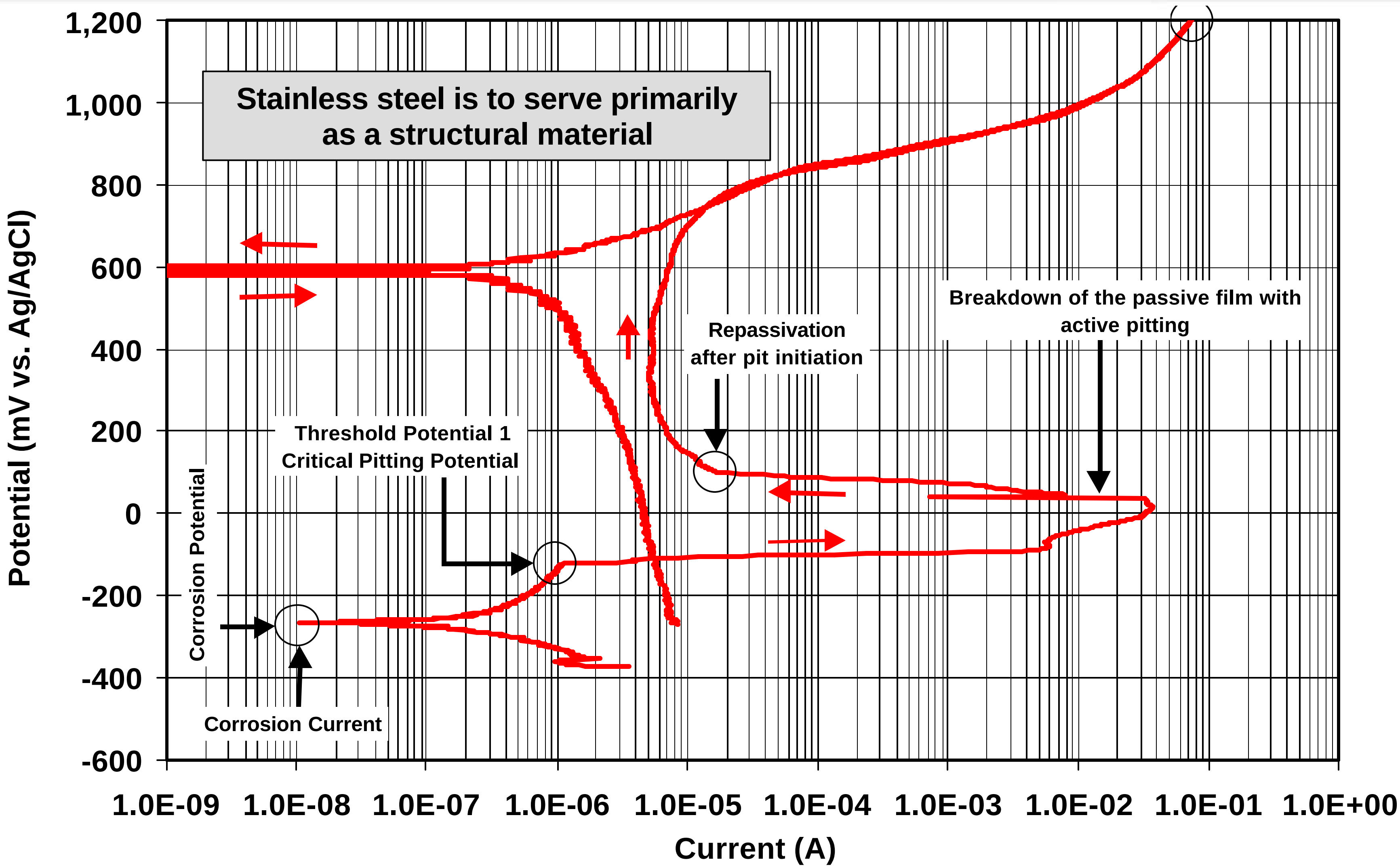
Type 1: Alloy 22 in SAW at 90° C (DEA002)



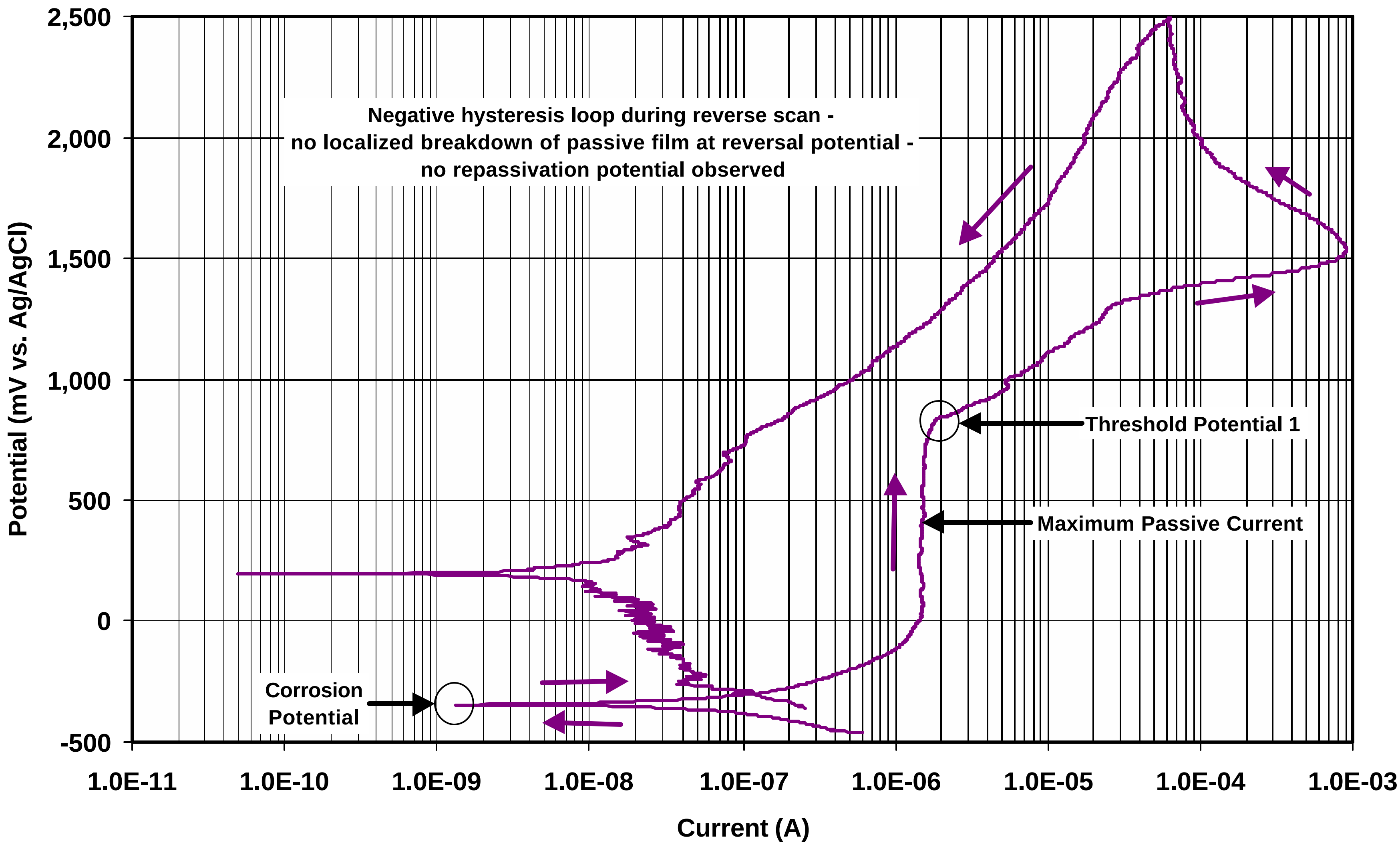
Type 2: Alloy in SCW at 90° C (DEA016)



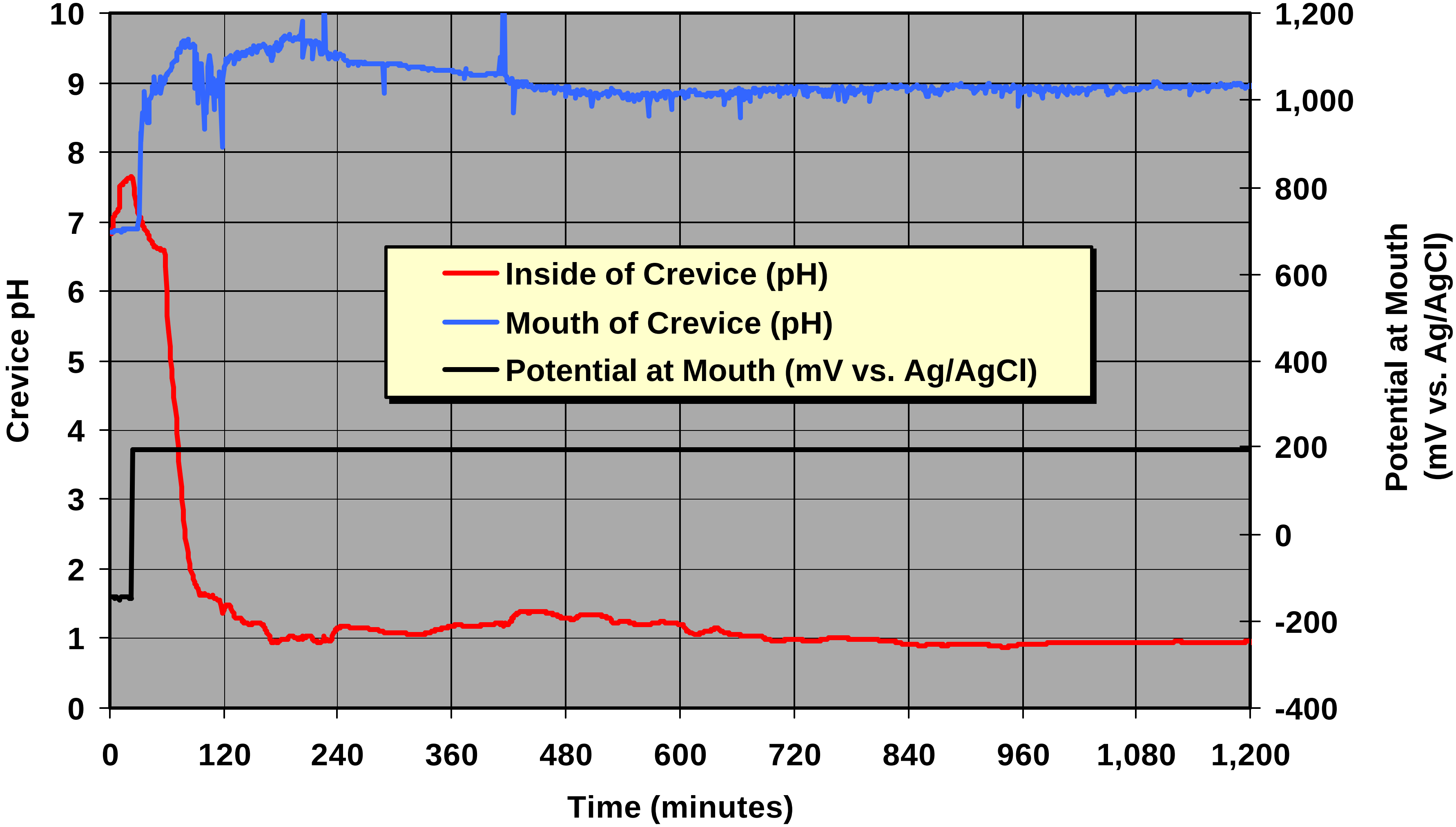
Type 3: 316L in SSW at 100° C (PEA016)



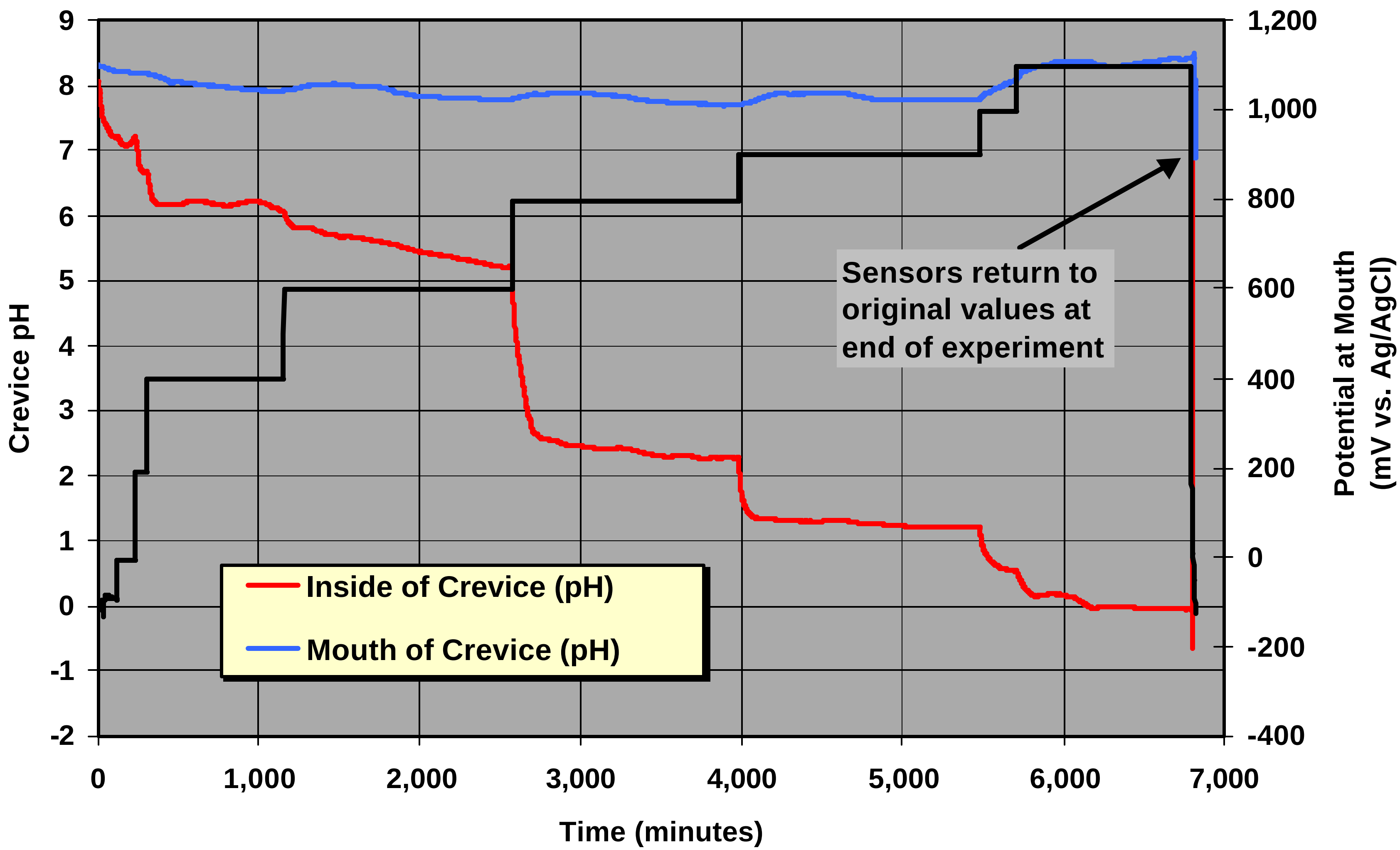
Type 4: Ti Gr 7 in SSW at 120° C (NEA031s)



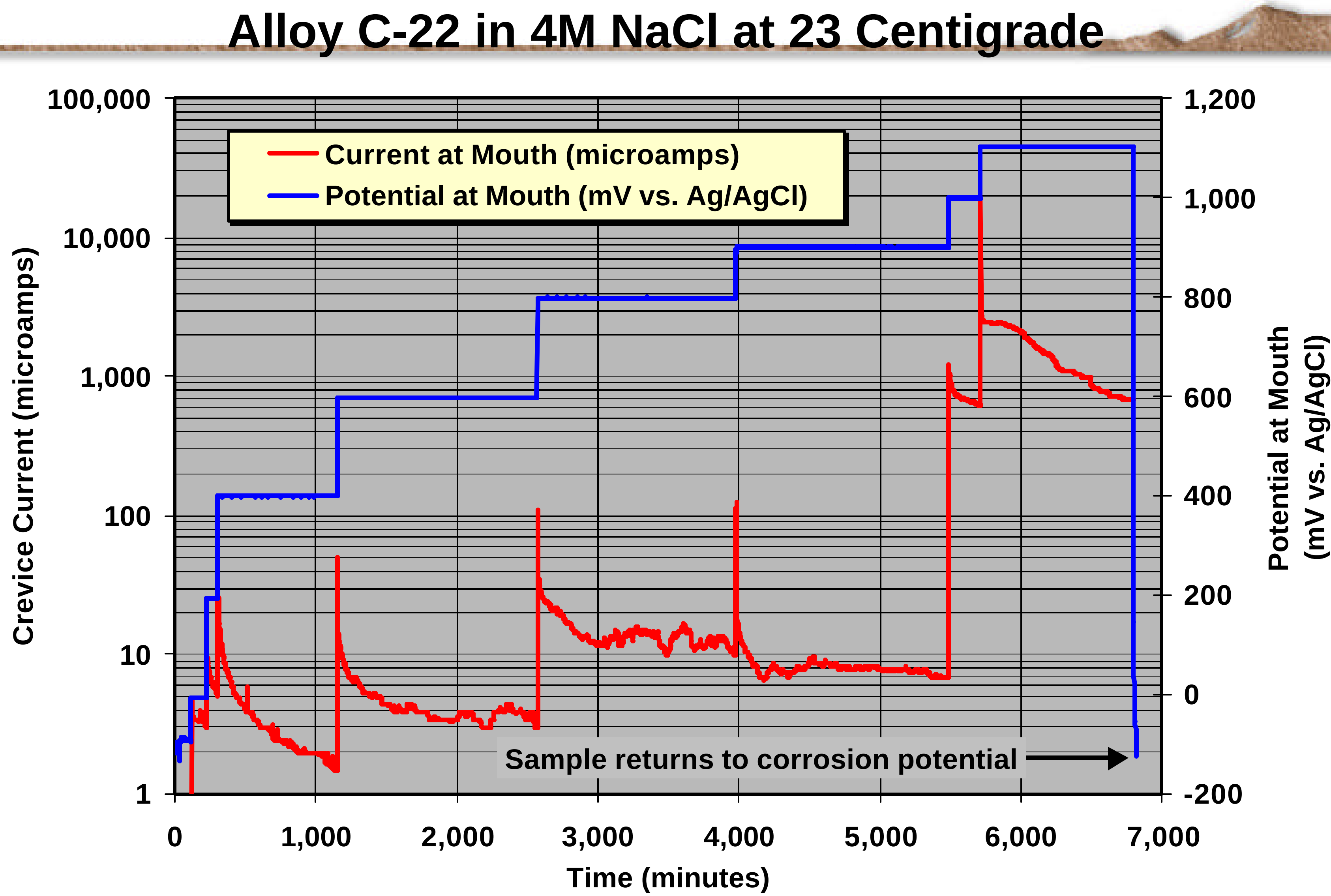
Stainless Steel 316L: 4 M NaCl, 200mV and 23° C



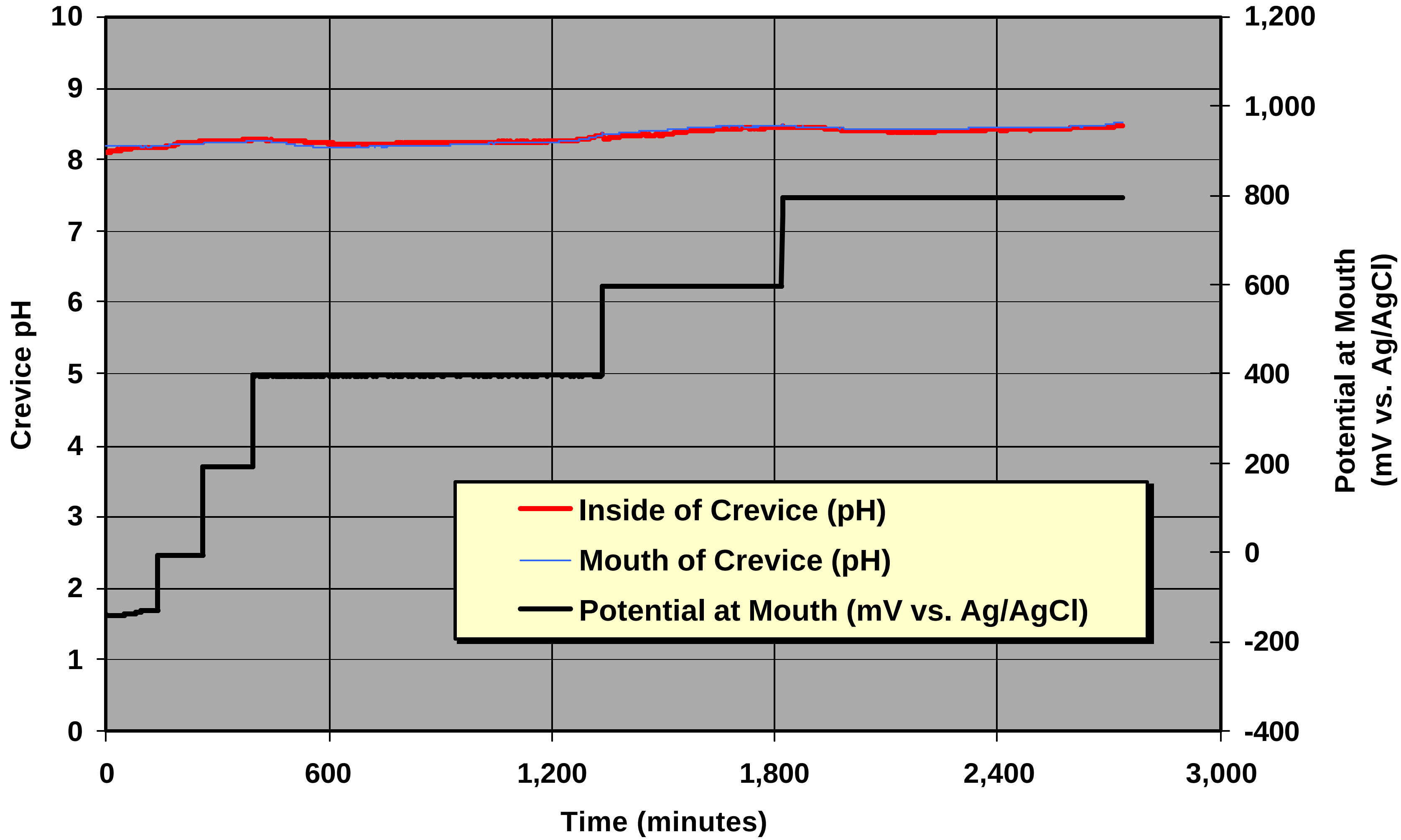
Alloy C-22 in 4 M NaCl at 23° C



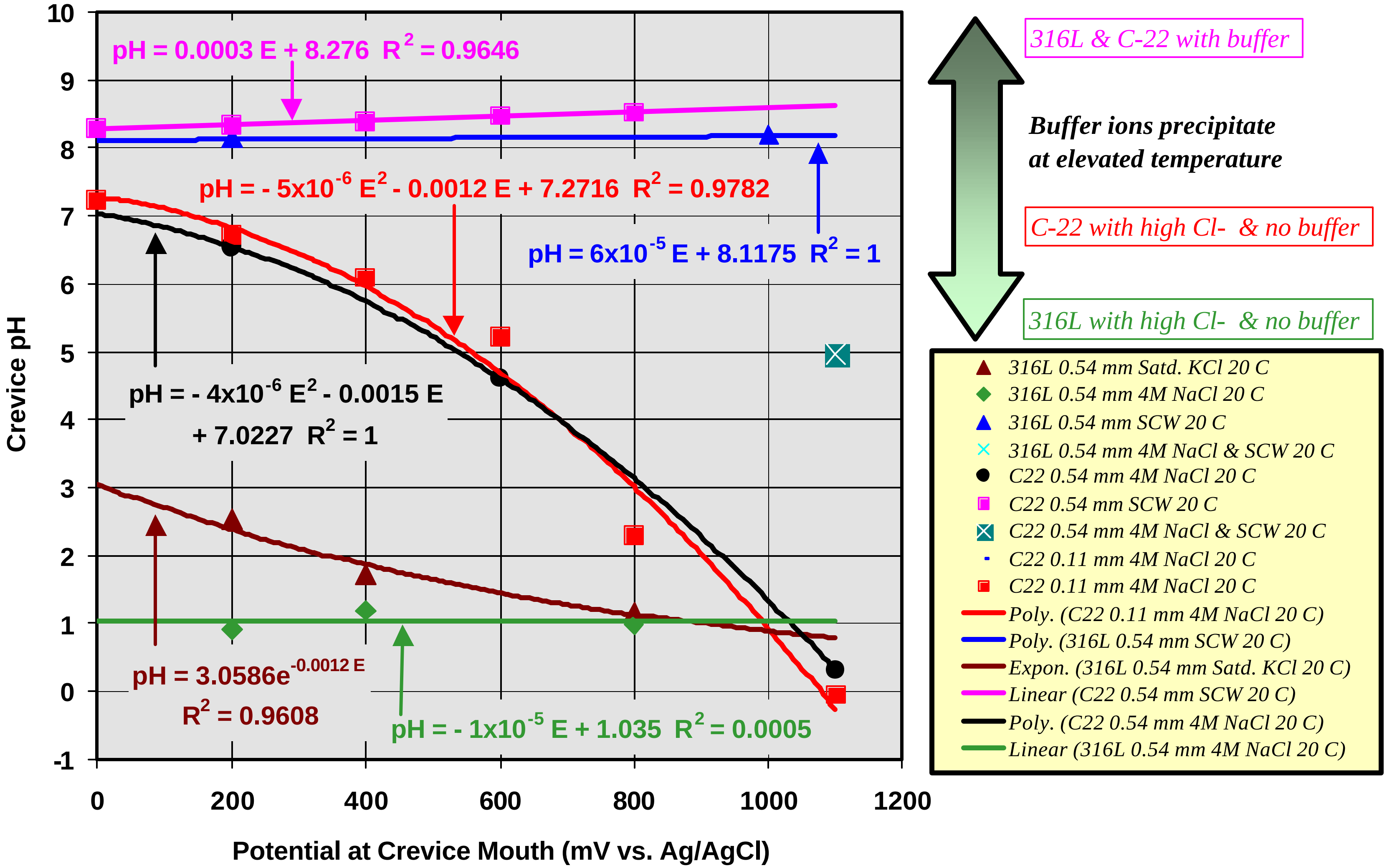
Alloy C-22 in 4 M NaCl at 23° C



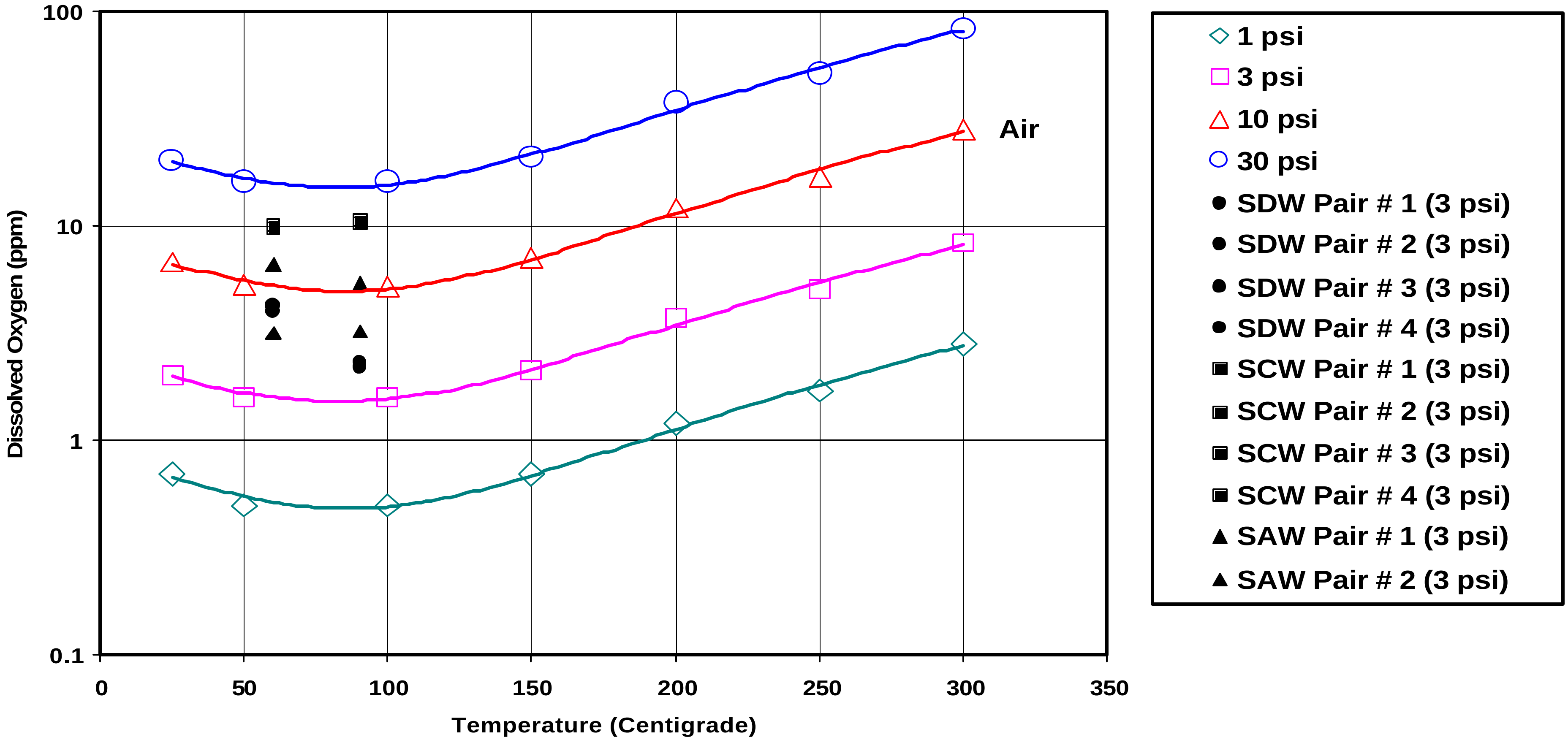
Alloy C-22 in SCW at 23° C



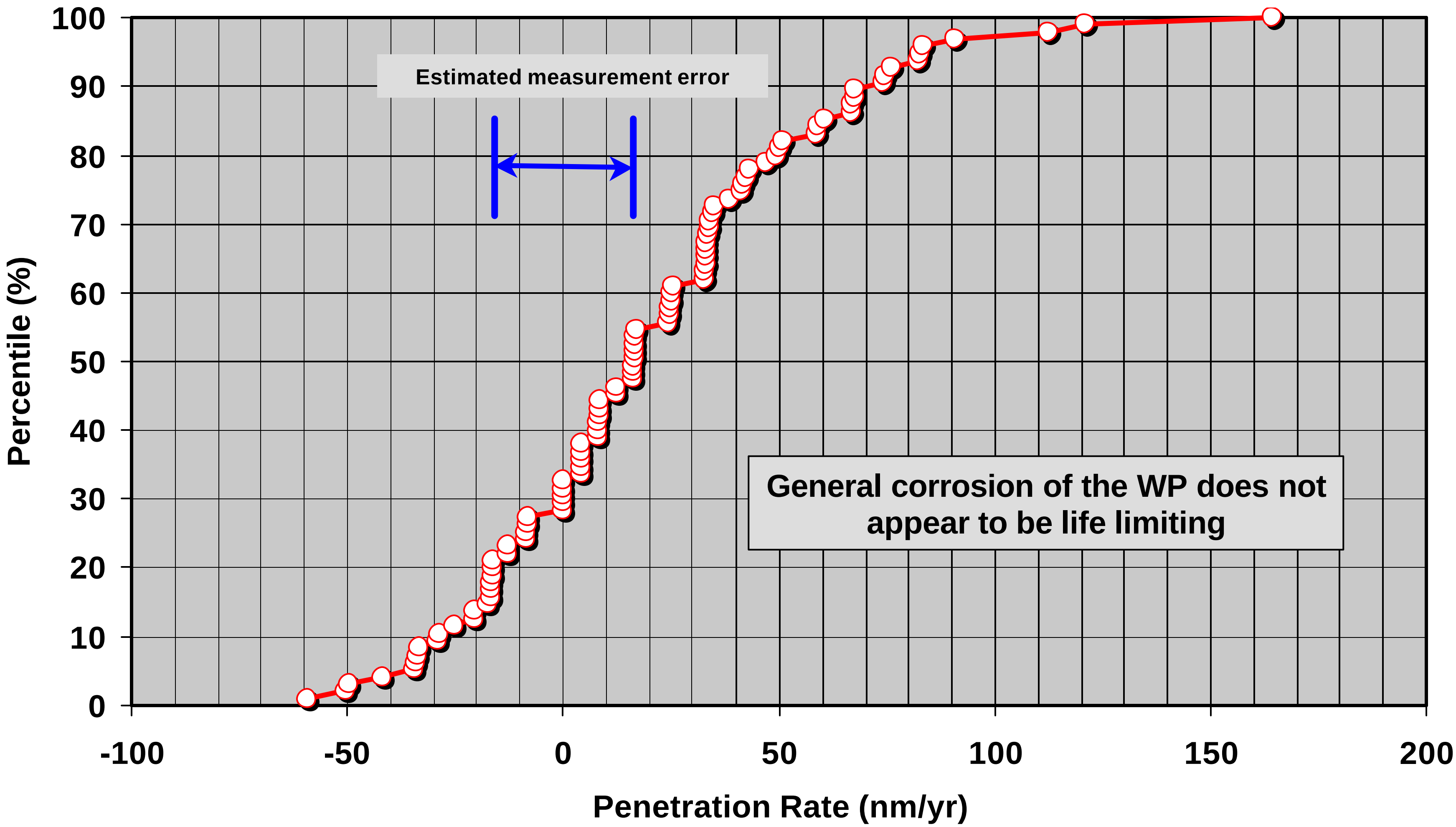
Determination of Crevice pH for Waste Package Materials



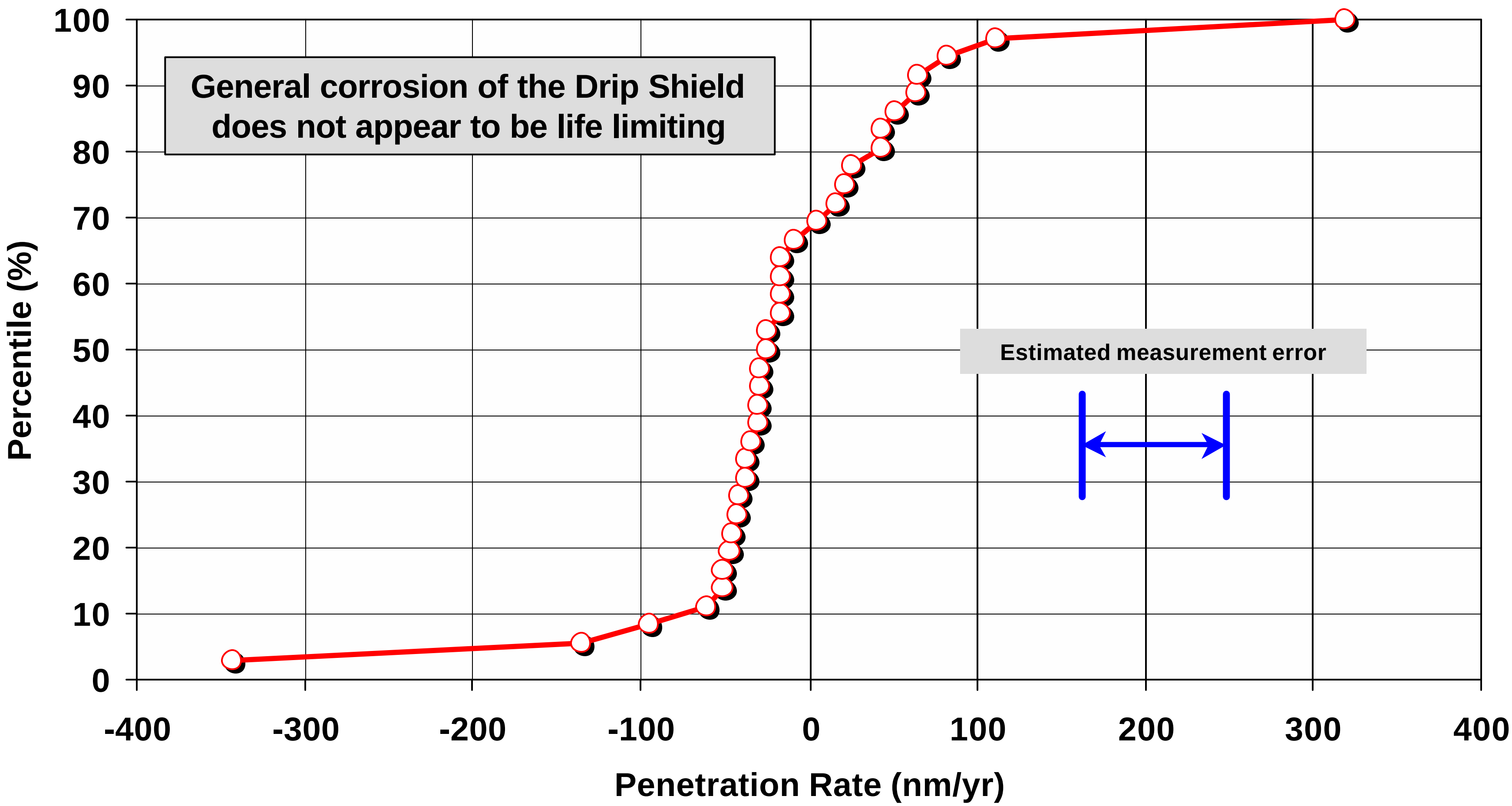
Comparison of Dissolved Oxygen Measurements in LTCTF to Data for Synthetic Geothermal Brine



General Corrosion of Alloy 22 Weight Loss Samples from LTCTF



General Corrosion of Ti Gr 16 Crevice Samples from LTCTF



Analysis of Error in Measurement of General Corrosion: Total Derivative

$$y = f(x_1, x_2, x_3, x_4 \cdots x_n)$$

$$dy = \frac{\partial y}{\partial x_1} dx_1 + \frac{\partial y}{\partial x_2} dx_2 + \frac{\partial y}{\partial x_3} dx_3 + \frac{\partial y}{\partial x_4} dx_4 + \cdots + \frac{\partial y}{\partial x_n} dx_n$$

$$dy = \sum_{j=1}^{n} \frac{\partial y}{\partial x_j} dx_j$$

$$\Delta y = \left|\frac{\partial y}{\partial x_1} \Delta x_1\right| + \left|\frac{\partial y}{\partial x_2} \Delta x_2\right| + \left|\frac{\partial y}{\partial x_3} \Delta x_3\right| + \left|\frac{\partial y}{\partial x_4} \Delta x_4\right| + \cdots + \left|\frac{\partial y}{\partial x_n} \Delta x_n\right|$$

$$\Delta y = \sum_{j=1}^{n} \left|\frac{\partial y}{\partial x_j} \Delta x_j\right|$$

Analysis of Error in Measurement of General Corrosion Rate: Application to Weight Loss Formula

$$\frac{dp}{dy} = \frac{w}{r \times t} \frac{1}{[2(a \times b) + 2(b \times c) + 2(a \times c)]} \qquad y = \frac{dp}{dt}$$

$$dy = \frac{\partial y}{\partial w} dw + \frac{\partial y}{\partial r} dr + \frac{\partial y}{\partial t} dt + \frac{\partial y}{\partial a} da + \frac{\partial y}{\partial b} db + \frac{\partial y}{\partial c} dc$$

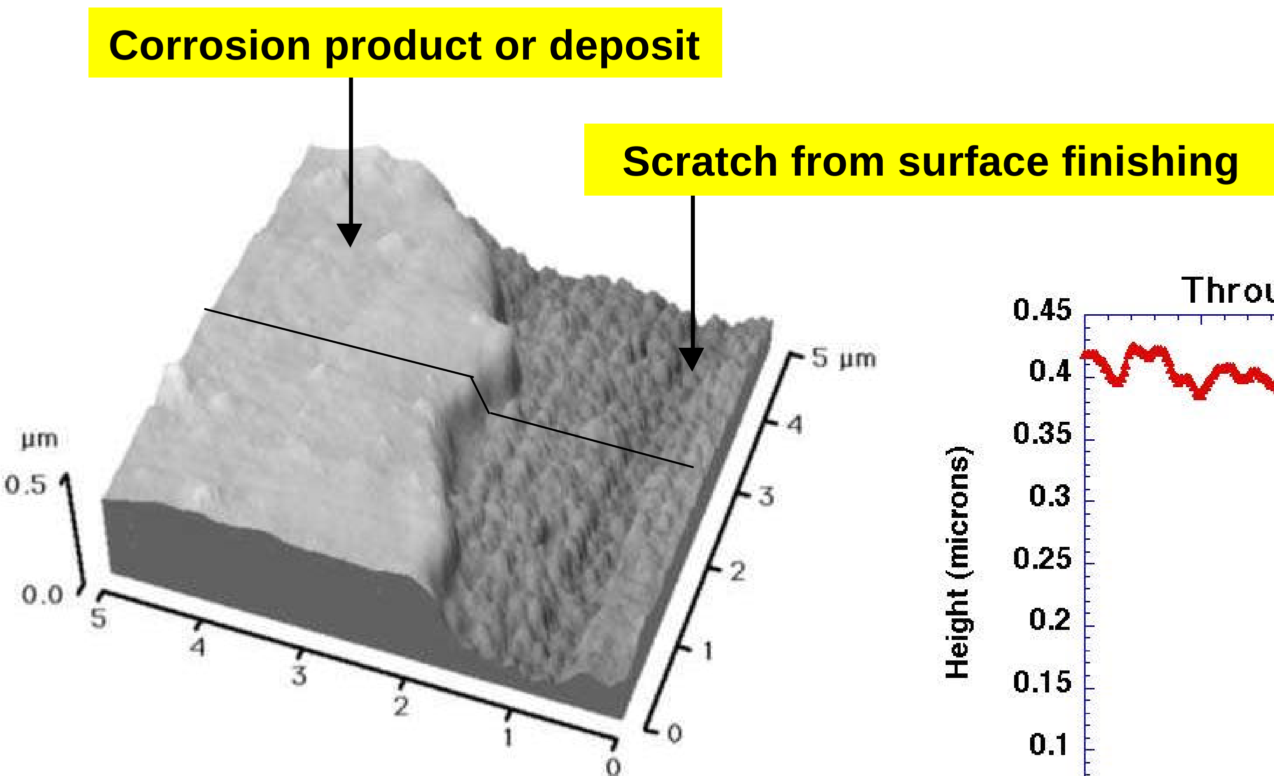
$$\Delta y = \left| \frac{\partial y}{\partial w} \Delta w \right| + \left| \frac{\partial y}{\partial r} \Delta r \right| + \left| \frac{\partial y}{\partial t} \Delta t \right| + \left| \frac{\partial y}{\partial a} \Delta a \right| + \left| \frac{\partial y}{\partial b} \Delta b \right| + \left| \frac{\partial y}{\partial c} \Delta c \right|$$

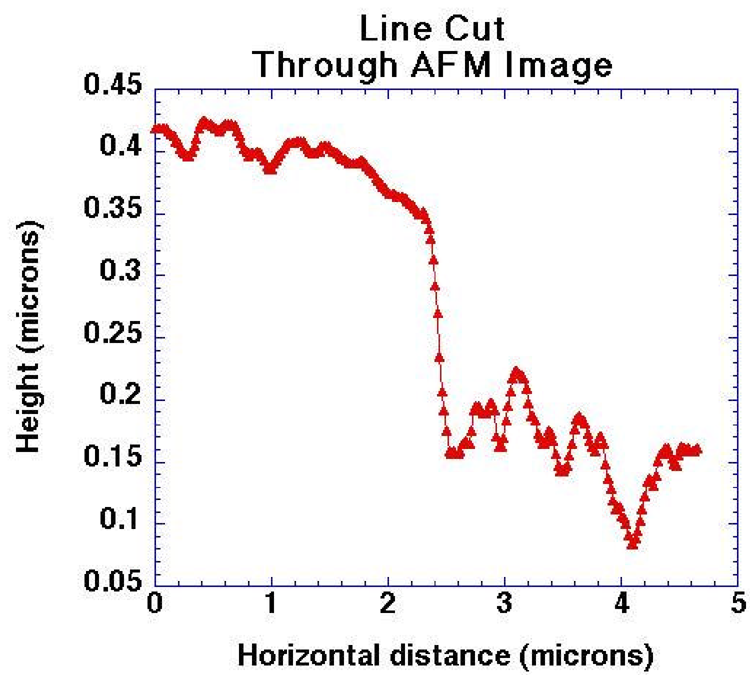
$$\frac{\partial y}{\partial w} = \frac{1}{r \times t} \frac{1}{[2(a \times b) + 2(b \times c) + 2(a \times c)]} \qquad \frac{\partial y}{\partial a} = \frac{w}{r \times t} \frac{[2b + 2c]}{[2(a \times b) + 2(b \times c) + 2(a \times c)]^2}$$

$$\frac{\partial y}{\partial r} = \frac{w}{r^2 \times t} \frac{1}{[2(a \times b) + 2(b \times c) + 2(a \times c)]} \qquad \frac{\partial y}{\partial b} = \frac{w}{r \times t} \frac{[2a + 2c]}{[2(a \times b) + 2(b \times c) + 2(a \times c)]^2}$$

$$\frac{\partial y}{\partial t} = \frac{w}{r \times t^2} \frac{1}{[2(a \times b) + 2(b \times c) + 2(a \times c)]} \qquad \frac{\partial y}{\partial c} = \frac{w}{r \times t} \frac{[2a + 2b]}{[2(a \times b) + 2(b \times c) + 2(a \times c)]^2}$$

Atomic Force Microscopy of Alloy 22 surface exposed to liquid phase SAW for 1 year at 90°C



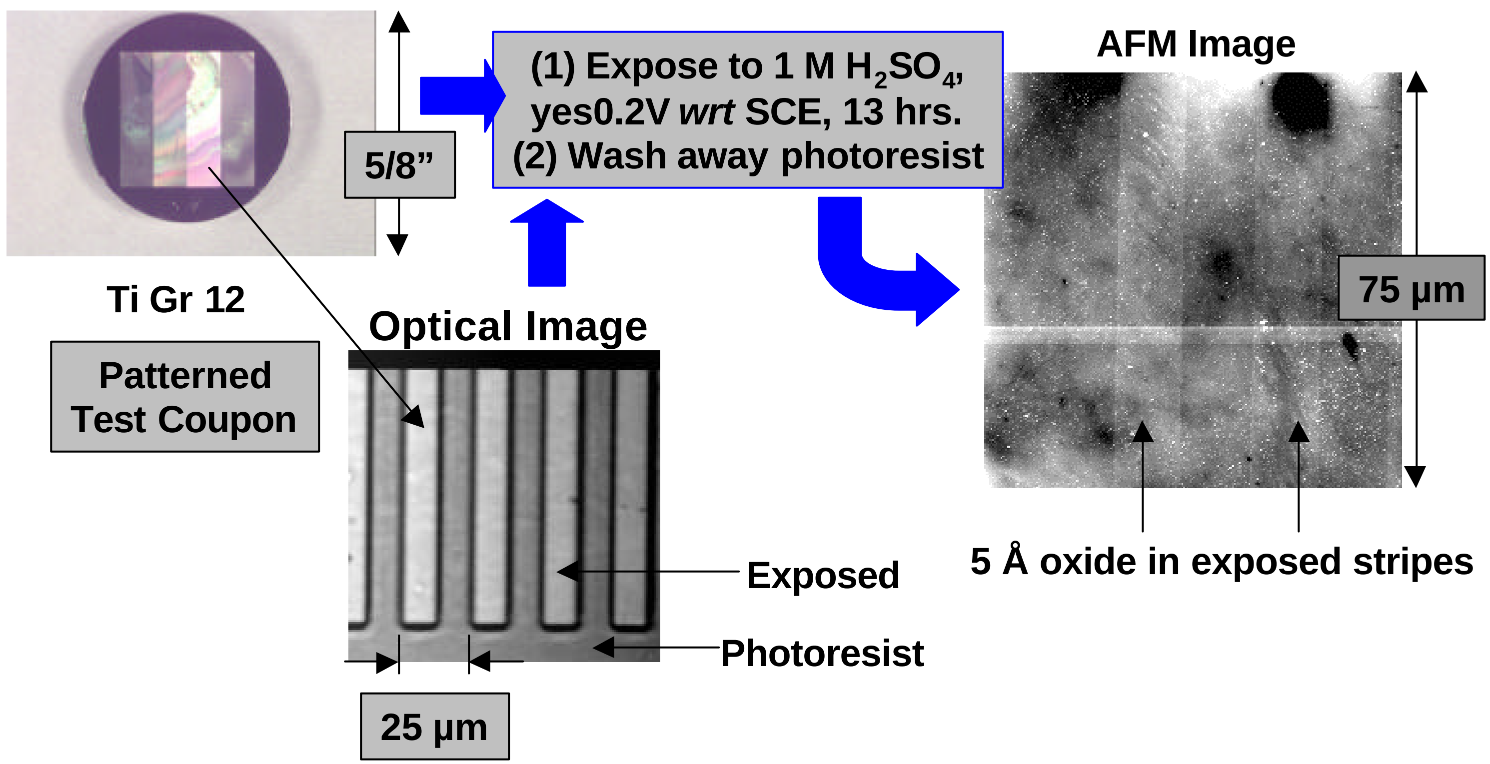


The thickness of the oxide grown in one year is consistent with the nominal corrosion rate of 0.05 to 1 micron per year.

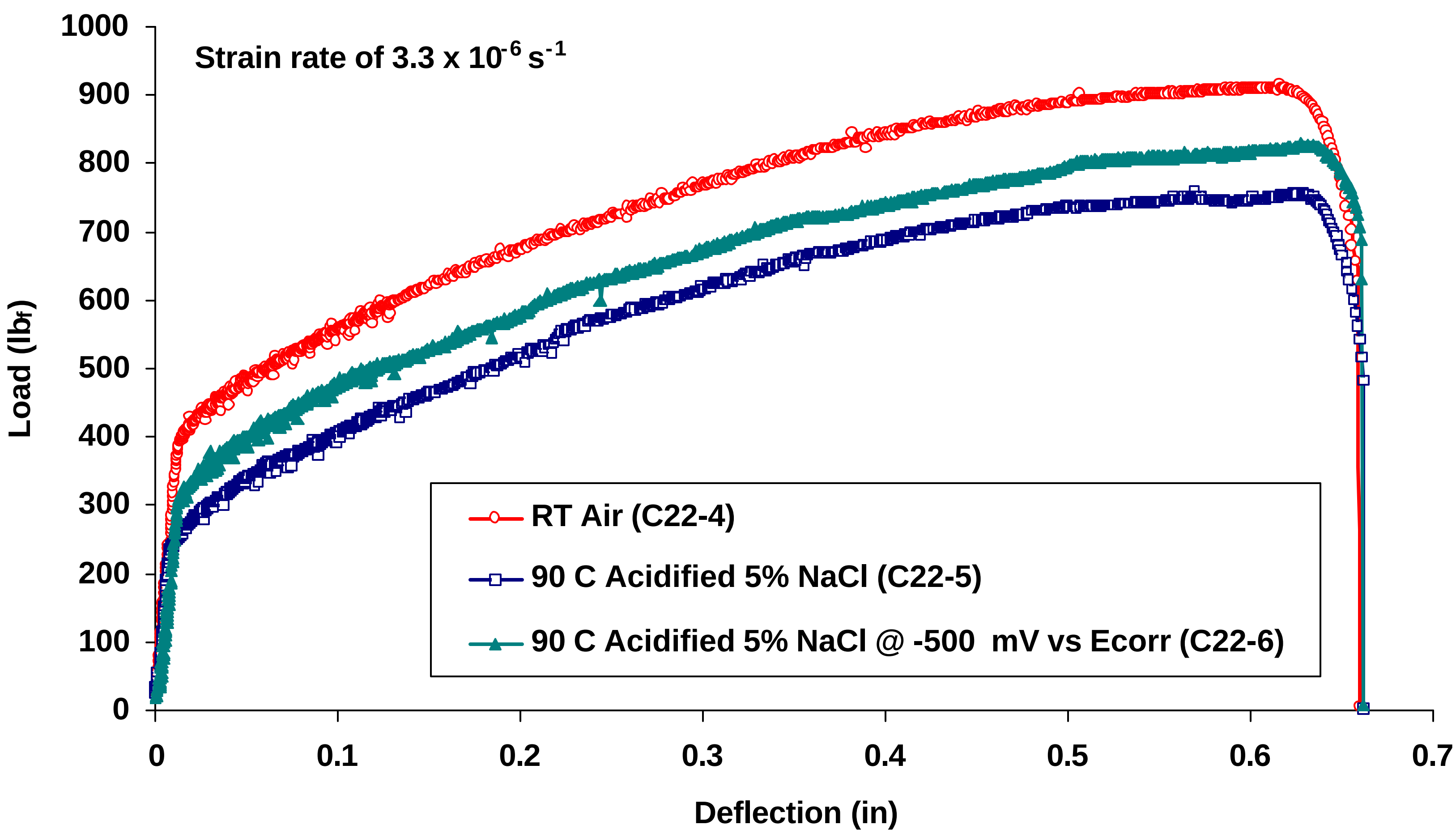
Long Term Corrosion Test Facility at LLNL

Reducing Uncertainty with Atomic Force Microscopy of Patterned Coupons

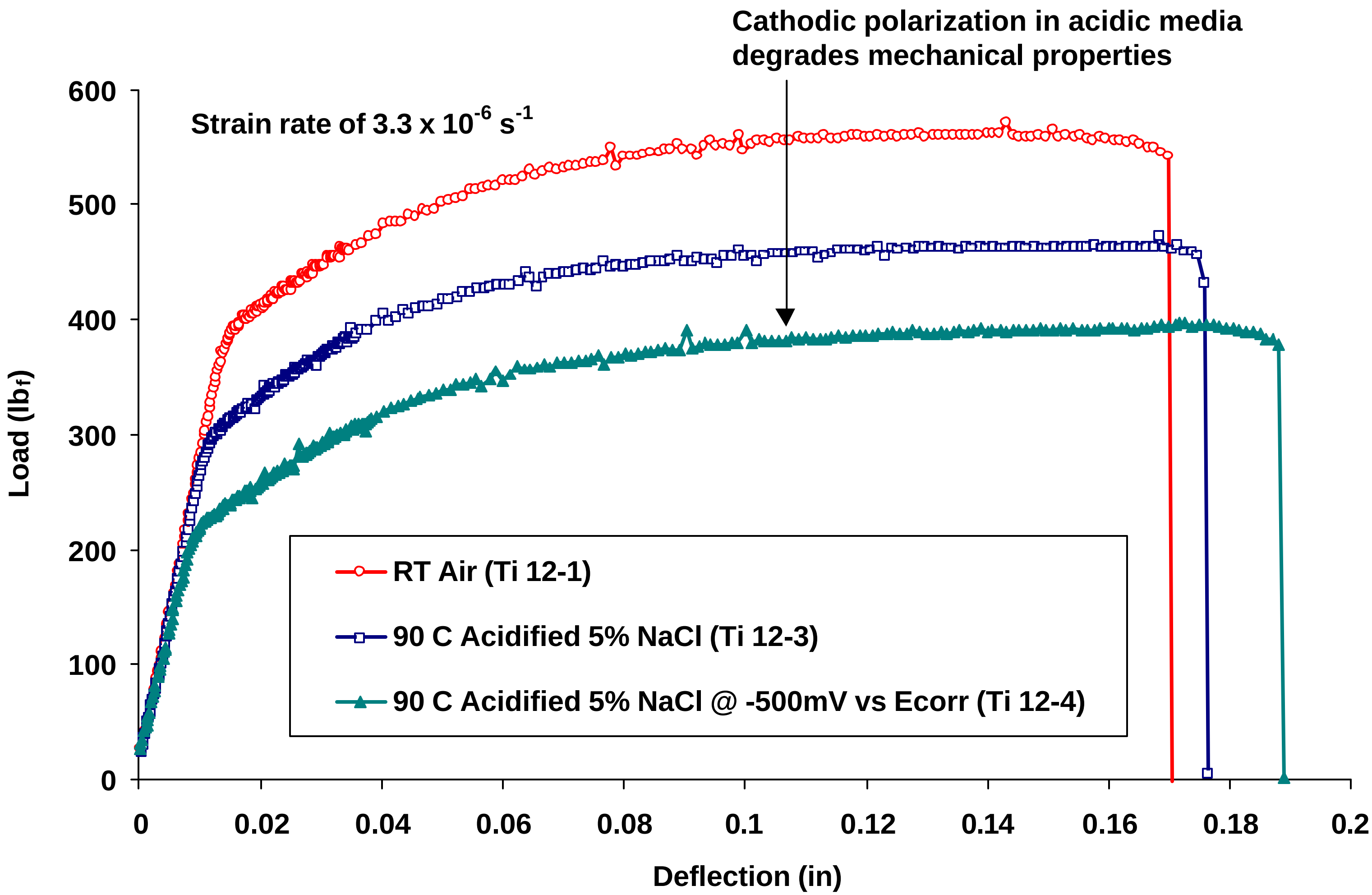
- **AFM offers sub-nanometer vertical resolution for oxide thicknesses, pit depths, general corrosion and swelling, while a photoresist protects base metal. This is a novel approach.**



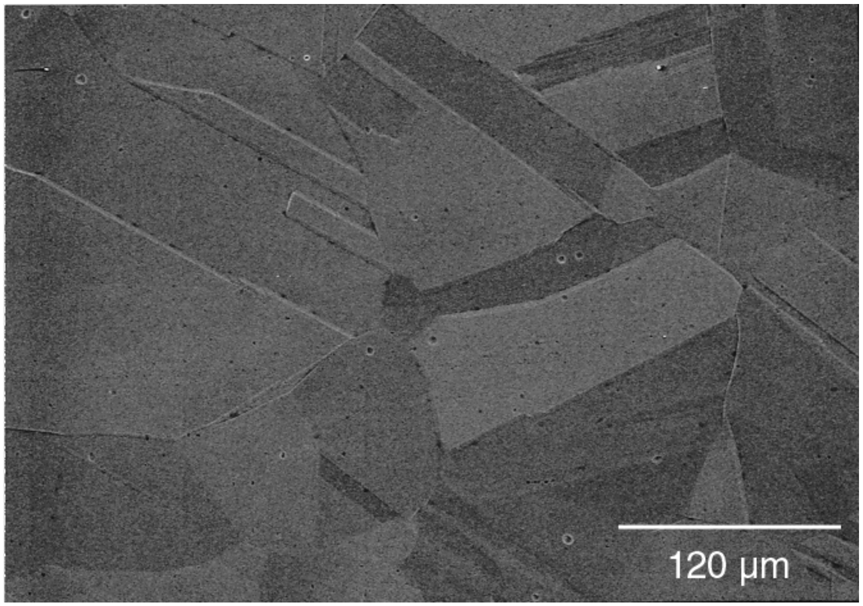
Slow Strain Rate Testing of Alloy 22



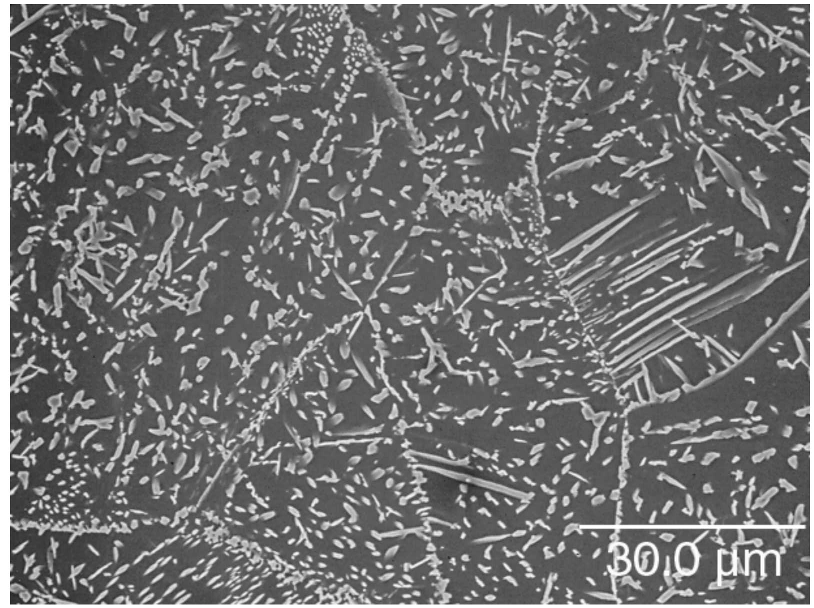
Slow Strain Rate Testing of Ti Gr 12



Alloy 22 Aged at at 760°C for 16,000 hrs

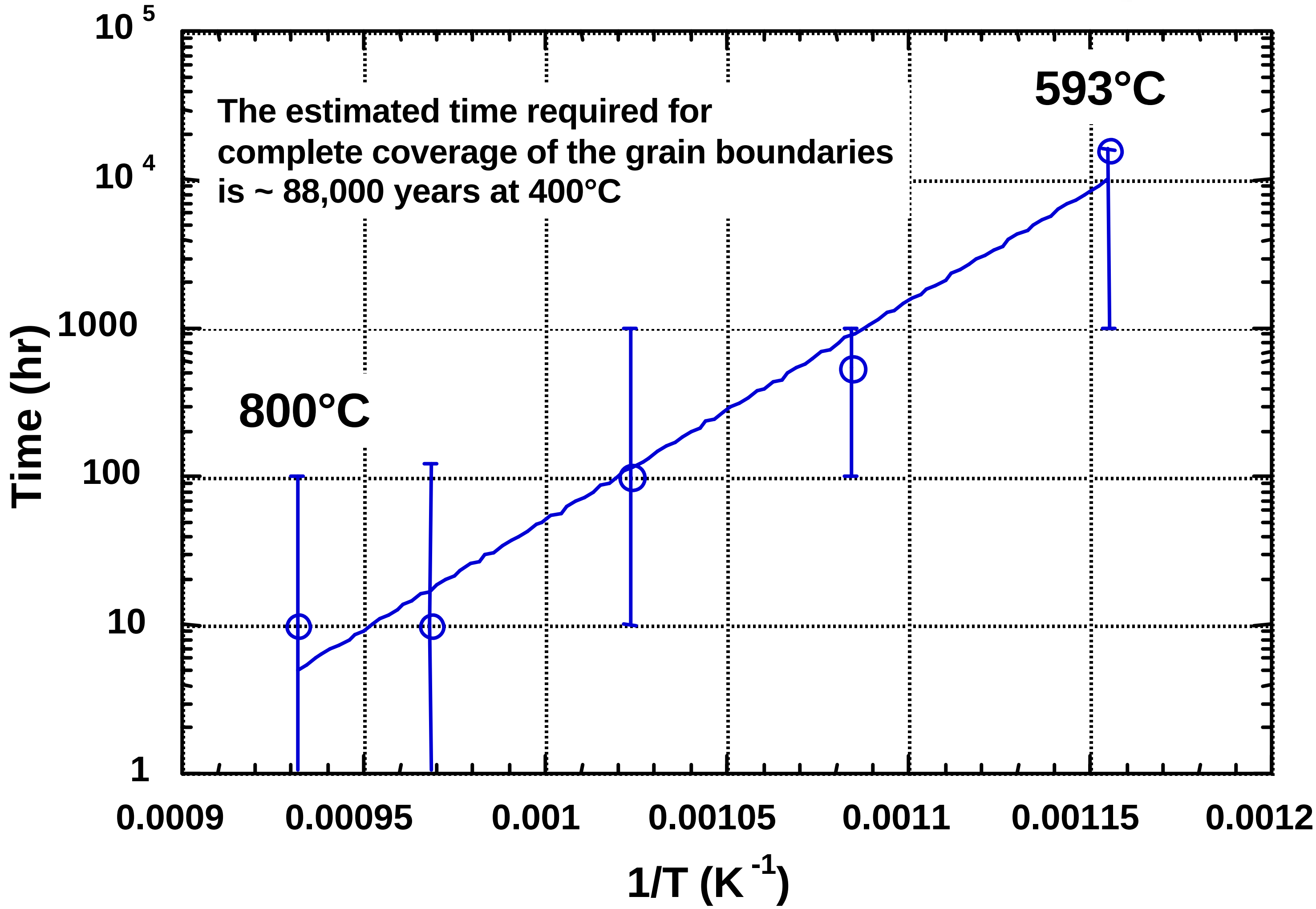


Mill Annealed



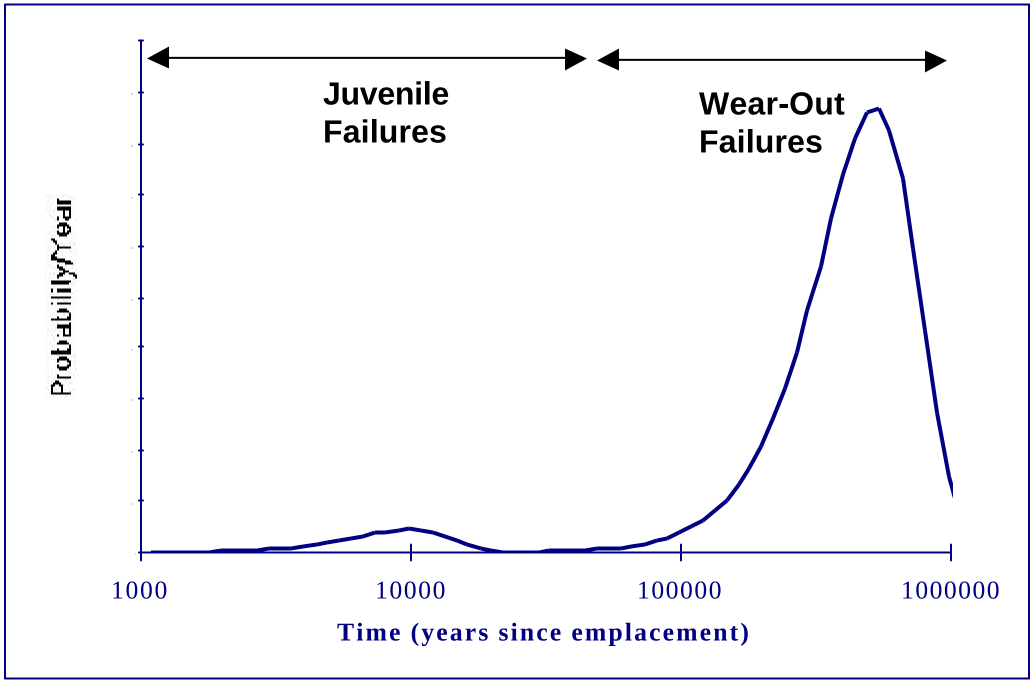
Aged Material

Time at Which Grain Boundaries Become Covered with Carbides, P and/or μ Phase



Definition of WP Juvenile Failure

- **Failure of a waste package, due to manufacturing or handling induced defects, at a time earlier than would be predicted by mechanistic degradation models for an "ideal" package**
- **Failure rates for all components exhibit a "bathtub" curve behavior over time**



Flaws in Shell and Lid Welds

- **Over 20 years of research into the density and size distribution of weld flaws and the mechanisms which produce them**
  - **Formation mechanisms include: Lack of fusion, porosity, slag inclusions, centerline cracking (generally hydrogen induced), heat-affected zone cracking**
  - **NRC has sponsored weld flaw density and size distribution research by Rolls Royce and PNL for a variety of materials, weld thickness, weld methods, and post-weld inspections**
  - **Research provides input to probabilistic fracture mechanics analyses and risk informed in-service inspection proposals**

Flaws in Shell and Lid Welds
(continued)

- **RR-PRODIGAL code developed to model flaw occurrence in welds**
  - **Surface breaking weld flaws expected to be most important contributor to WP performance**
  - **Represent pre-existing pits or crevices, and potential SCC sites**
  - **Unlike pressure vessels, no growth of embedded flaws expected due to lack of cyclic stresses**

Juvenile Failure Model

- **Work currently in progress to develop initial probability and consequence estimates for remaining flaw types**

- **Future work includes:**
  - **Modeling of WP welds using RR-PRODIGAL code**
  - **Refined estimates of flaw occurrence probability**
  - **Refined estimates of flaw effects on WP performance**