Planned Agenda

1. **NRC Introduction & Meeting Purpose:** *M. Srinivasan*
2. **Overview of PNNL Research Project:** *S. Bruemmer*
3. **Review of SCC Crack-Growth Test Systems:** *M. Toloczko*
4. **Test Plans and Initial Test Results:** *Bruemmer, Toloczko*
5. **Discussion of Programmatic Challenges:** *S. Bruemmer*
6. **Opportunity for Public Questions/Comments**
7. **Crack and Crack-Tip Observations on Alloy 600 and Alloy 182 CRDM Components:** *S. Bruemmer*

Agenda

4. SCC Test Plans & Initial Results

- ***Approach to Capability Demonstration***
- **Conditioning & Initial Results for System #1**
- **Specific Demonstration & Validation Plans for SCC Crack-Growth Test Systems**
- **Selected Evaluation Tests on Alloy 600/182/82**
- **Evaluation Tests on Alloy 690/152/52**

Approach to Capability Demonstration

- **Establish basic crack-growth system performance during conditioning**
  - temperature, pressure, flow rate, load control
  - transitioning, growth under cyclic load & constant K
- **Round-robin tests in BWR & PWR environments**
  - cold-worked stainless steels and alloy 600
  - as-welded alloy 182

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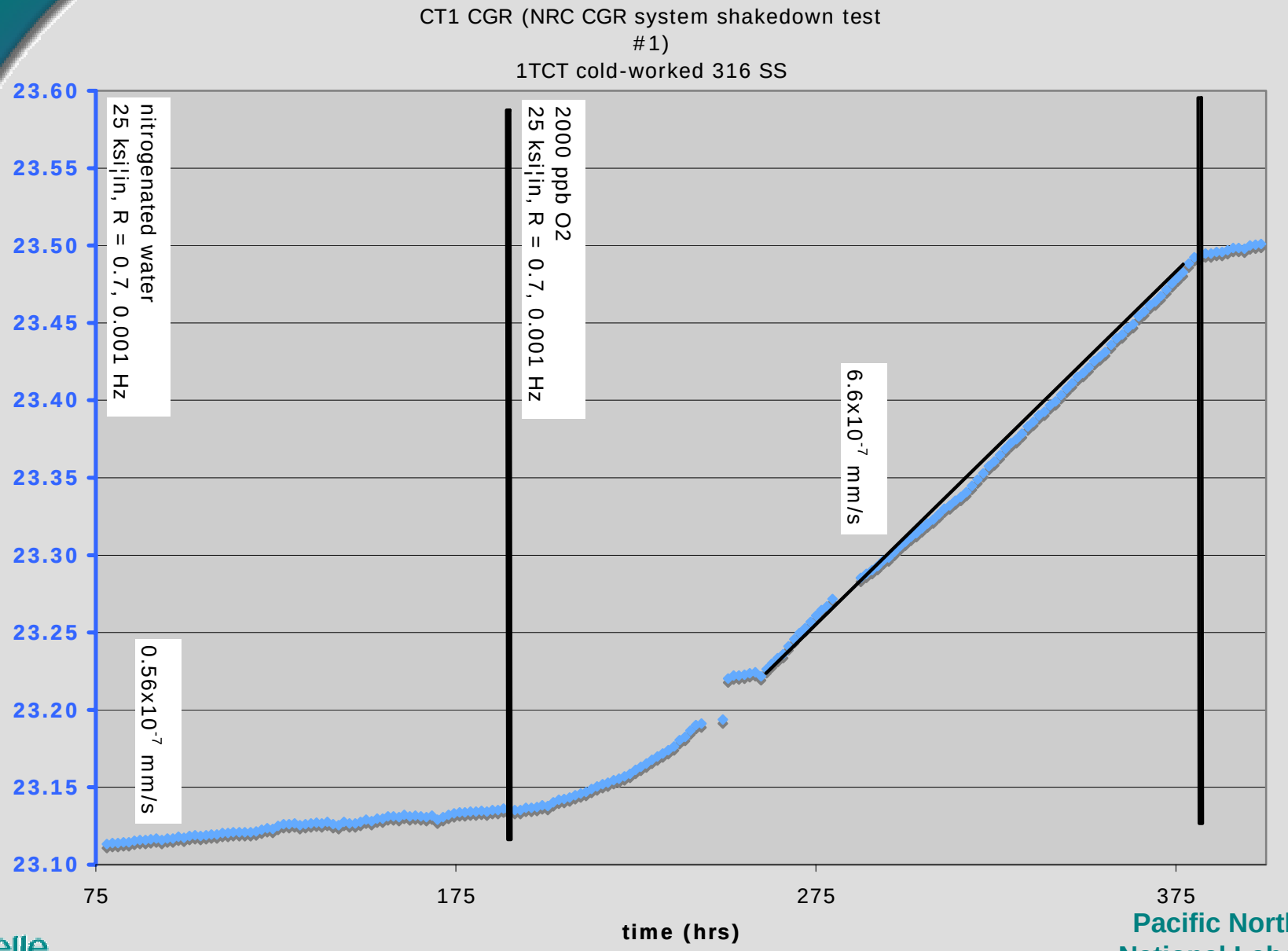
Tasks & Key Milestones

1. Test System Construction
   a) System Design & Order Components — Sept 2004
   b) System #1 Completion/Set-up — Feb 2005
   c) System #2 Completion/Set-up — June 2005
   d) System #3 Completion/Set-up — Apr 2006

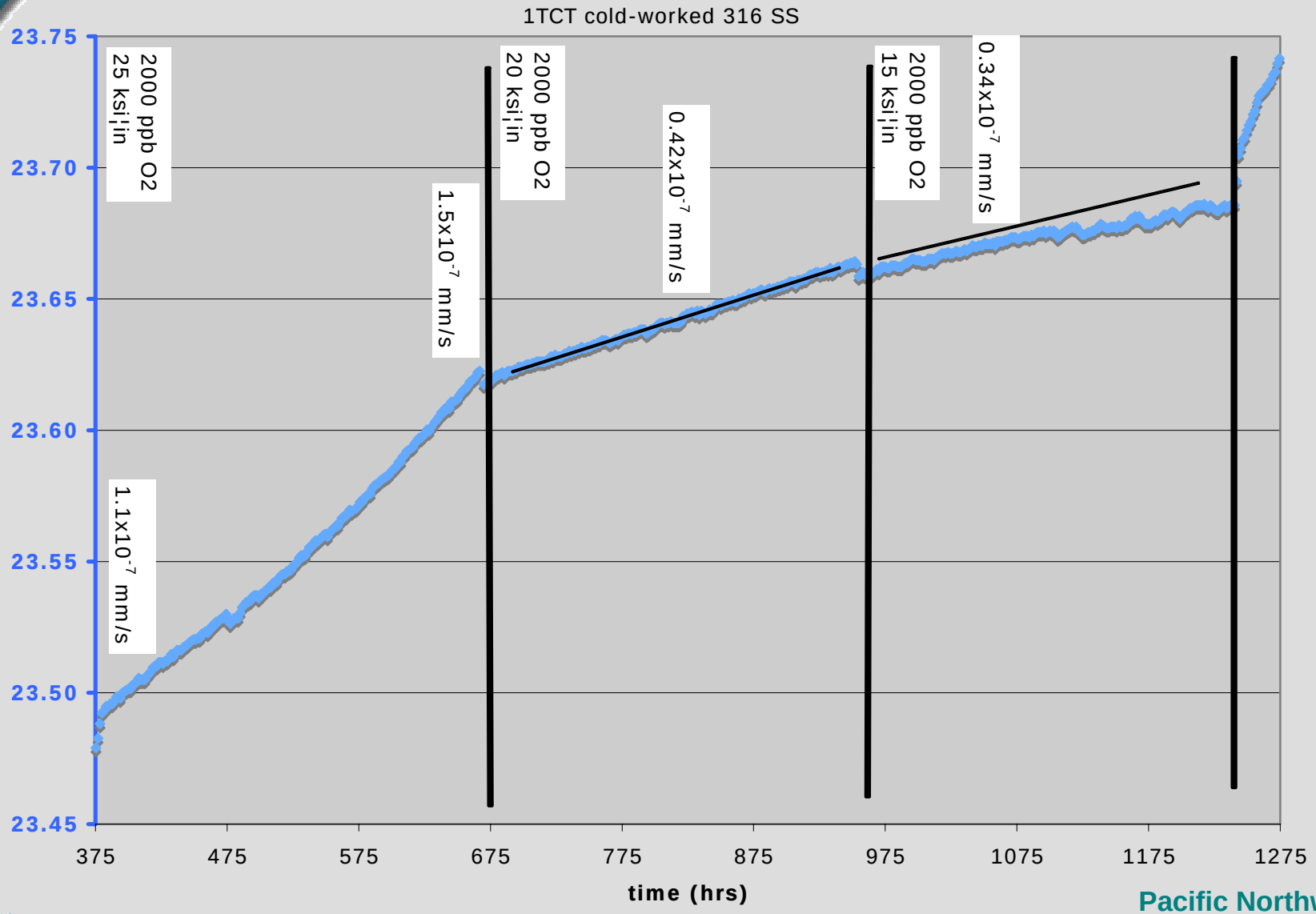
2. System Testing & Demonstration
   a) System #1 Conditioning — May 2005
   b) System #2 Conditioning — Sept 2005
   c) Complete Demonstration Tests — Apr 2006
   d) System #3 Conditioning — Aug 2006

Test System #1 Conditioning & Initial Test

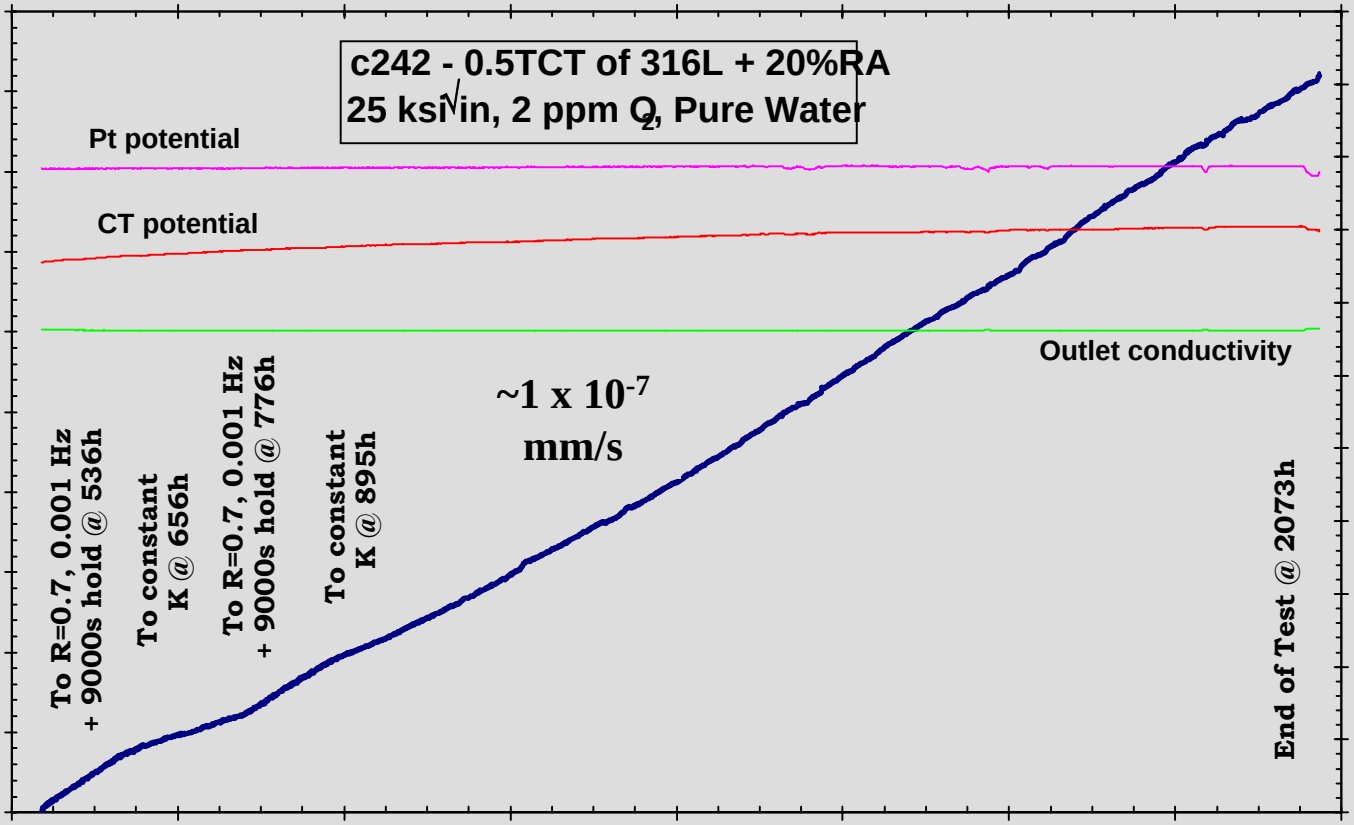
Test System #1 Conditioning & Initial Test



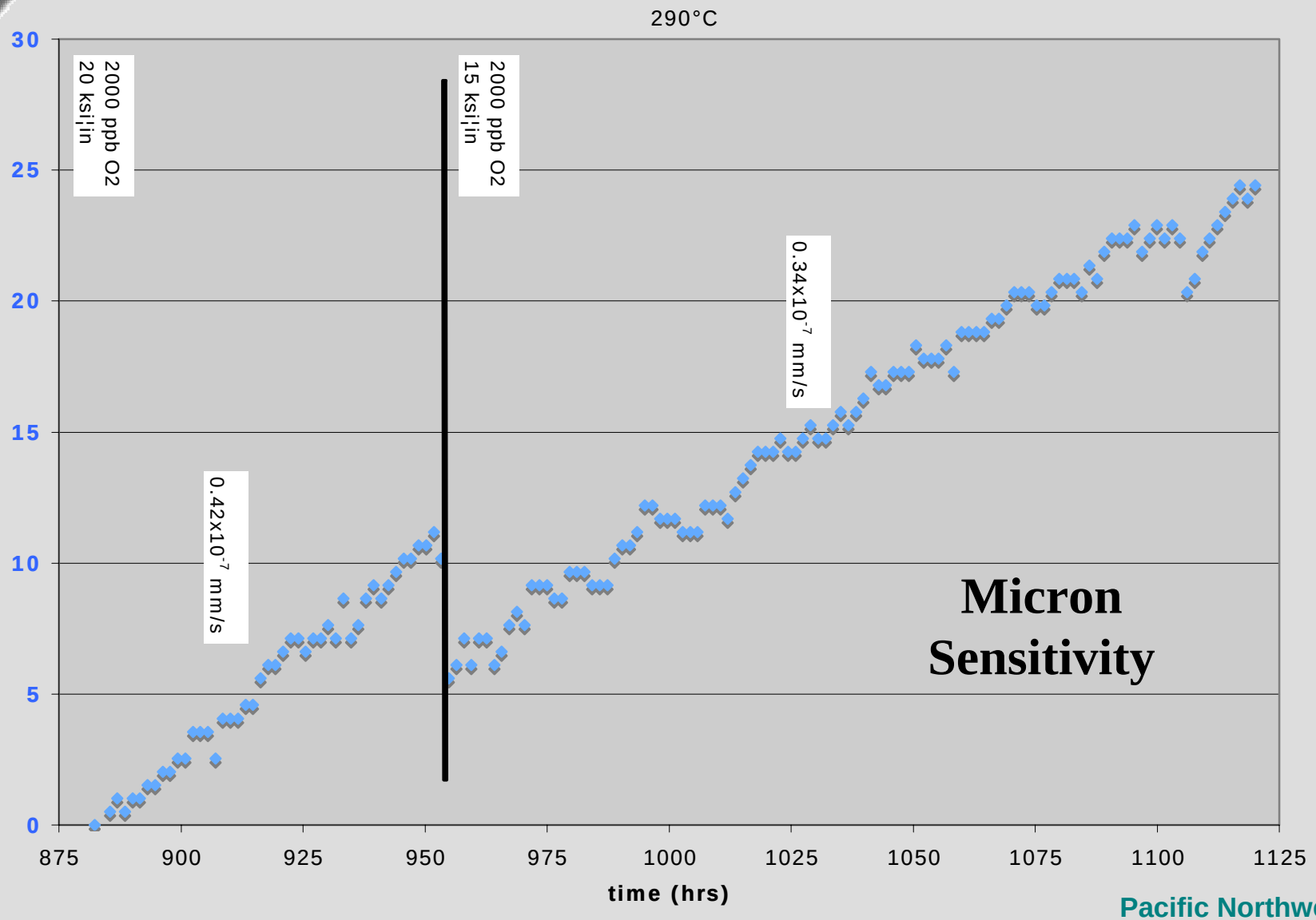
Test System #1 Conditioning & Initial Test



Constant K Response at GE Global



DCPD Measurements of Crack Length



Test System #1 Conditioning & Initial Test

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Specific Demonstration & Validation Plans for SCC Crack-Growth Test Systems

- **Round-Robin Tests in BWR & PWR Environments**
  - cold-worked stainless steels - two heats from GE Global, tests in oxidizing BWR and BWR+HWC, perhaps PWR
  - cold-worked alloy 600 - ICG-EAC round robin heat (without defects), tests in BWR, BWR+HWC, PWR
  - as-welded alloy 182 - ICG-EAC round robin heat tests in BWR, BWR+HWC, PWR

Initial Examinations of the Round Robin Alloy 182 Weld and Comparisons to Service Welds

John Vetrano and Steve Bruemmer
Pacific Northwest National Laboratory

ICG-EAC 2005
Antwerp, Belgium

April 11-14, 2005

Research Supported by
U.S. Department of Energy - NERI
Nuclear Regulatory Commission

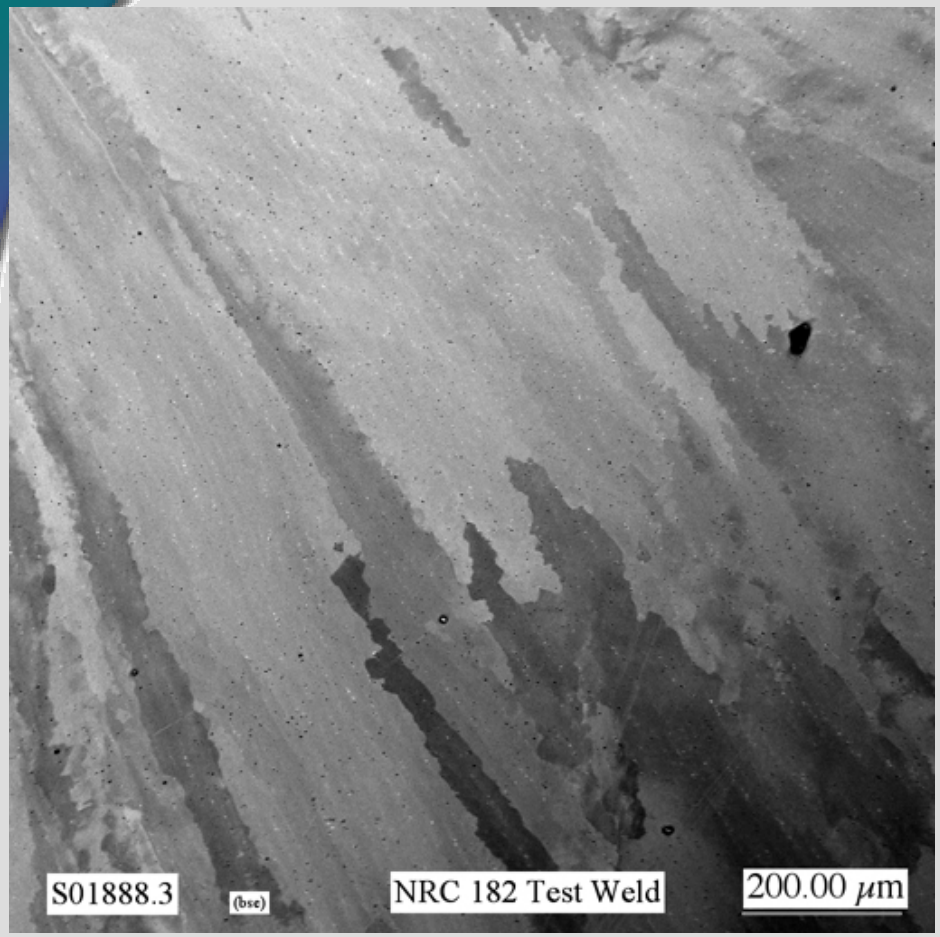
Battelle

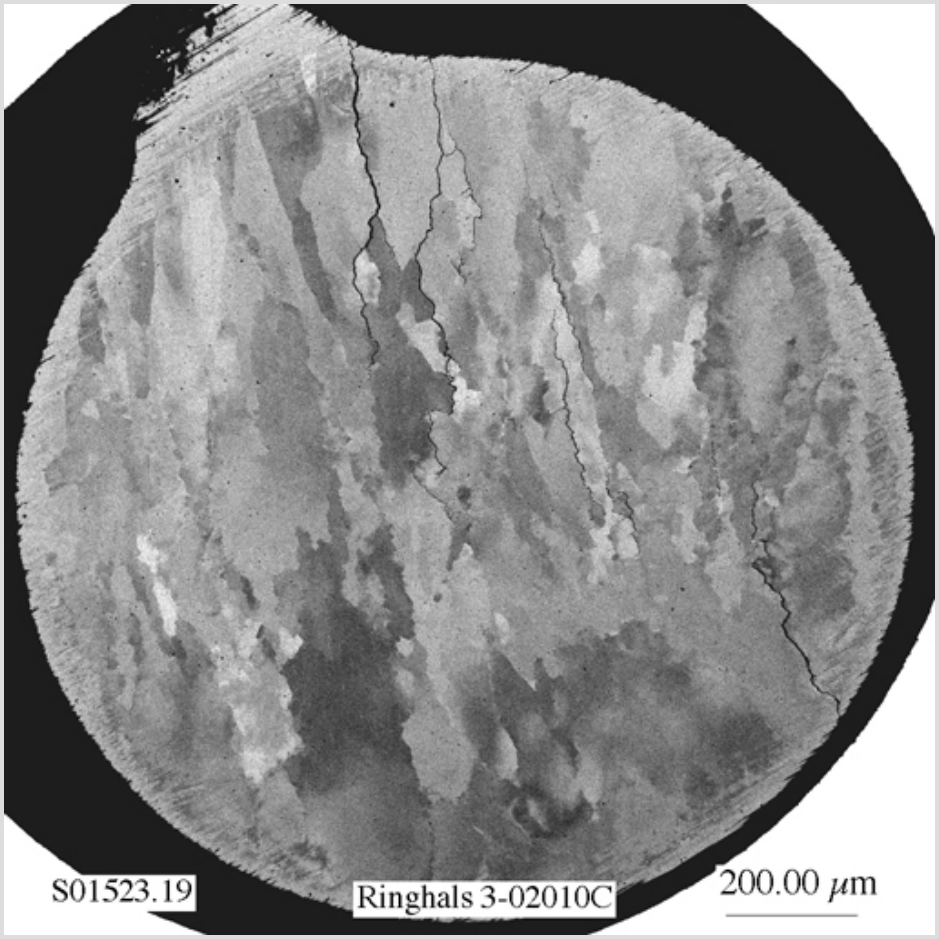
Pacific Northwest National Laboratory

Initial SEM Examinations

Microstructural characterization on the ICG-EAC round robin sample was initiated last month. Preliminary SEM examination show significant differences in microstructure from three different in-service alloy 182 J-groove welds from Davis-Besse, Ringhals 3 and Ringhals 4 where IGSCC was observed.

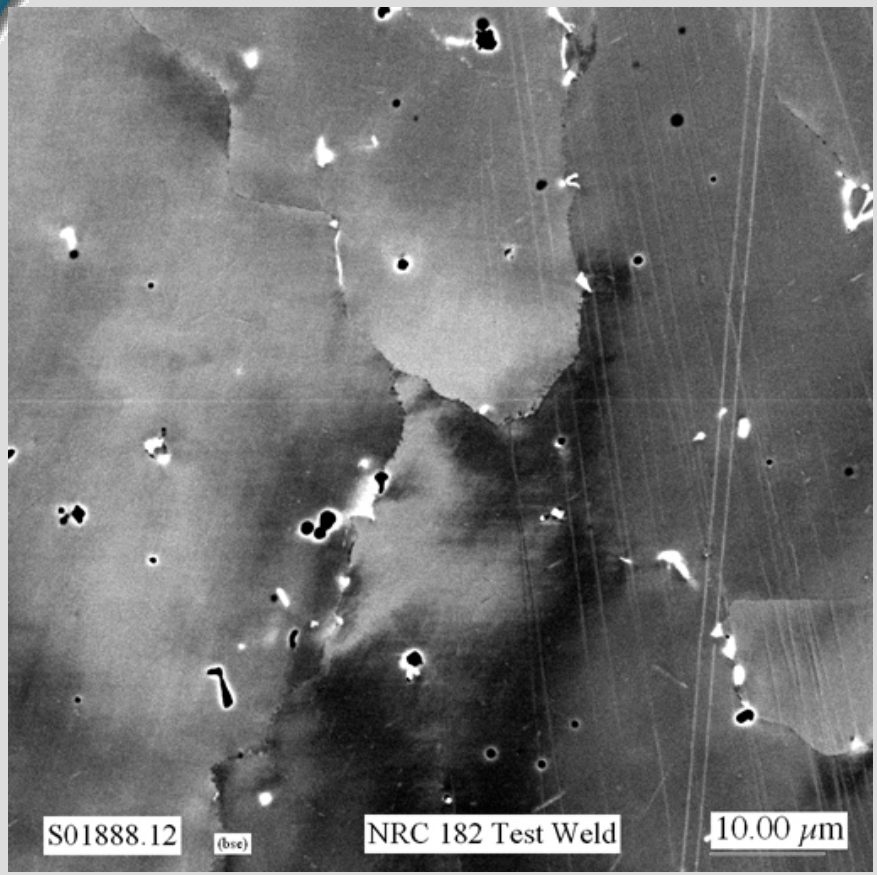
Round Robin versus Service Welds

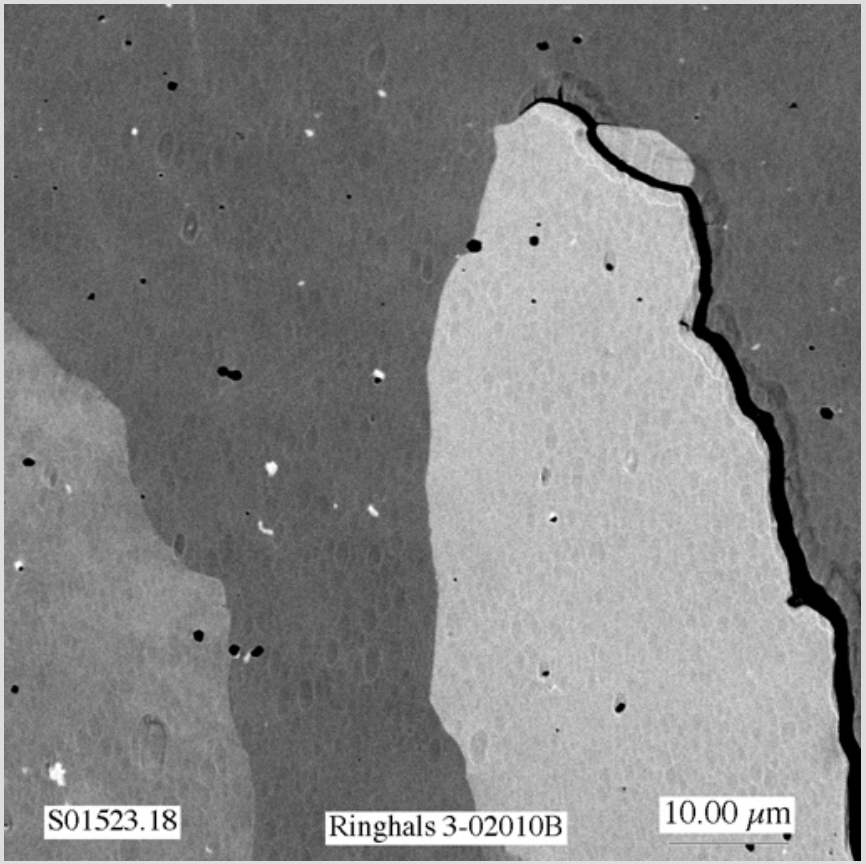




Grain size and matrix precipitate distributions appear quite different, suggests slower cooling rate in round robin weld enhancing dendrite growth?

Round Robin vs Ringhals Service Weld





The boundaries in the round robin sample has much higher density of IG precipitates and is more "crenellated" than the Ringhals examples. Davis Besse did show fine MC and $M_{23}C_6$ carbides on grain boundaries.

Initial TEM Examinations

Initial TEM studies on the round robin material were performed over the last 2 weeks. Preliminary results are compared to more extensive studies on service welds.

The RR samples showed extensive MC and $M_{23}C_6$ precipitation as well as significant Cr depletion (sensitization) at grain boundaries. Ringhals examples revealed few IG precipitates, while the Davis Besse example showed similar high density of MC fine carbides with $M_{23}C_6$ on some boundaries.

Very early results on single grain boundary, much more detailed characterization needed.

Microstructural Differences Suggested by Initial Examinations

- Compared to three alloy 182 weld examples removed from PWR service, the round robin welds show:
  - Larger grains
  - More elongated grains
  - More crenellated boundaries on a fine scale
  - Linear array of NbC particles instead of 2-D array
  - Small boundary particles, both MC and $M_{23}C_6$
  - Interaction between MC particles and boundaries
  - Significant Cr depletion (sensitization) at grain boundaries
  - More detailed characterizations will be performed
- SCC crack-growth testing planned for late 2005

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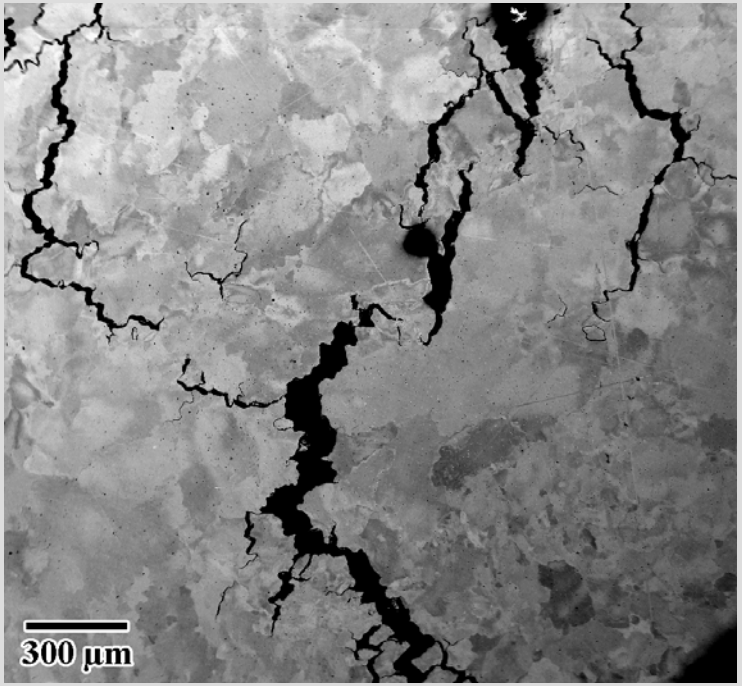
- **Evaluation Tests on Alloy 690/152/52**

Alloy 600/182/82 Issues

- Limited fundamental understanding of SCC in primary water
- Significant heat-to-heat variability
- Important materials variables:
  - processing, fabrication & heat treatments impacting yield strength, microstructure & carbide distribution
  - welding & repair welding impacting yield strength & microstructure
  - heat-affected zone susceptibility?
- Important environmental variables:
  - temperature
  - impurities (S?)



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Alloy 690/152/52 Issues

- Clearly much more SCC-resistant alloys than alloy 600/182 in PWR primary water
- Service experience excellent
- Specific Potential Issues
  - limited quantitative assessment of SCC crack-growth rates for alloy 690
  - limited evaluation of bulk composition, thermomechanical processing and microstructure on SCC resistance
  - limited testing of alloy 152/52 welds
  - heat-affected zone susceptibility?
  - low-temperature crack propagation
  - weld hot cracking

Alloy 690 Materials

Multiple heats of alloy 690 CRDM tubing with different bulk compositions and wall thicknesses.

Image from GE

Six heats of alloy 690 CRDM tubing were obtained from Vallourec including one heat with two different wall thicknesses. Tubes are in ~2-ft lengths with wall thicknesses sufficient to machine 0.5T CT samples for crack-growth tests. Characterization and microstructural processing will begin in FY06.

Alloy 690 Materials

Multiple heats of alloy 690 CRDM tubing including sleeves and adaptors with and without honing performed.

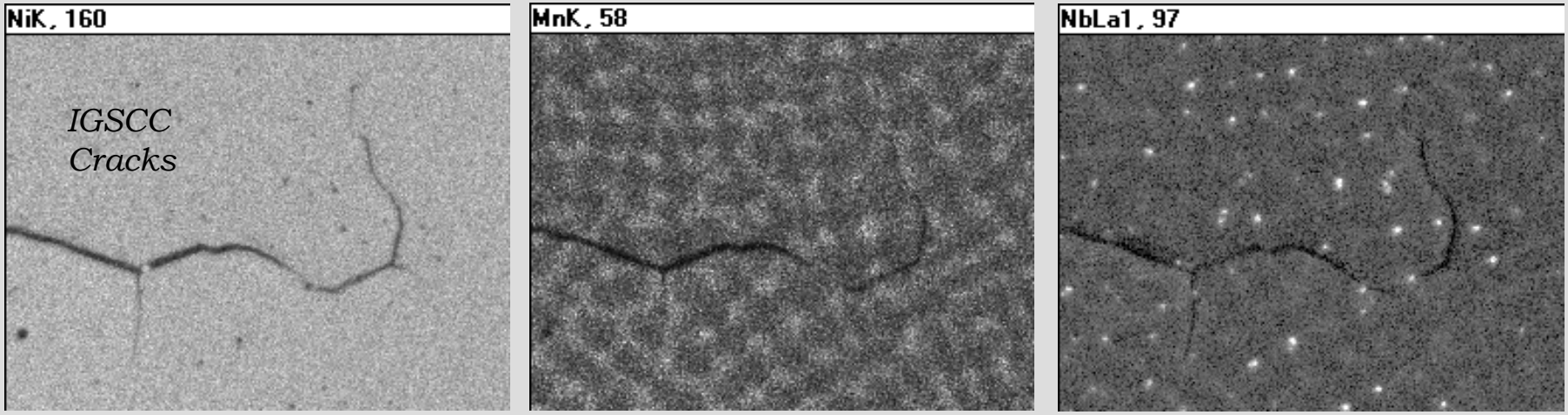
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Selected PWR CRDM materials were received on 4/29 from AREVA Chinon and are being inventoried. The four expected items were: (1) a sleeve (no honing) from a US reactor vessel closure head (RVCH), Westinghouse design; (2) an adaptor (with honing) from a US RVCH, Westinghouse design; (3) an adaptor (with honing) from EDF RVCH; (4) an adaptor (with honing) from US RVCH, B&W design. Components are shown above.

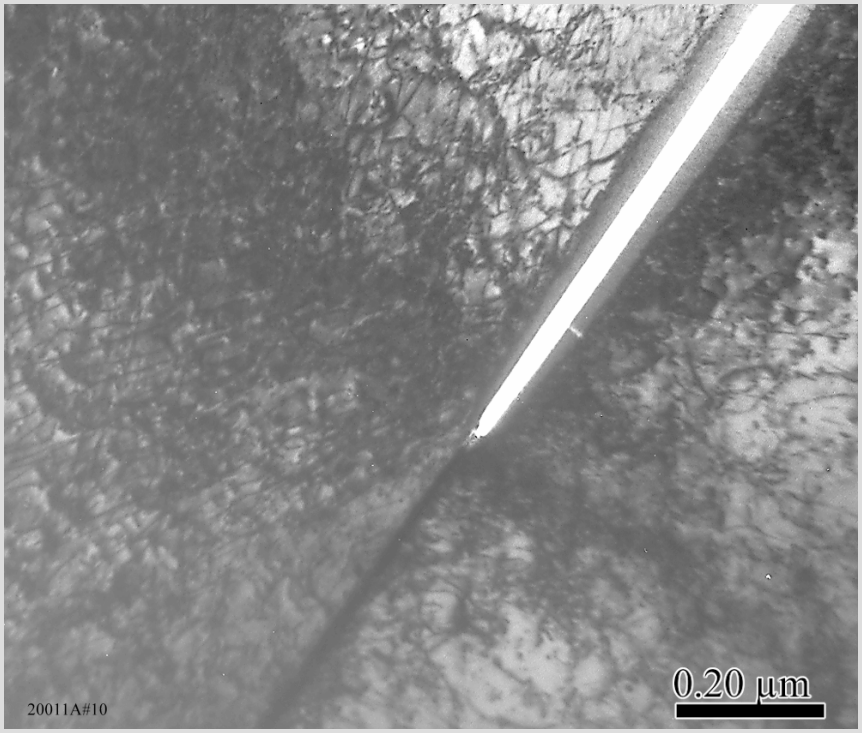
Materials Characterization and Microstructural Evaluation

An additional aspect of the testing program will be materials characterization required to establish microstructural conditions of the base metals, heat-affected zones and weld metals. Resulting information is required for performance comparisons among various regions of individual components and among different heats. The weld metal in particular offers a complex distribution of microstructural features that could impact SCC behavior including the influence of pre-existing hot cracks, large inclusions and solidification-induced segregation/precipitation at interdendritic and grain boundaries.

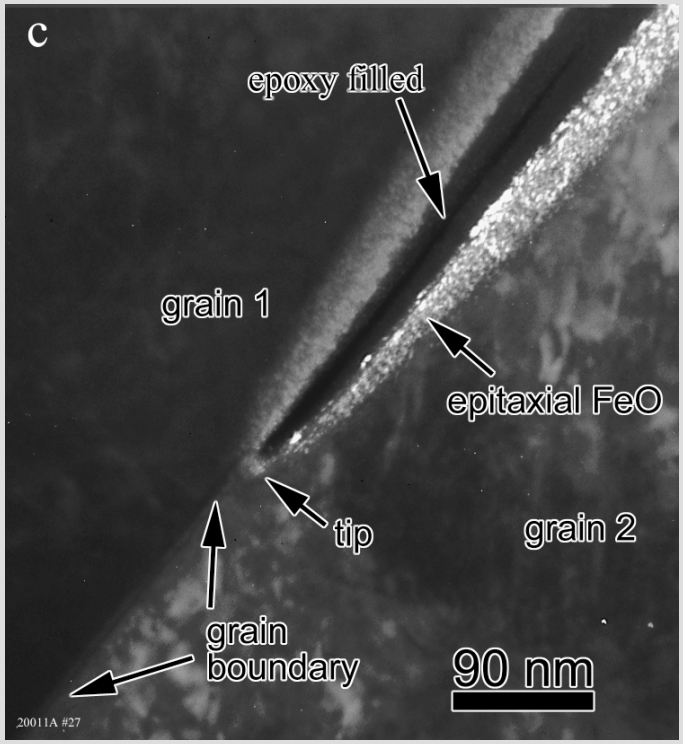


Macrosegregation in Alloy 182 Weld Metal

High-Resolution Crack-Tip Examinations Help Elucidate IGSCC Mechanisms in LWR Components



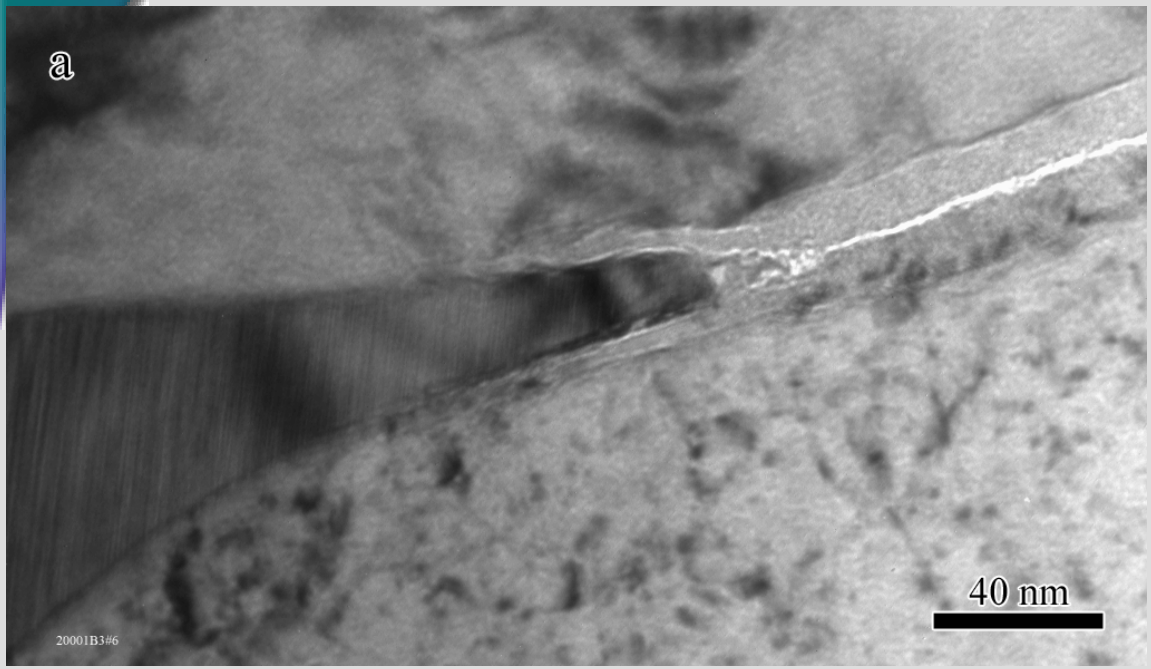
Brightfield Image

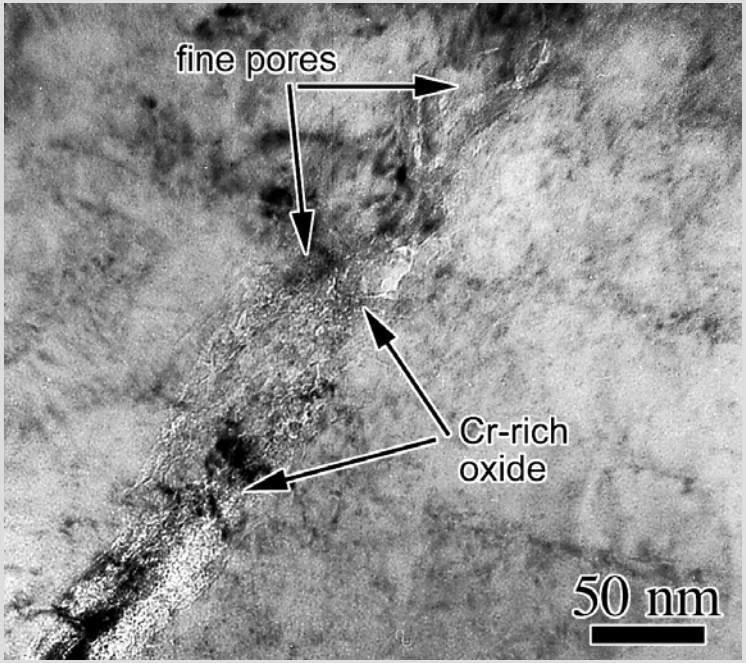


Oxide darkfield

Cr-rich epitaxial, non-porous oxide films present at highly strained crack tips and on crack walls in austenitic stainless steel. Observations consistent with film rupture/slip oxidation models for crack propagation.

Oxidation Leads IGA/SCC in Alloy 600





Example shown for mill-annealed alloy 600 cracked in PWR primary water. IGSCC cracks end in oxidation along grain boundaries or at carbide interfaces. Leading edge of corrosive attack on right shows Cr-rich oxide and ends within grain boundary. Isolated pores and tunnels found in boundary plane ahead of corrosion product oxide. Consistent with active-path corrosion mechanism of advance, quite different that IGSCC for stainless steels in similar environments.

Agenda

5. Expected Programmatic Challenges

- **Slow Crack-Growth and Long Test Times for Alloy 690/152/52 under Normal Conditions**
- **Test Matrix Limitations without Support for Additional SCC Crack-Growth Systems**
- **Necessary to Establish Realistic Off-Normal Material and Environmental Conditions**

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