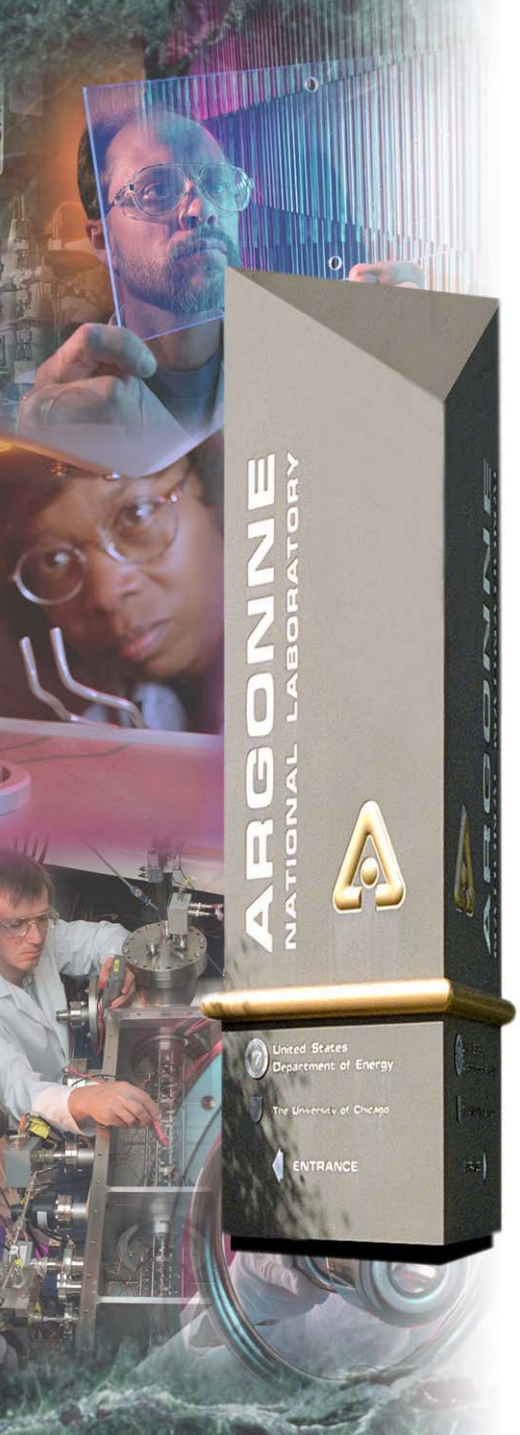


Mechanical Property Testing

NRC-EPRI Program for High Burnup Cladding Performance

Rob Daum, Jakub Dobrzynski, Saurin Majumdar, and Mike Billone

Argonne National Laboratory

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

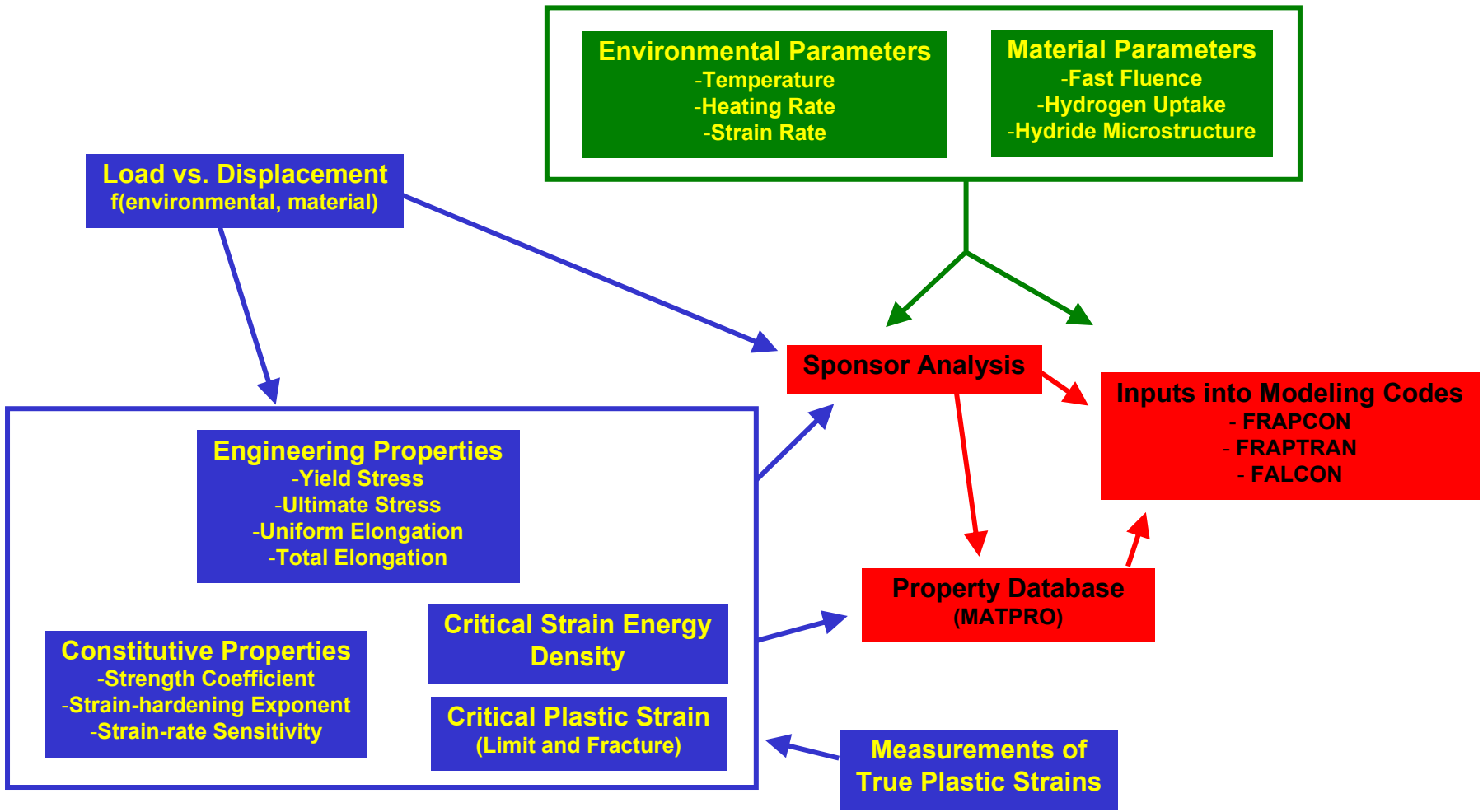
Office of Science
U.S. Department of Energy

Objective of Mechanical Property Testing

- Determination of stress-strain, deformation, and fracture behavior of Zircaloy-2 and Zircaloy-4 irradiated to high fuel burnups using ring-stretch and axial tensile specimens and biaxial burst specimens relevant to RIA and LOCA transients and dry cask storage conditions.
- Develop a database of engineering and constitutive stress-strain properties and critical strains for inclusion into fuel modeling codes.

Cladding Type	**Condition**	**Avg. Fast Fluence (E > 1 MeV)** (10^{22} **neutrons/cm^2**)	**Rod Avg. Fuel Burnup** (GWd/MTU)
Zircaloy-4	Cold-Worked, Stress-Relieved	0	0
Surry Zircaloy-4	Cold-Worked, Stress-Relieved	0.7	36
TMI-1 Zircaloy-4	Cold-Worked, Stress-Relieved	0.9	50
HBR Zircaloy-4	Cold-Worked, Stress-Relieved	1.4	67
Zircaloy-2	Recrystallized-Annealed	0	0
Limerick Zircaloy-2	Recrystallized-Annealed	1.1	57

Experiment-Model Interface



Overview

- **Mechanical Testing Plans & Procedures**
  - Testing Plans
  - Engineering and Constitutive-based Properties
  - Critical Strain-based Properties

- **Irradiated Specimen Preparation & Testing (to-date)**
  - Machining & Dimensional Measurements
  - First Irradiated Test
  - Facility Upgrades

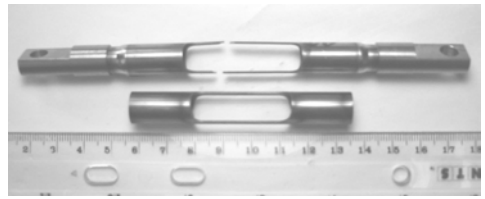
- **Future Schedule**

Non-irradiated Testing Plan

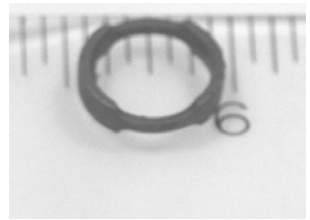
Reference: IPS-263-Rev.3

T (°C) \ ε̇ (s^{-1})	0.1%		100%	
	Zr-2	Zr-4	Zr-2	Zr-4
25	1 3 3	1 3 3	1 2 2	1 2 2
150	1 3 3			
300	1 3 3	1 3 3	2	
400	1 3	1 3 3	1 2	1 2 2
450	1 3	1 3 3		
500	1 3	1 3	1 2	1 2
550	1	1		
600	1	1	1	1
650	1	1		
700	1	1	1	1
750	1	1		
800	1	1	1	1

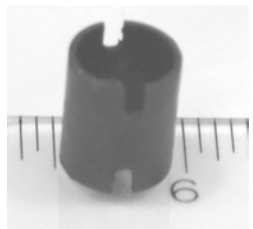
- Uniaxial Axial-Tube



- Uniaxial Ring-stretch



- Plane Strain Ring-stretch



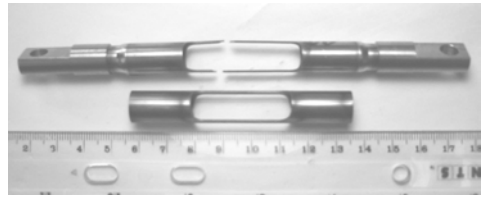
-Biaxial Burst LOCA
- -Constant Pressure 800, 1600 psig (5.52, 11 MPa)
- -Temperature Ramp at 1 and 10°C/sec
- -Determine Rupture Temperature

Irradiated Testing Plan

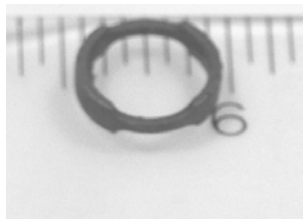
Reference: IPS-263-Rev.3 * - denotes specimens from different grid spans

T (°C) \ ε̇ (s^{-1})	0.1%		100%	
	Zr-2	Zr-4	Zr-2	Zr-4
25	1 3 3	2* 6* 6*	1 2 2	2* 4* 4*
150	1 3 3			
300	1 3 3	2* 5* 5*	2	
400	1 3	2* 6* 3*	1 2	2* 4* 2*
450	3	1 5* 5*		
500	1 3	1 6*	1 2	1 4*
550	1	1		
600	1	1	1	1
650	1	1		
700	1	1	1	1
750	1	1		
800	1	1	1	1

- Uniaxial Axial-Tube

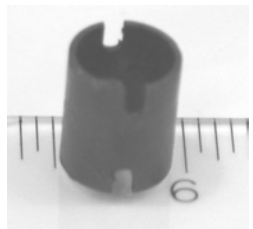


- Uniaxial Ring-stretch



Additional T's between 300-400°C may be tested to determine hydride ductility transition

- Plane Strain Ring-stretch



-Biaxial Burst LOCA
- -Constant Pressure 800, 1600 psig (5.52, 11 MPa)
- -Temperature Ramp at 1 and 10°C/sec
- -Determine Rupture Temperature

Uniaxial Properties – Zr-4

Published in the proceedings of the 4th Symposium on Small Specimen Test Techniques, Reno, NV, January 23-25, 2001

- **Determination of transverse (hoop) stress-strain response [f(*T*,*ε*)] using the following procedure:**

Longitudinal Load (*P*) vs. Displacement (*d*) Response

Simple Calculation of Longitudinal *S* vs. *e*

Transformation to Longitudinal *σ* vs. *ε*

Assumes degree of anisotropy

Transverse Load (*P*) vs. Displacement (*d*) Response

Finite Elemental Analysis using ABAQUS
Iterative Calculations of Transverse *σ* vs. *ε* to match Transverse *P* vs. *d* based Longitudinal Data

Final Determination of Transverse *σ* vs. *ε*

Transformation to Transverse *S* vs. *e*

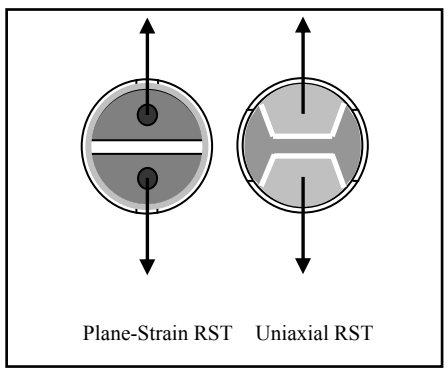
Extrapolate to Final Engineering Stress-strain Response

Optimization of Loading Grip Geometry to Limit Bending and Friction Effects

Design of Uniaxial Ring-stretch Specimen to Optimize Uniform Distribution of stress-strain

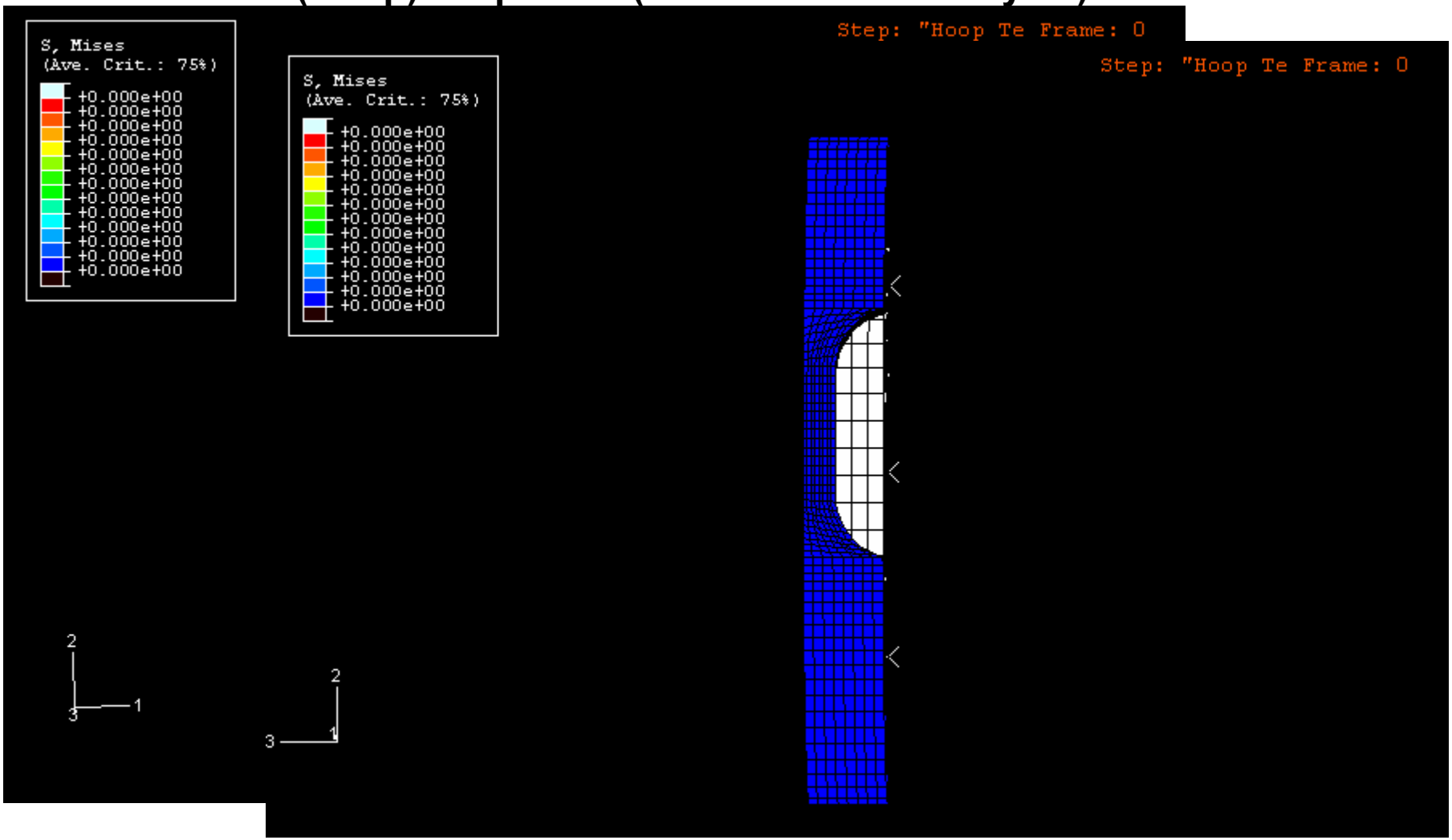
FEA Development of Loading Grip Geometry and Effects of Friction & Lift-off

Analysis of Stress-strain Distribution in Plane-strain Ring-stretch Specimen



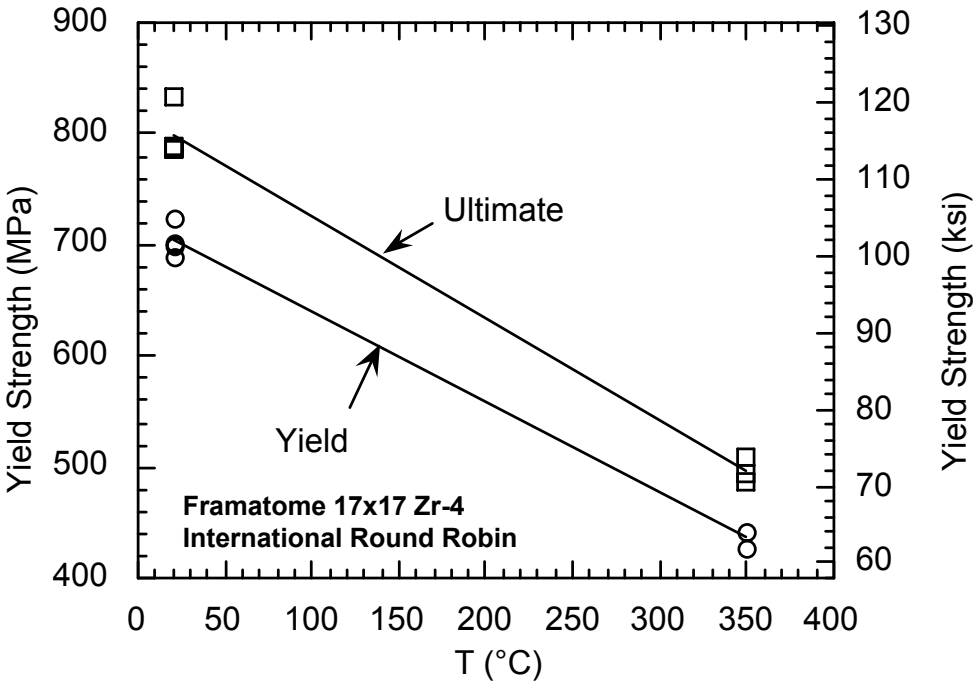
Uniaxial Properties

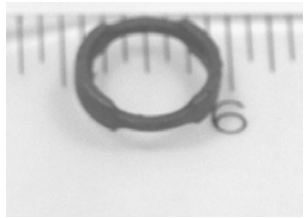
- **Transverse (Hoop) Properties (Finite Element Analysis)**

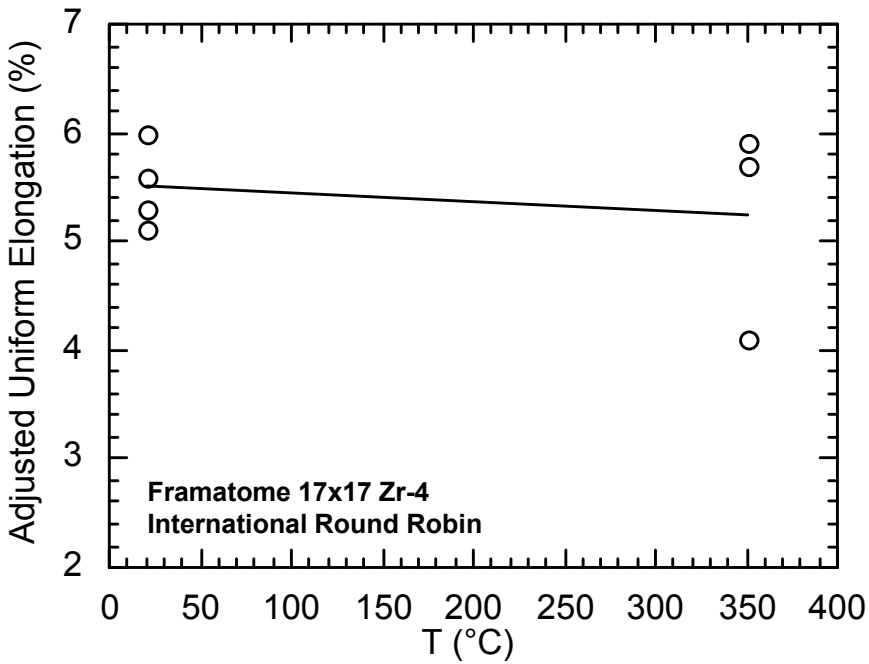


Uniaxial Properties – Zr-4

- **Transverse (Hoop) Properties**

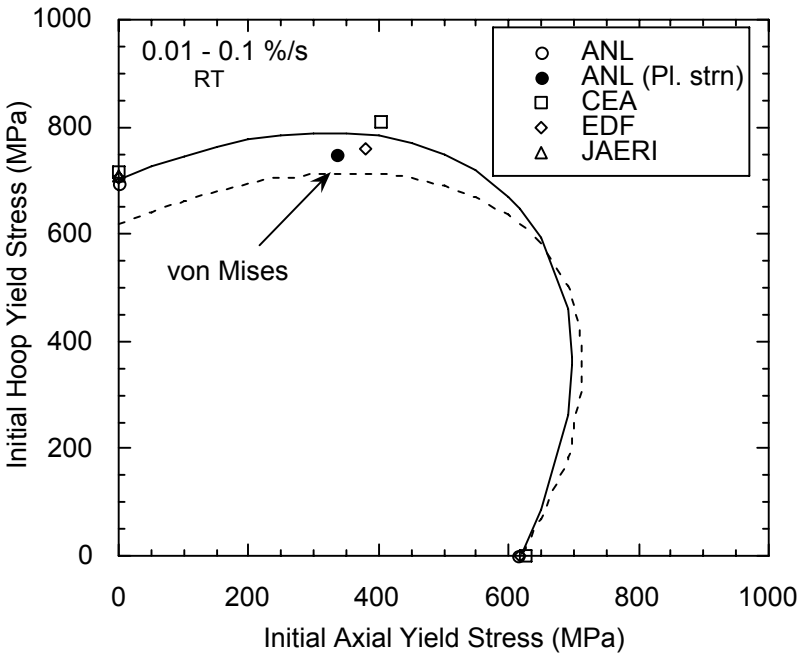


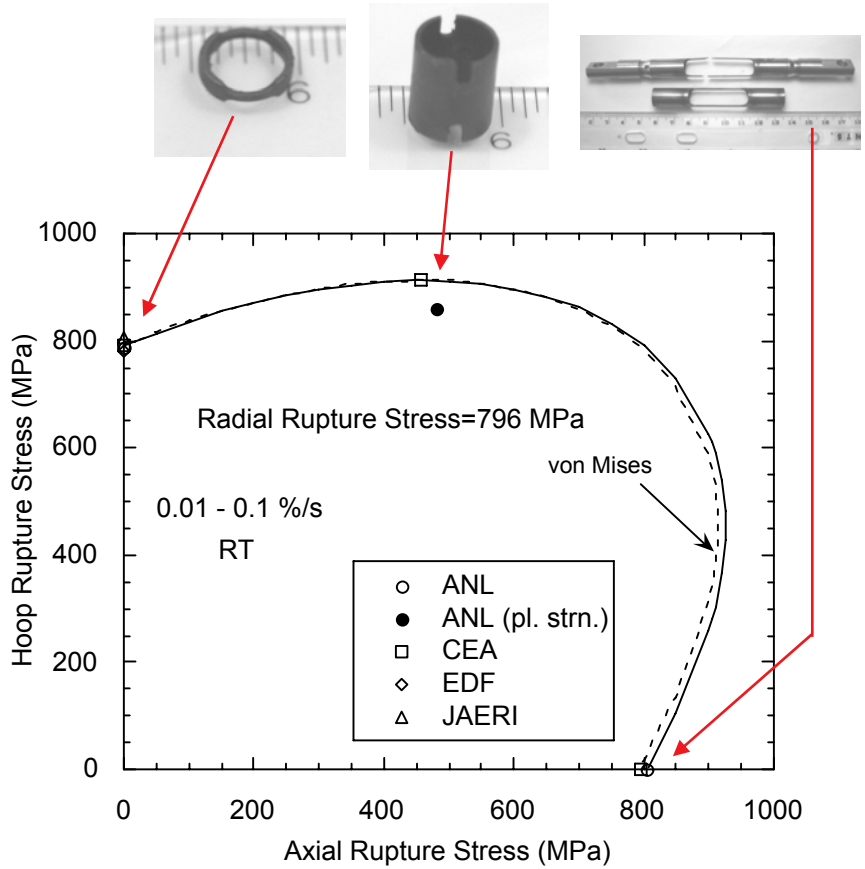




Biaxial Properties – Zr-4

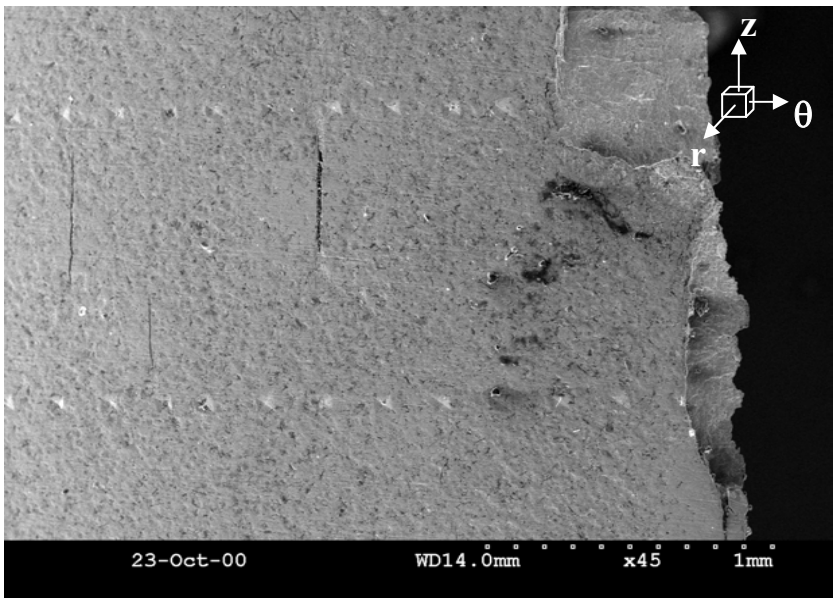
- **Biaxial state of stress for mapping Yield and Rupture Loci**

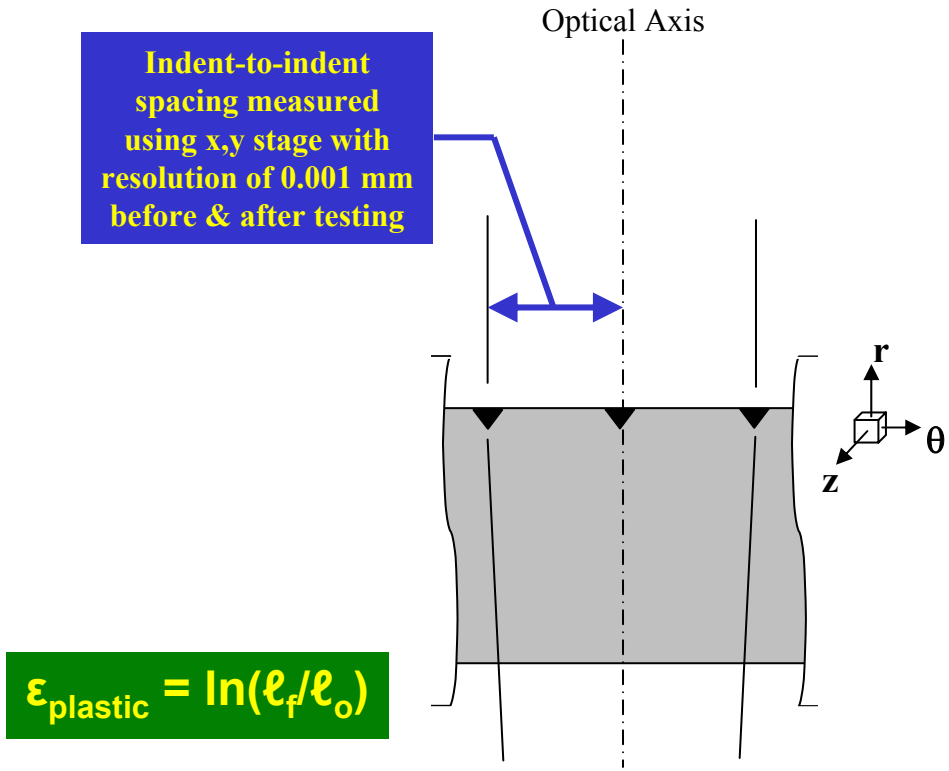




Critical Strain-based Properties

- **True hoop plastic strains measured using microhardness indent arrays**
- **Used to:**
  - Measure hoop cladding ductility
  - Supplement RST uniform elongation analysis

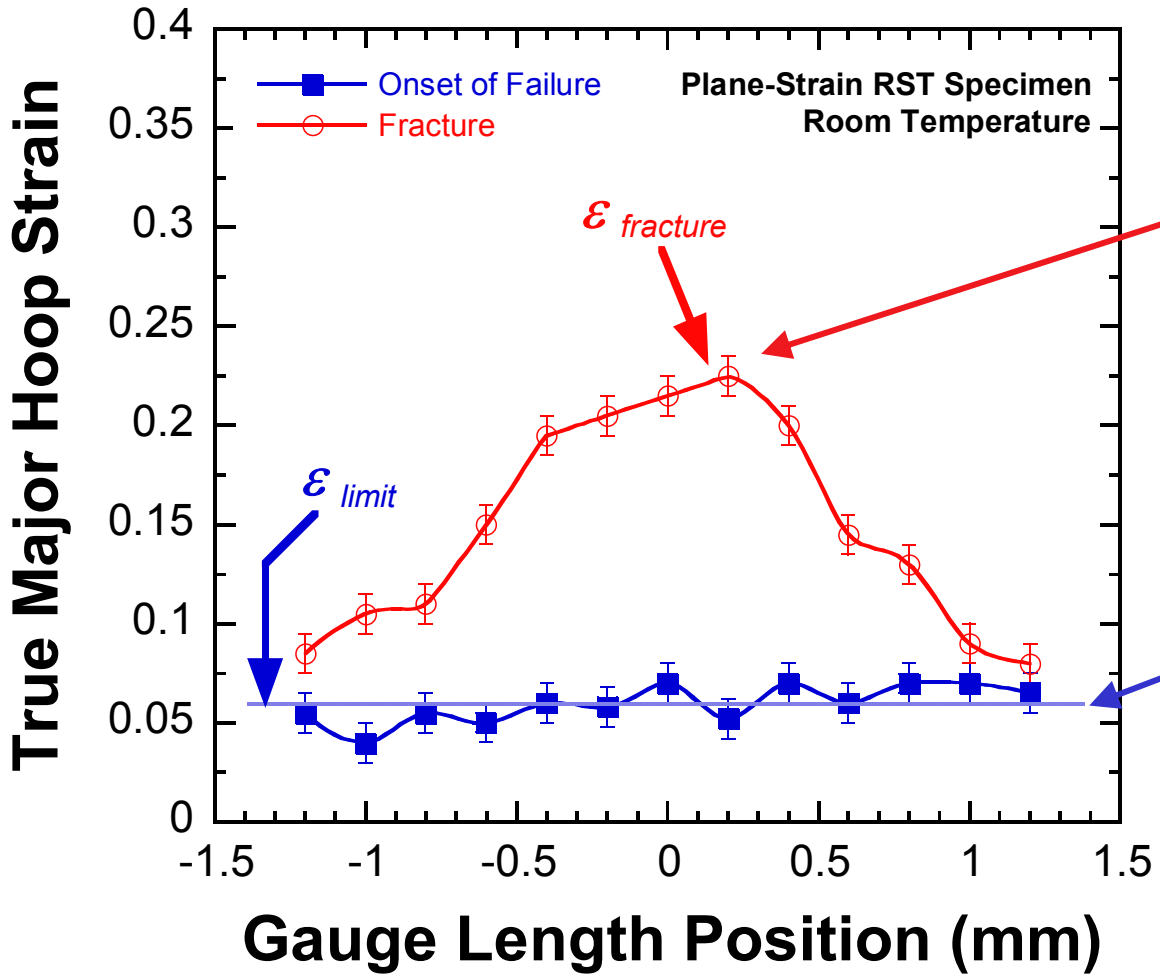




$\varepsilon_{plastic} = \ln(\ell_f/\ell_o)$

$0.005 < \text{Strain Error} < 0.01$

Critical Strain Definitions

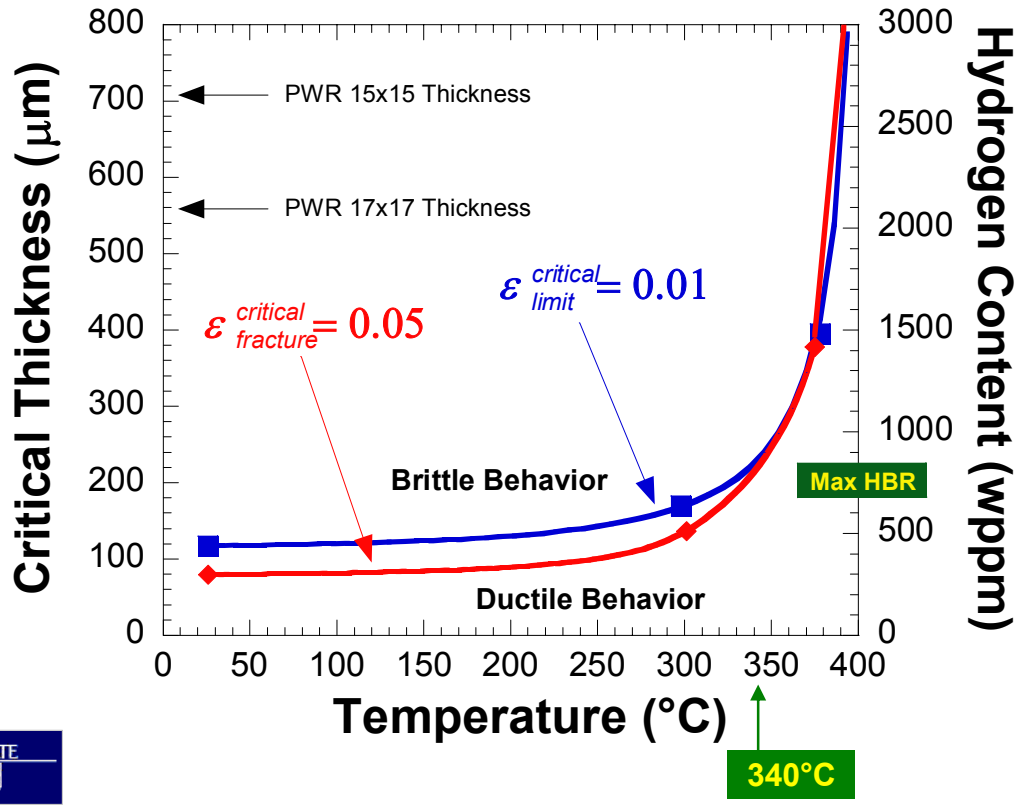


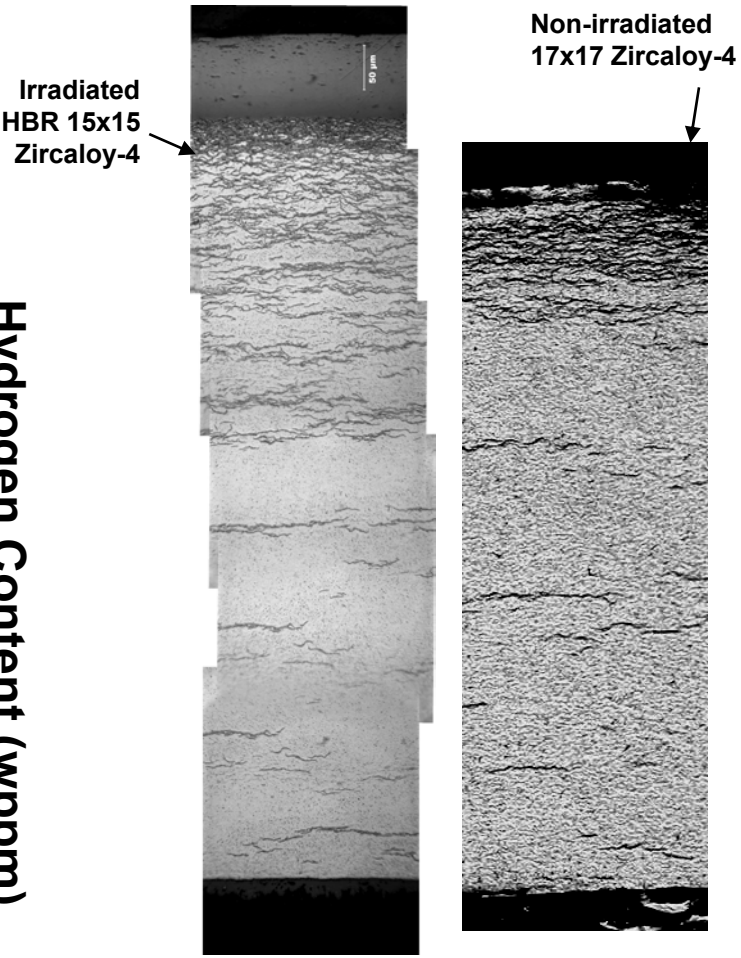
Fracture Strain = local strain across fracture surfaces

Limit Strain = uniform strain at onset of necking/failure; calculated using numeric integration

Critical Strain Results

- **Determine the influence of localized (layered) hydride precipitation on plane-strain ductility relevant to postulated RIA conditions.**



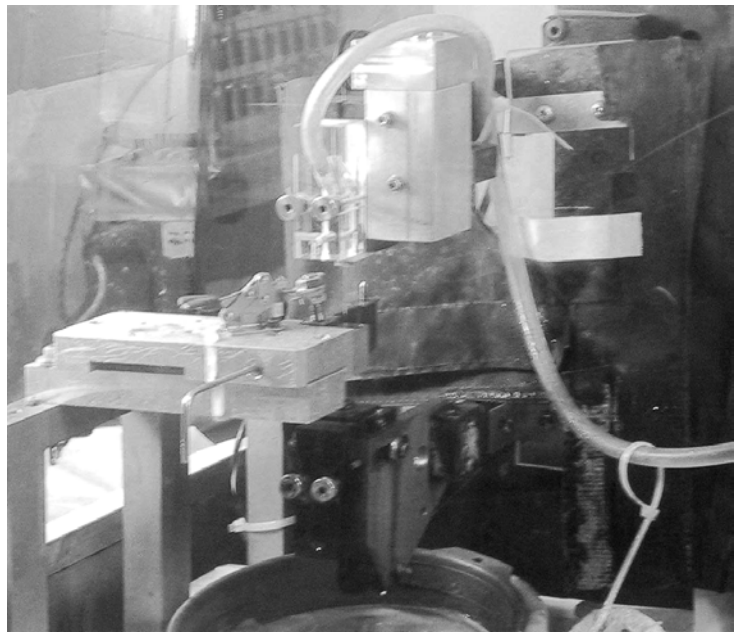


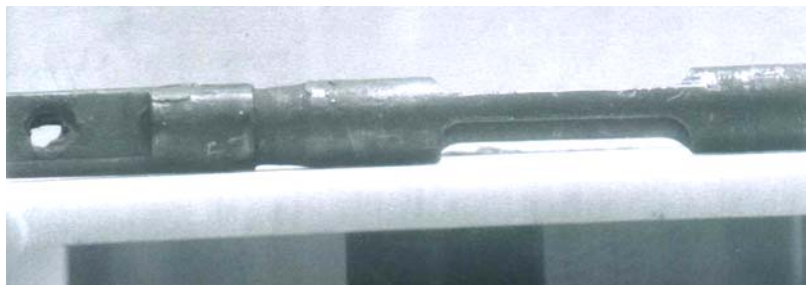
Published in the proceedings of the International Conference on Hydrogen Effects on Material Behavior and Corrosion Deformation Interactions, Moran, WY, September 22-27, 2002

Irradiated Specimen Preparation

- **Specimen Inventory (End of July 03):**
  - 12 RST and 4 Plane-Strain (TMI-1)
  - 7 Axial (5 – Surry and 2 – HBR)

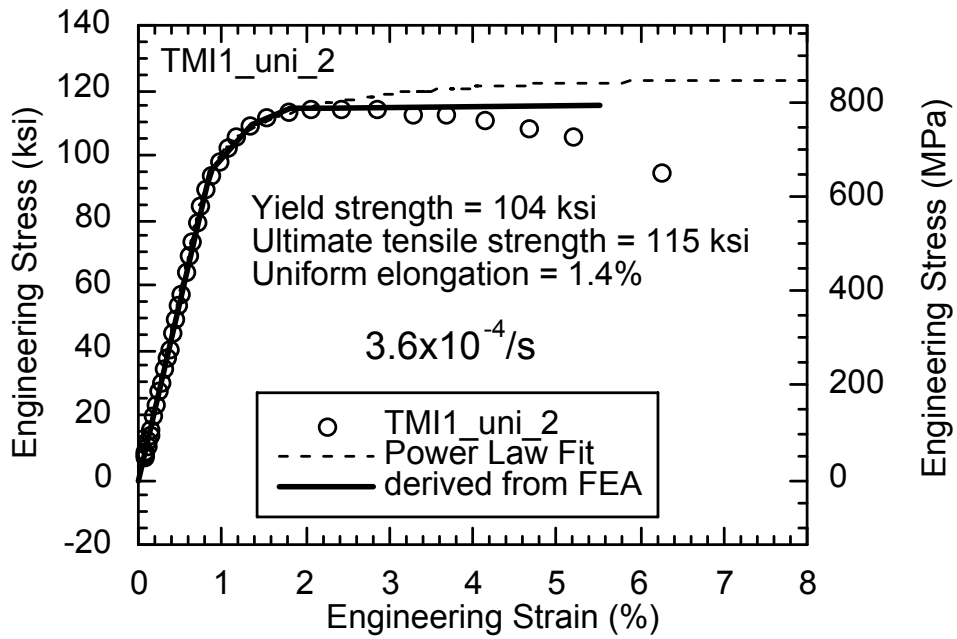
Sectioning	**Completed**
Defueling	**Completed**
Oxide Removal	**Completed**
Endcap Welding	**Completed**
EDM	**On-going**
Testing	**Not Complete**
Post-test Analysis	**Not Complete**

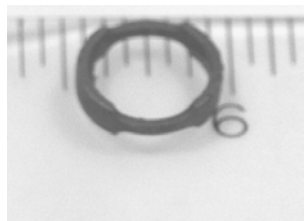




First Irradiated Test – TMI-1 Uniaxial RST

- **Successfully completed July 2002**
- **ALARA assessment**
  - Engineering barriers sufficient during test but significant contamination present during disassembly - HOLD POINT
  - Develop better contamination containment
- **Recommendation for radiological glovebox system**

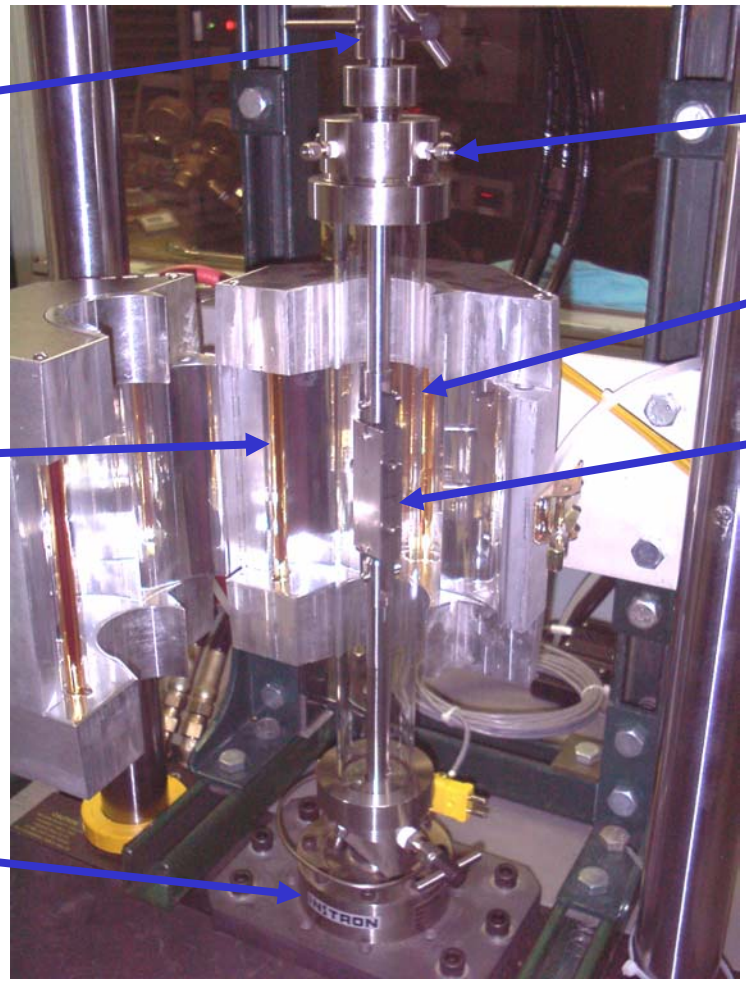


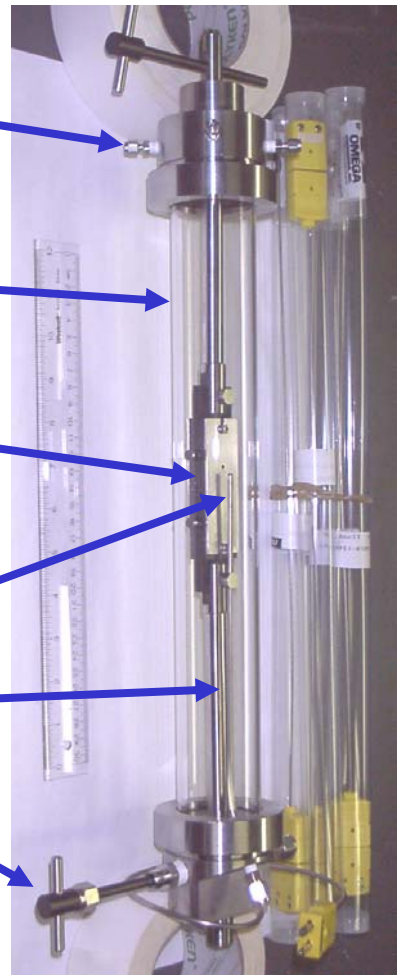


Testing Facility Upgrades

- **Radiological Glovebox**
  - Primary purpose is contamination control
  - ANL ALARA Funding ($150K)
  - Conceptual design & operations
  - DOE Mandated Reviews
    - Design
    - Experiment Safety
    - ALARA
  - Construction
  - Validate concept of operations

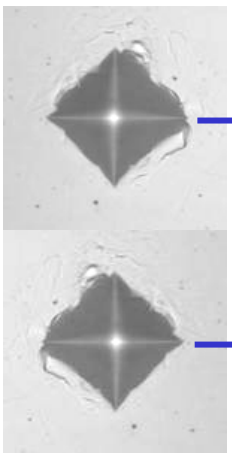
Testing Facility Upgrades





Testing Facility Upgrades

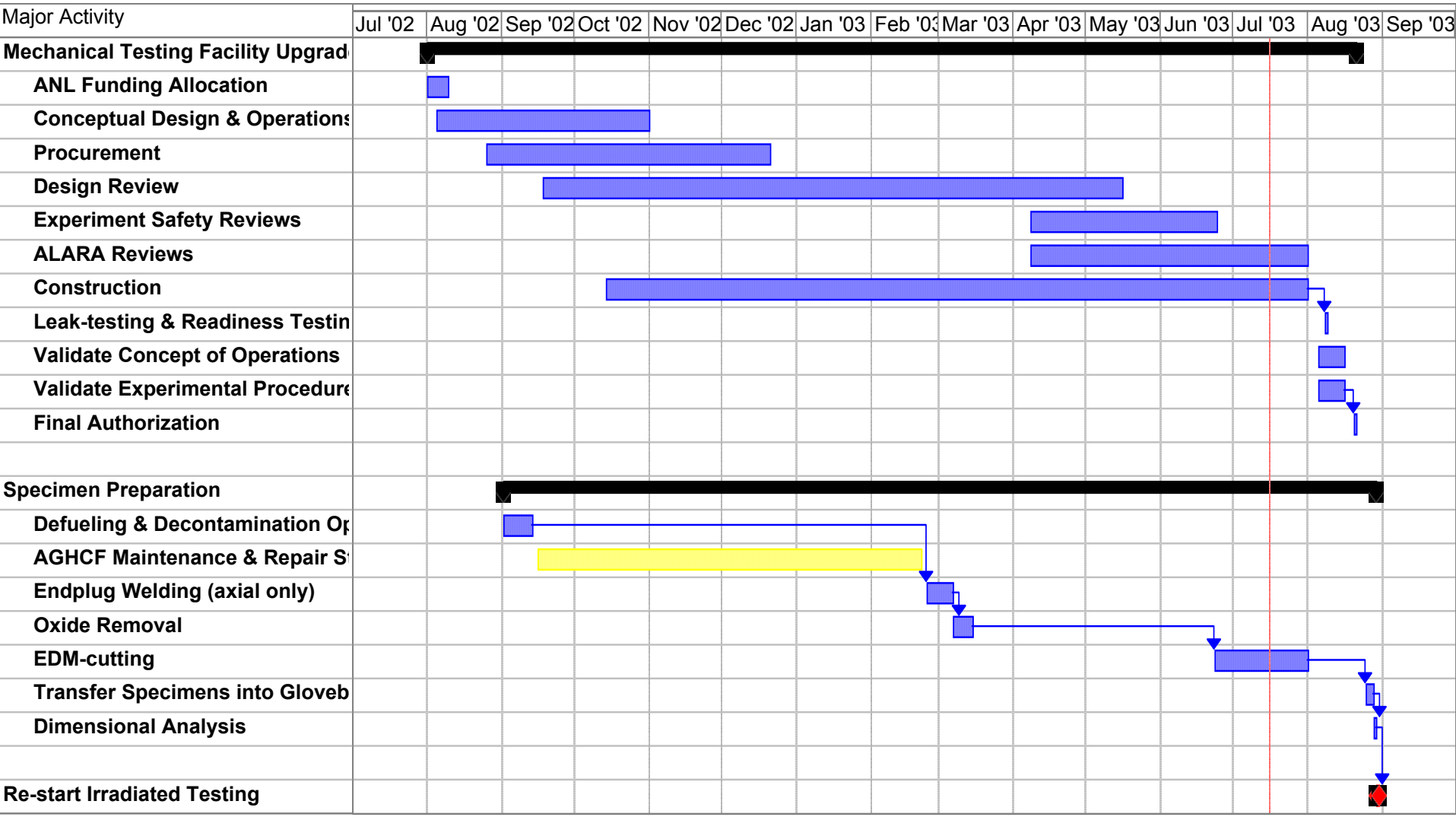
- **Automated Indentation System**
  - Training
  - Modification
  - Installation into glovebox
  - Validate concept of operations
  - Experiment Safety & ALARA Reviews

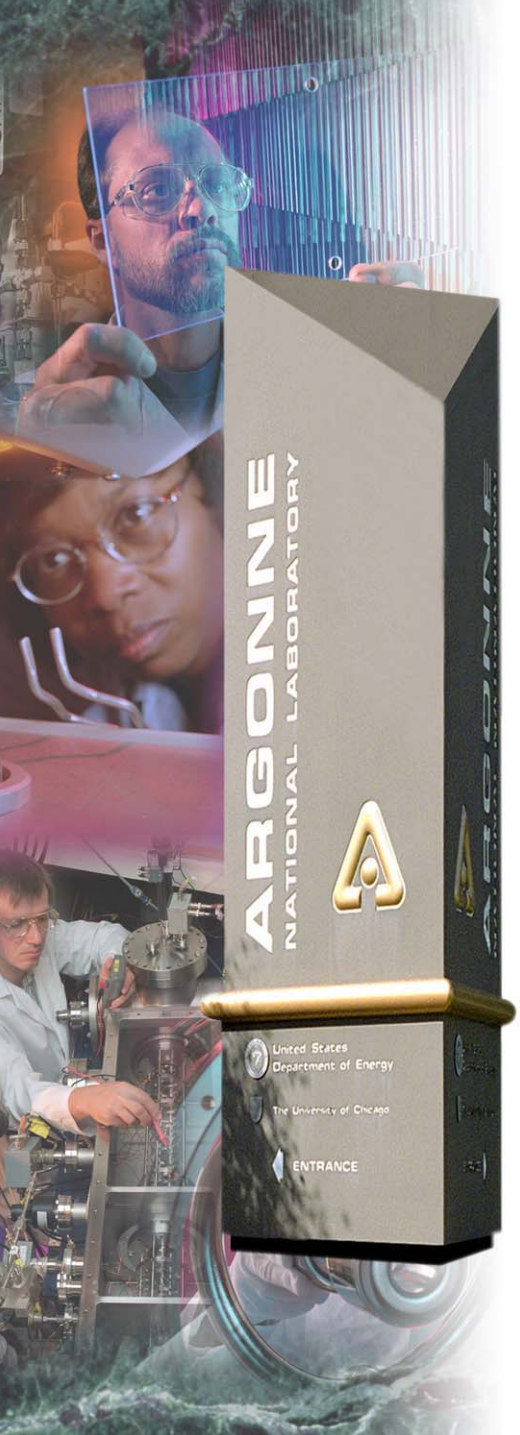


Measure prior and after testing

Calculate
$\varepsilon_{plastic} = \ln(\ell_f/\ell_o)$

Schedule for Re-starting Irradiated Testing





Questions?

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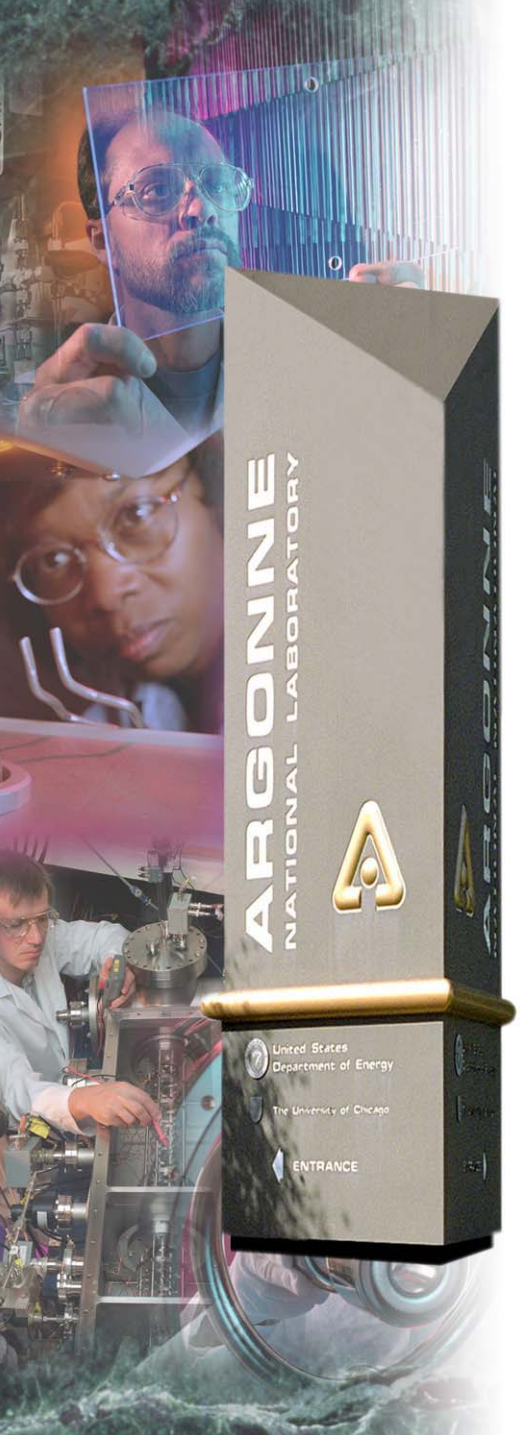

Backup Slides

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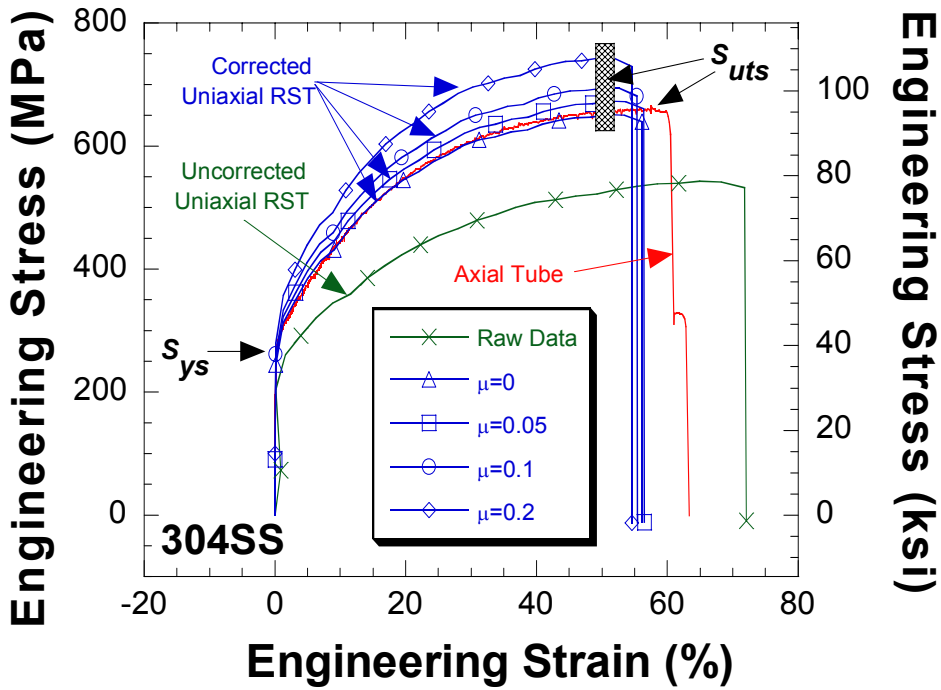
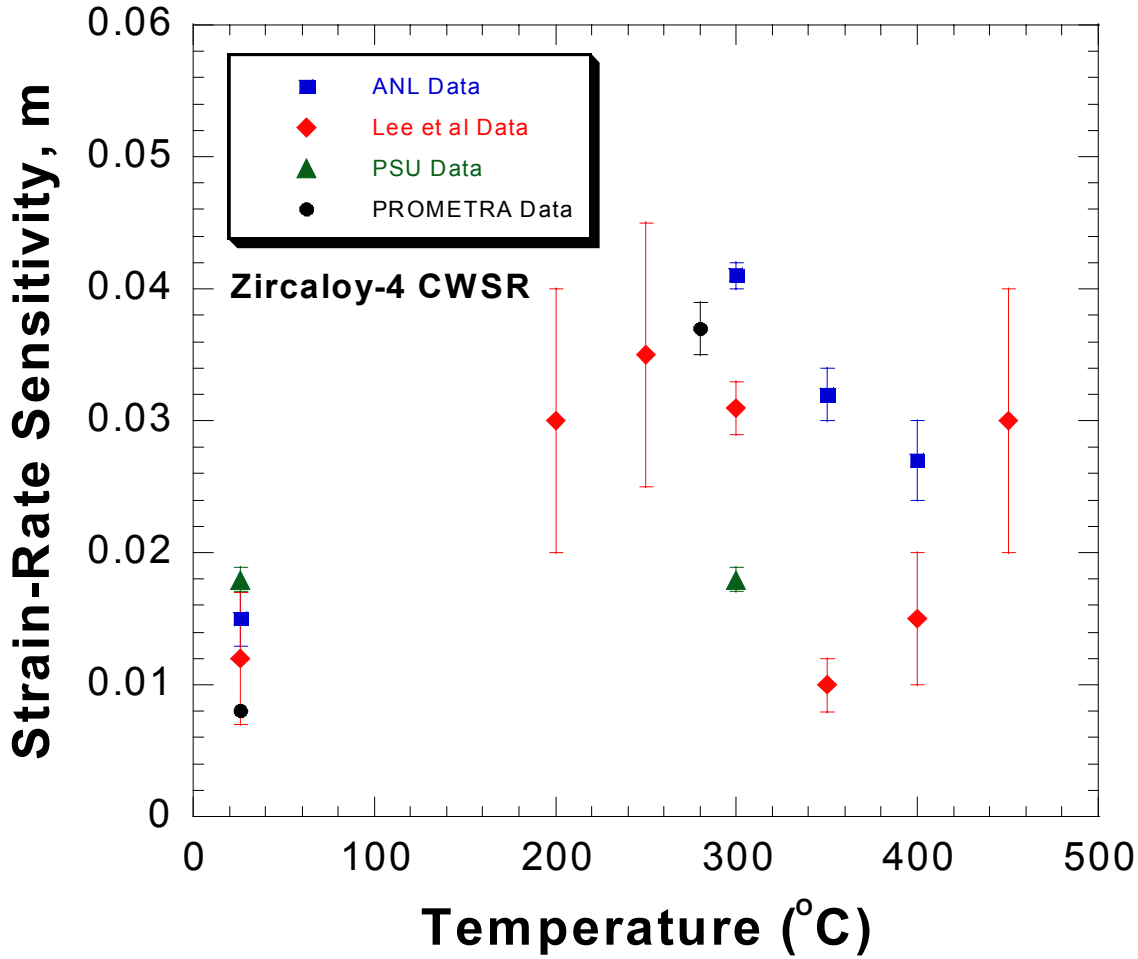
RST Procedure based on 'Isotropic' 304SS

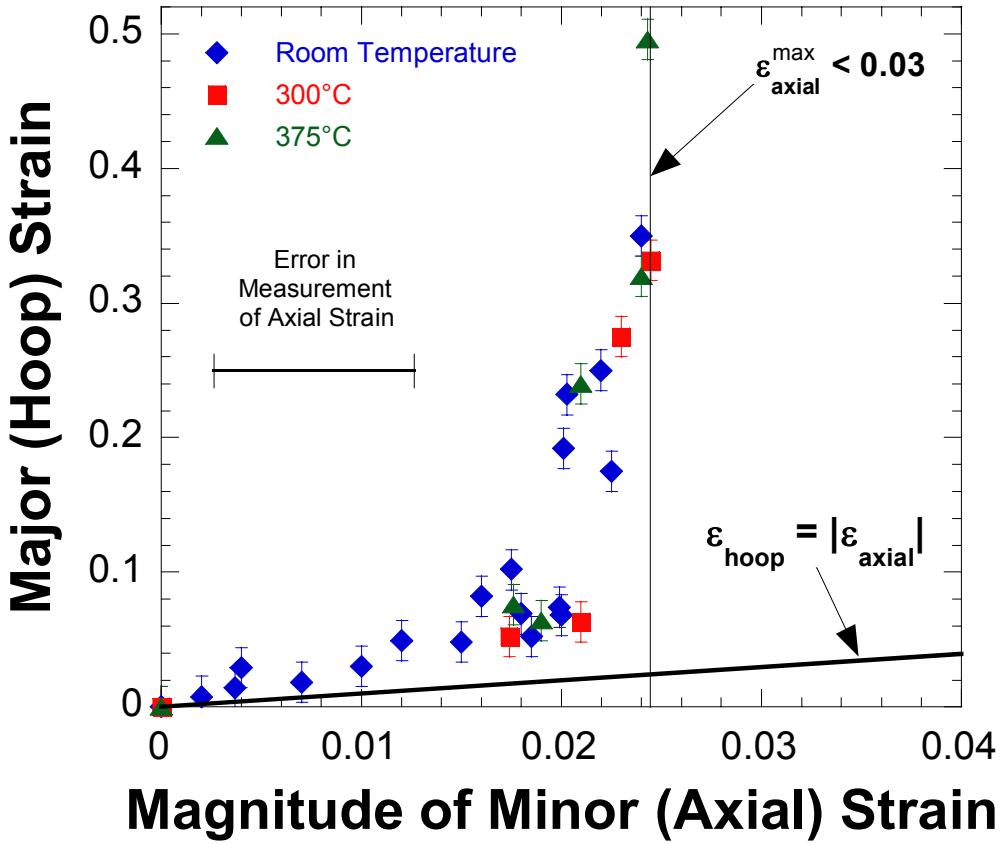
- Assumes isotropic plasticity of 304SS tubing.
- Uniaxial RST data indicates $0<\mu<0.05$.
- FEA is used to correct for effects of loading grips & friction, as well as, an "effective" gauge length as a function of plastic displacement.



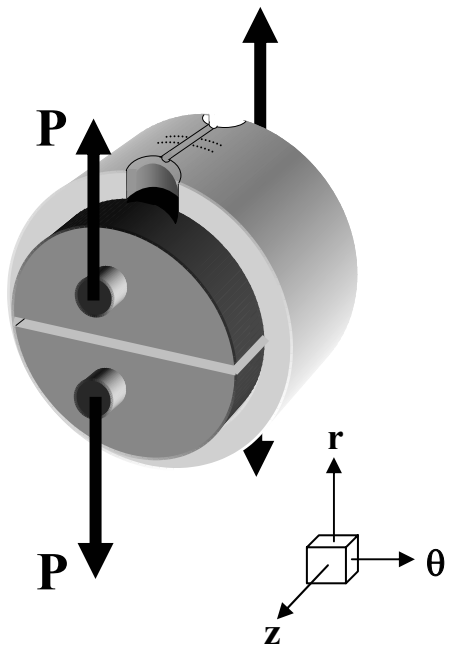
Hoop Strain-rate Sensitivity



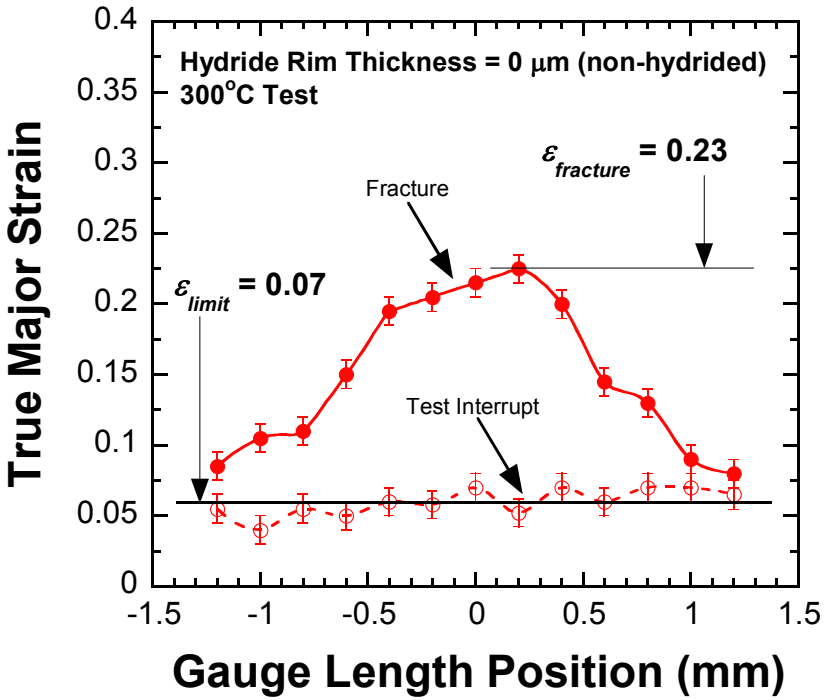
Near Plane-strain Condition

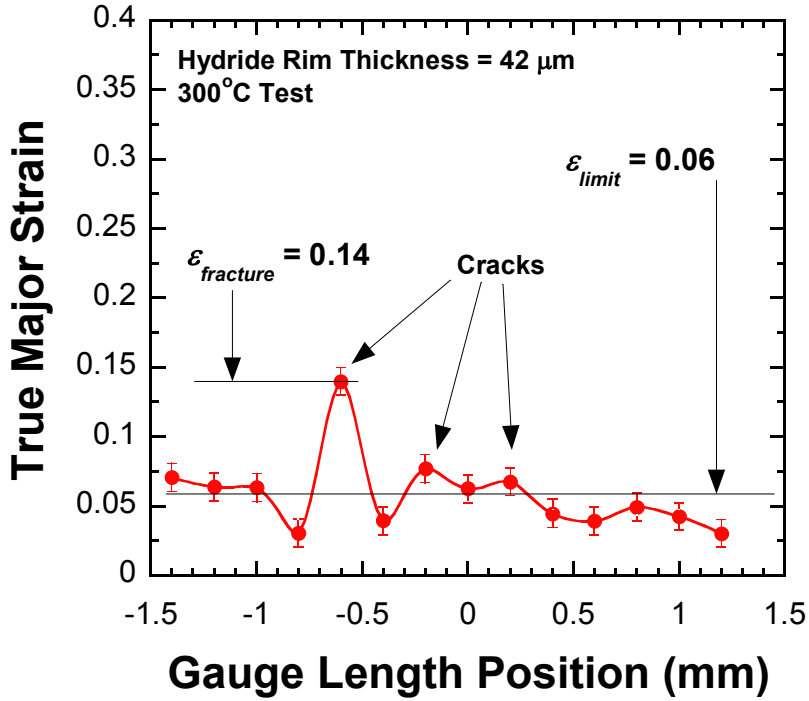


"Near" plane-strain condition is located in center 2-3 mm of gauge section.

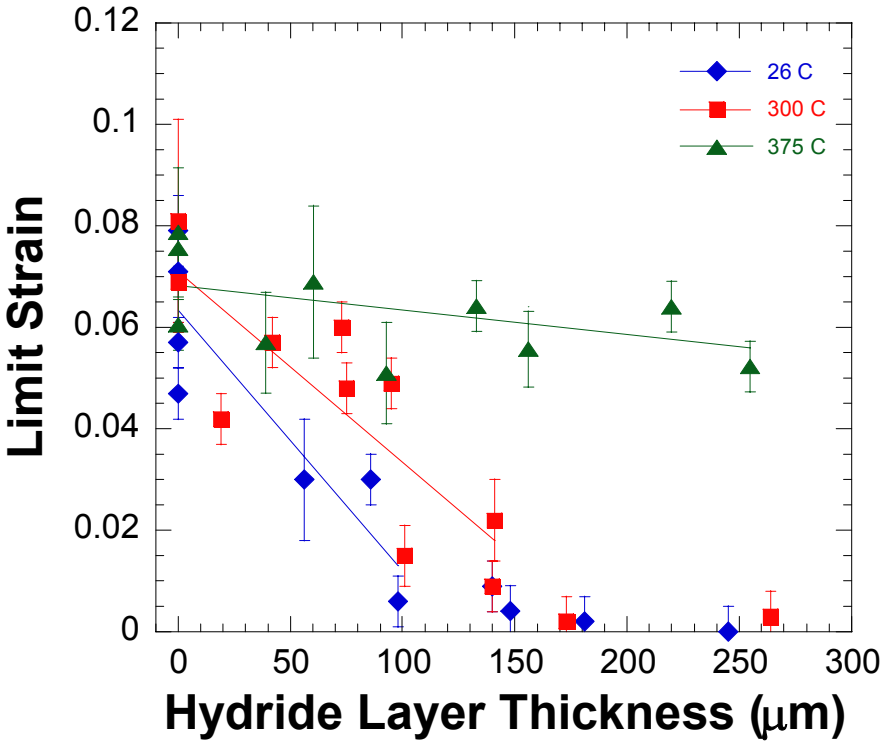


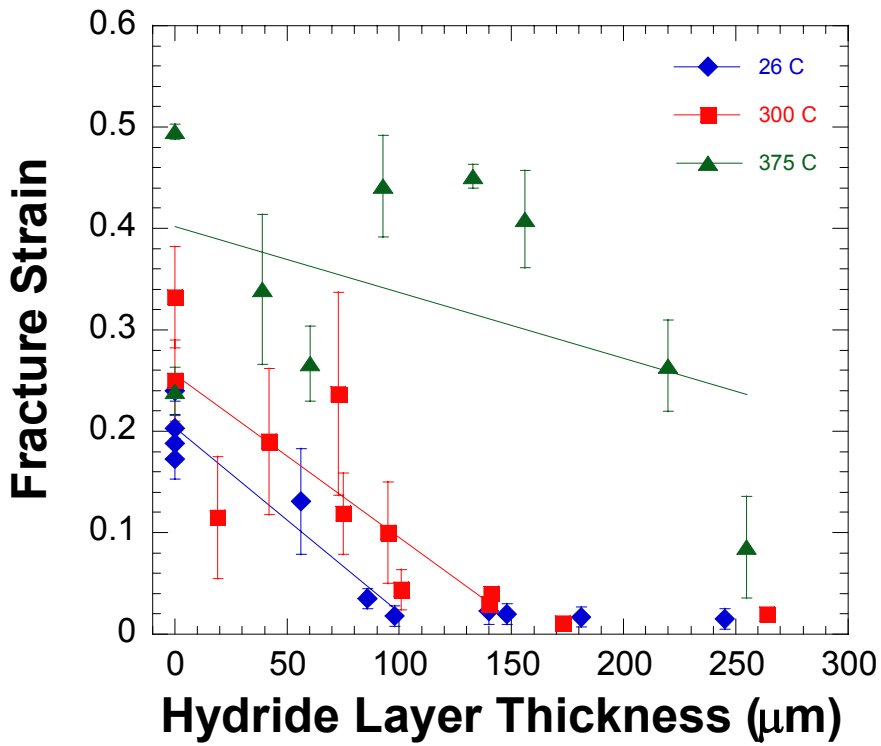
Hydrided Specimen Plasticity vs. Cracking





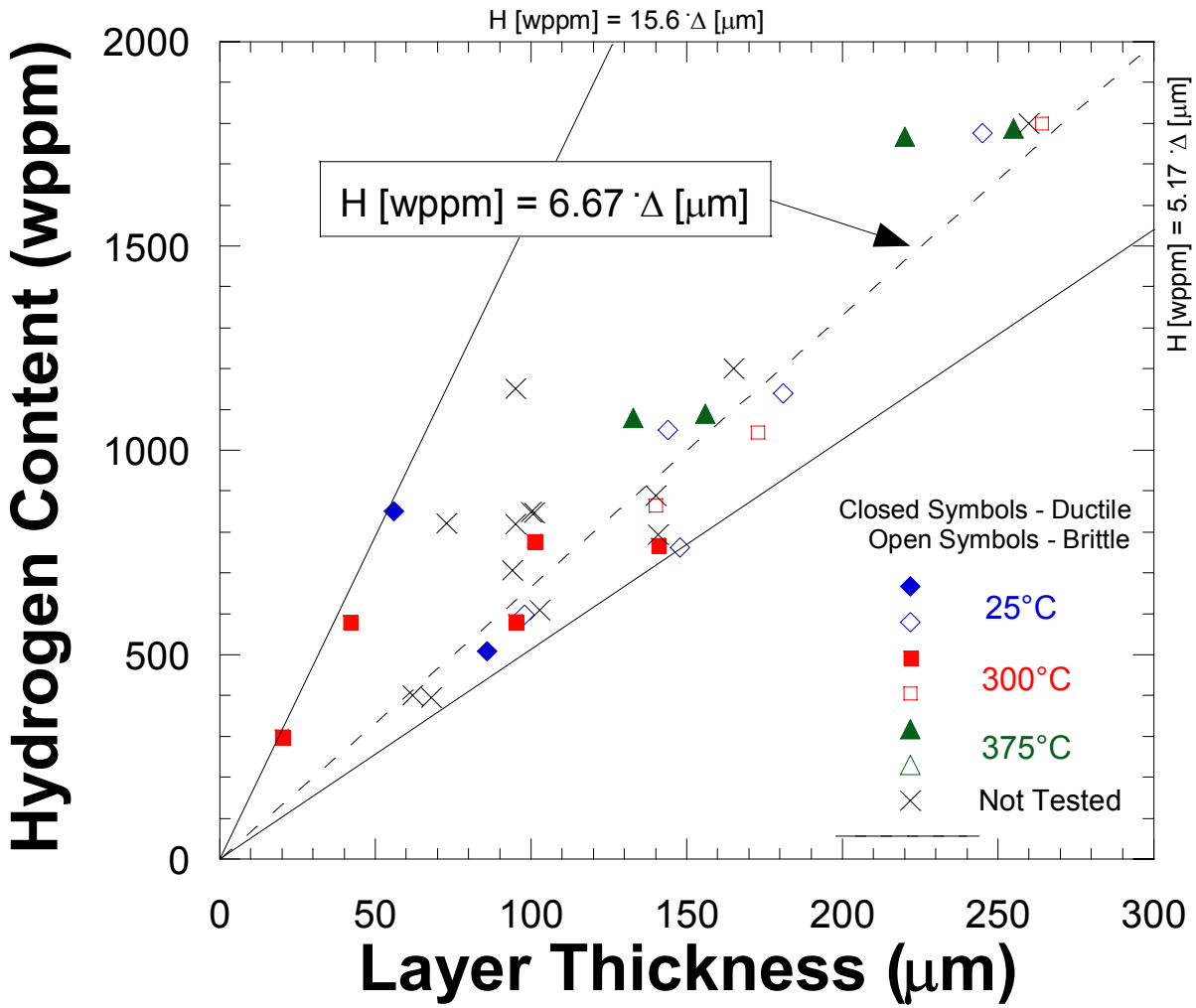
Hydrided Specimen Ductility



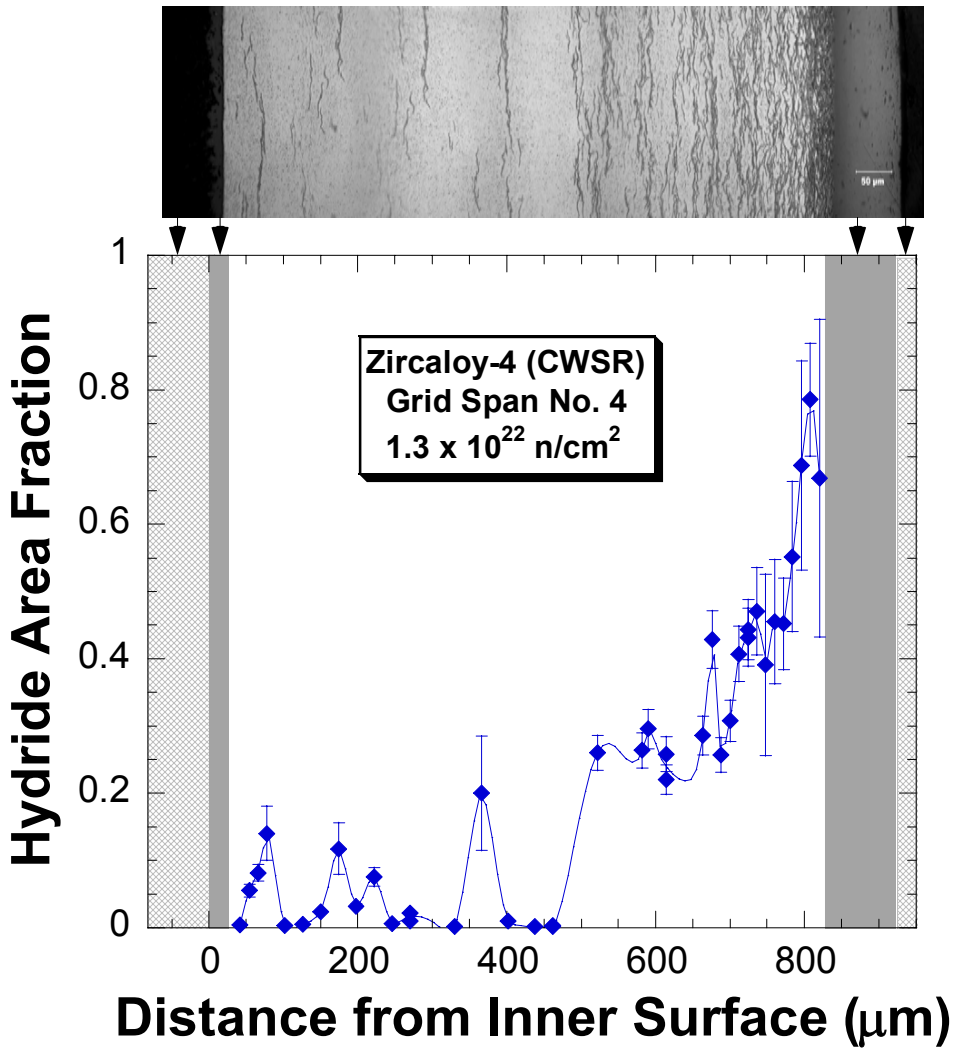


- **Ductile-to-brittle transition occurs at approximately:**
  - **100 μm for 26°C**
  - **140 μm for 300°C**
  - **>270 μm for 375°C**

Correlation of H Content to Hydride Layer

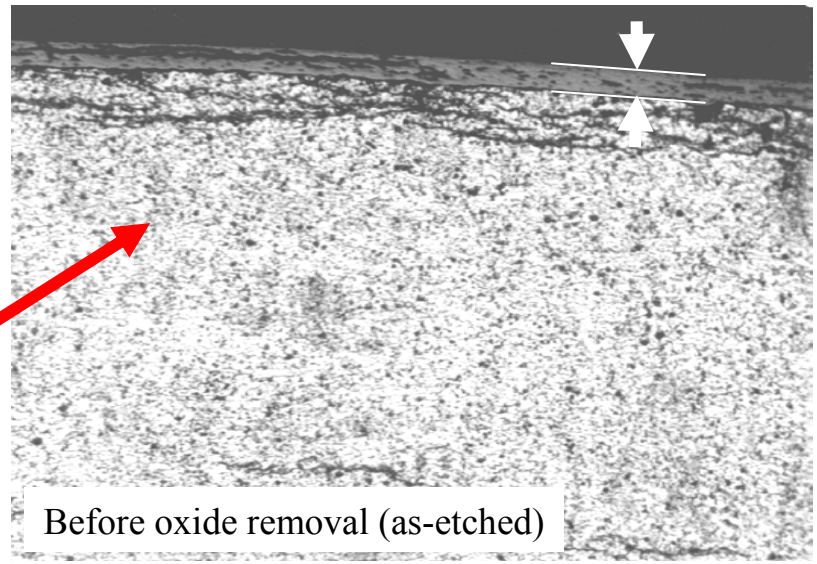


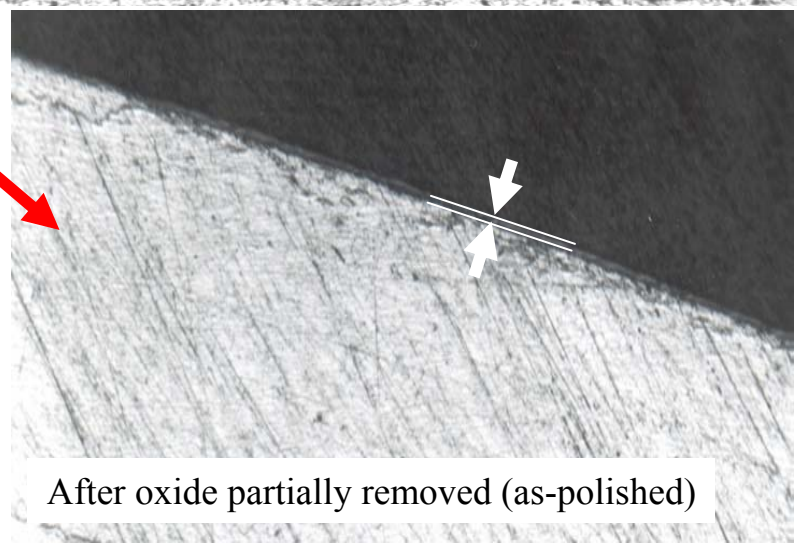
HBR Hydride Distribution



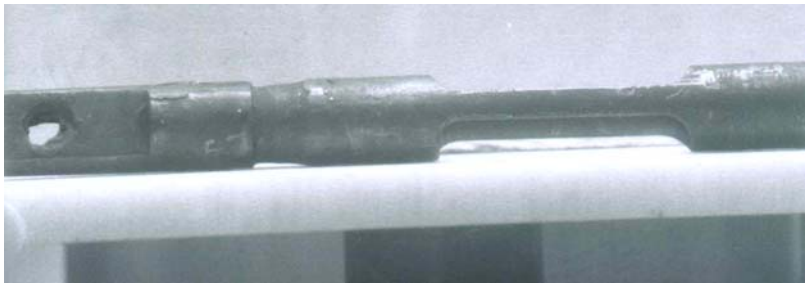
Irradiated Specimen Preparation

- Sectioning rod into 3 to 6-inch long segments
- Defueling in nitric acid bath
- Partial removal of OD oxide for electrical continuity
- Welding endcaps for axial tensile specimens
- Machining of gauge sections using EDM

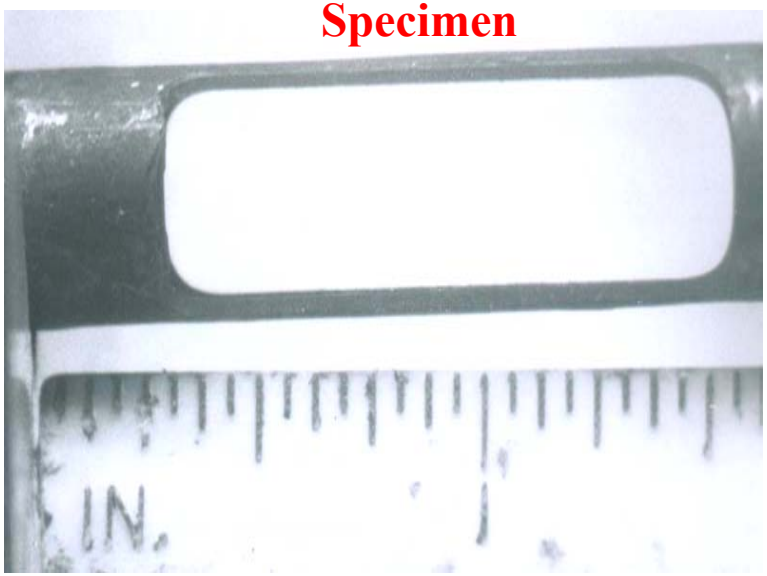


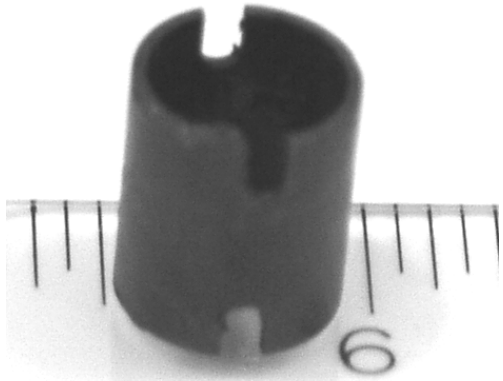


Irradiated Specimen Preparation

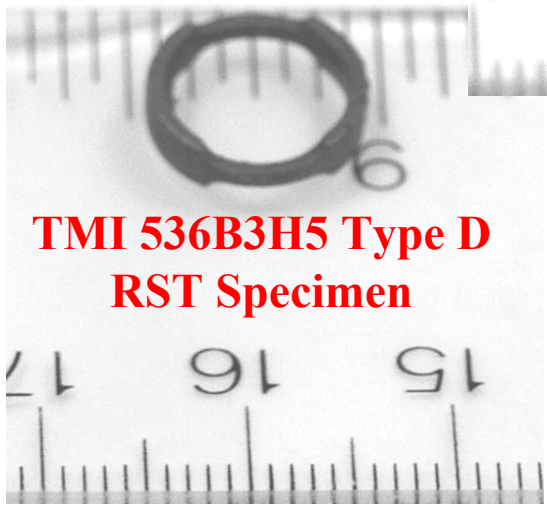


Surry 591C2C Axial Tensile Specimen





TMI 536B3H13 Plane-Strain Specimen



TMI 536B3H5 Type D RST Specimen