

Mechanical Property Testing

NRC-EPRI Program for High Burnup Cladding Performance

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Office of Science
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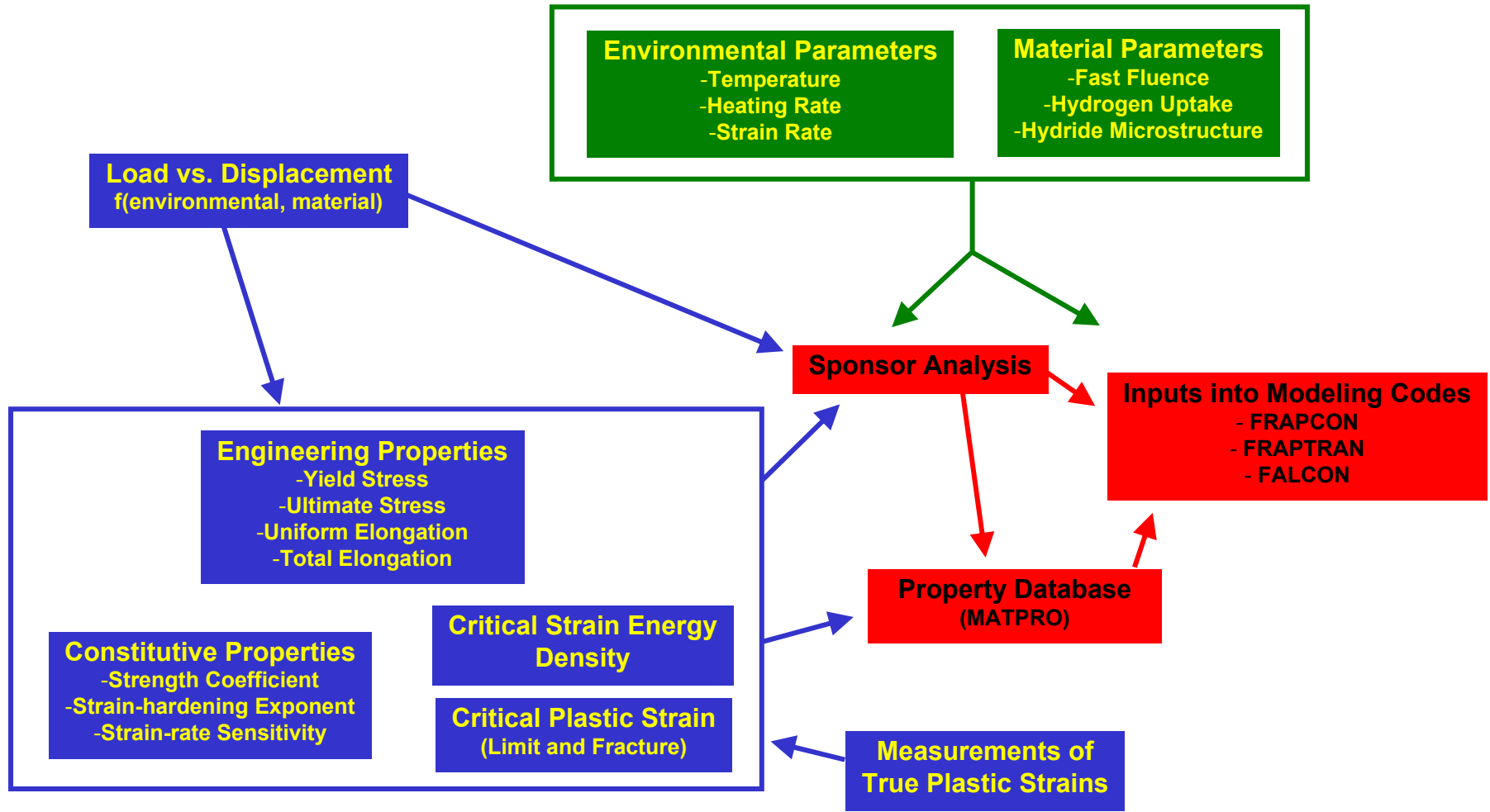


Objective of Mechanical Property Testing

- 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

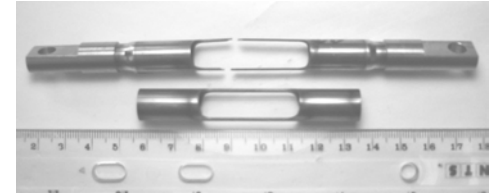
- **Mechanical Testing Plans & Procedures**
 - Testing Plans
 - Engineering and Constitutive-based Properties
 - Critical Strain-based Properties
- **Irradiated Specimen Preparation & Testing (to-date)**
 - Machining & Dimensional Measurements
 - First Irradiated Test
 - Facility Upgrades
- **Future Schedule**

Non-irradiated Testing Plan

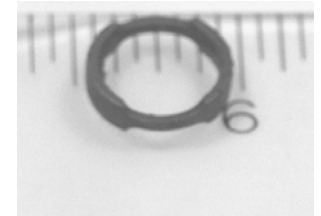
Reference: IPS-263-Rev.3

T (°C) \ $\dot{\epsilon}$ (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	

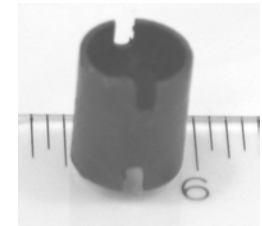
 - Uniaxial Axial-Tube




 - Uniaxial Ring-stretch



 - Plane Strain Ring-stretch



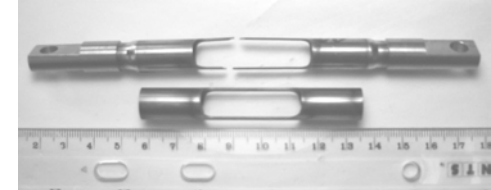
 -Biaxial Burst LOCA
 -Constant Pressure 800, 1600 psig (5.52, 11 MPa)
 -Temperature Ramp at 1 and 10°C/sec
 -Determine Rupture Temperature

Irradiated Testing Plan

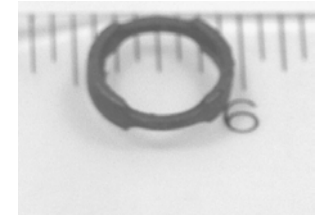
Reference: IPS-263-Rev.3 * - denotes specimens from different grid spans

T (°C) \ $\dot{\epsilon}$ (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

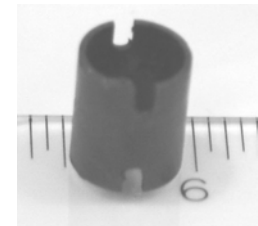


▨ - Uniaxial Ring-stretch



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

■ - Plane Strain Ring-stretch

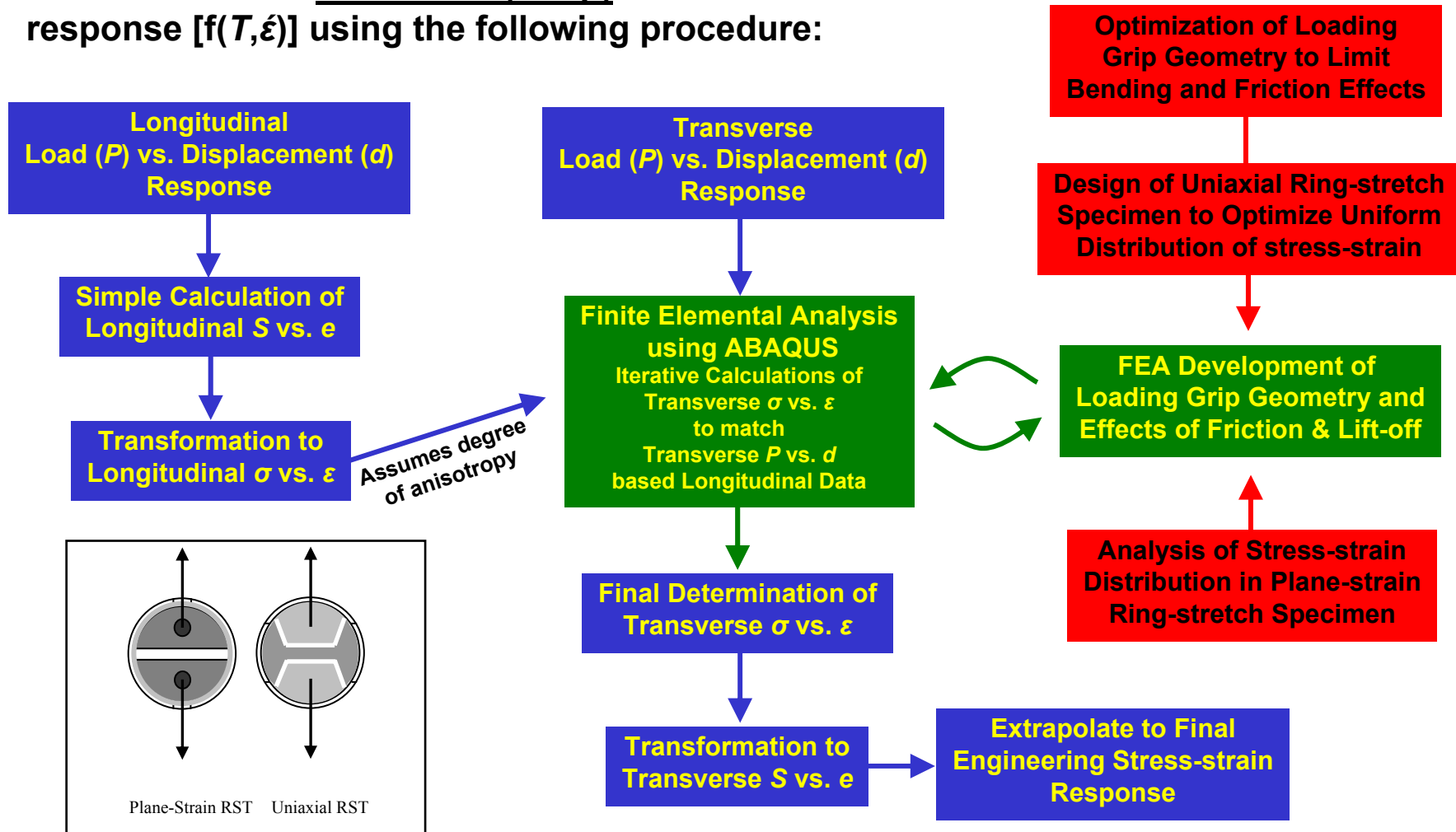


▣ - Biaxial Burst LOCA
 -Constant Pressure 800, 1600 psig (5.52, 11 MPa)
 -Temperature Ramp at 1 and 10°C/sec
 -Determine Rupture Temperature

Uniaxial Properties – Zr-4

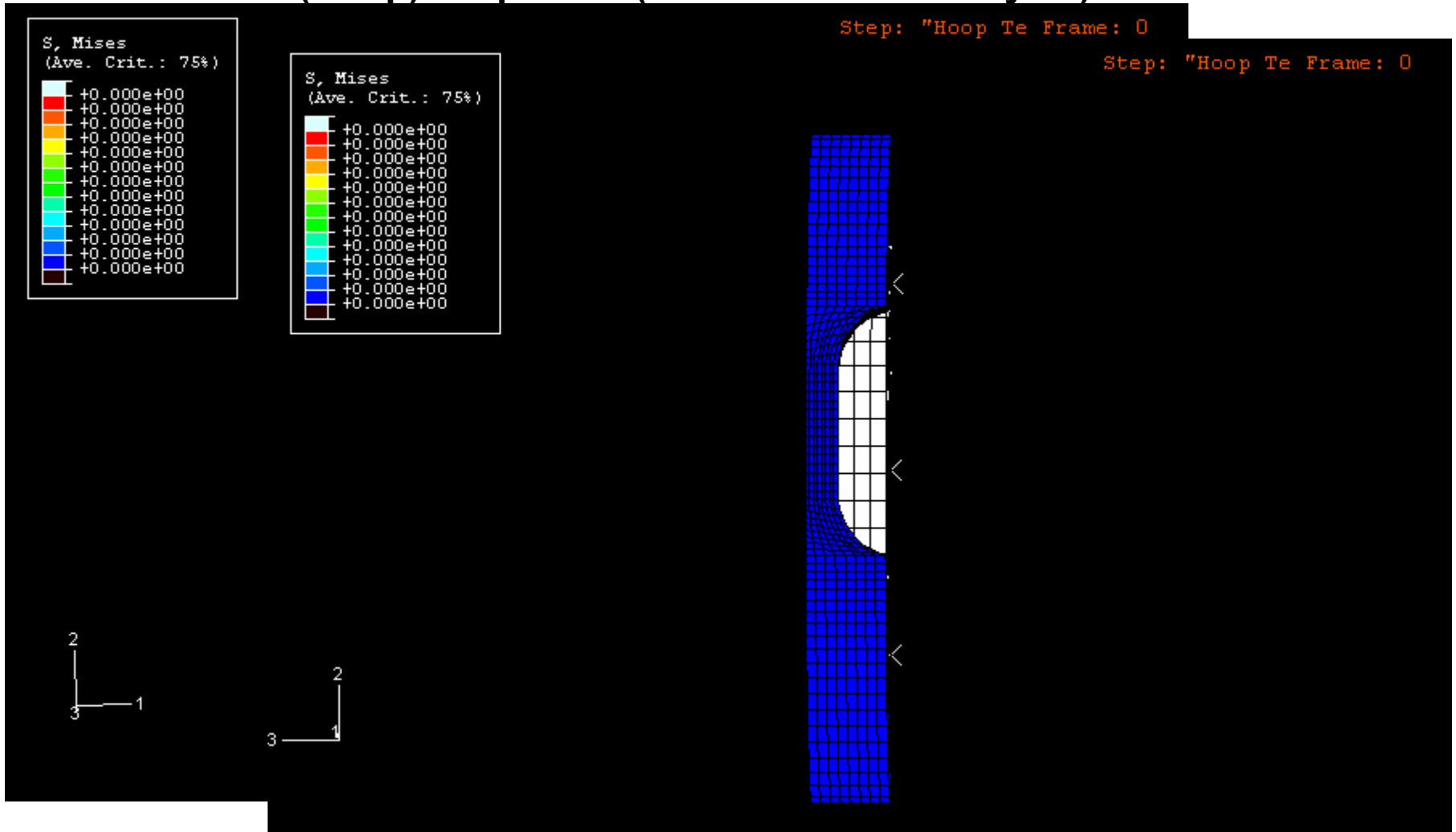
Published in the proceedings of the 4th Symposium on Small Specimen Test Techniques, Reno, NV, January 23-25, 2001

- Determination of transverse (hoop) stress-strain response [$f(T, \dot{\epsilon})$] using the following procedure:



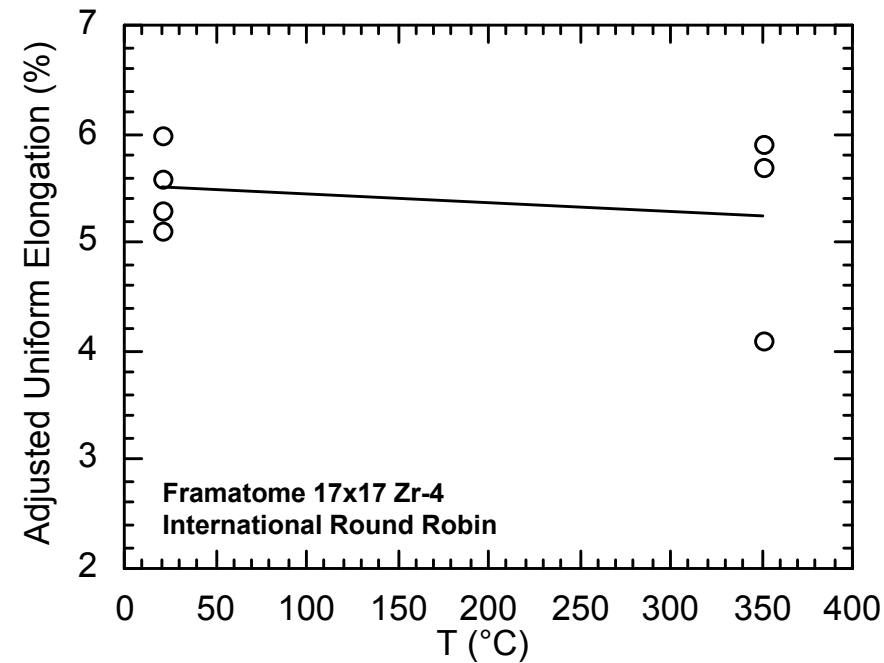
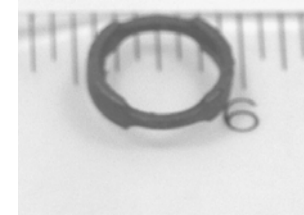
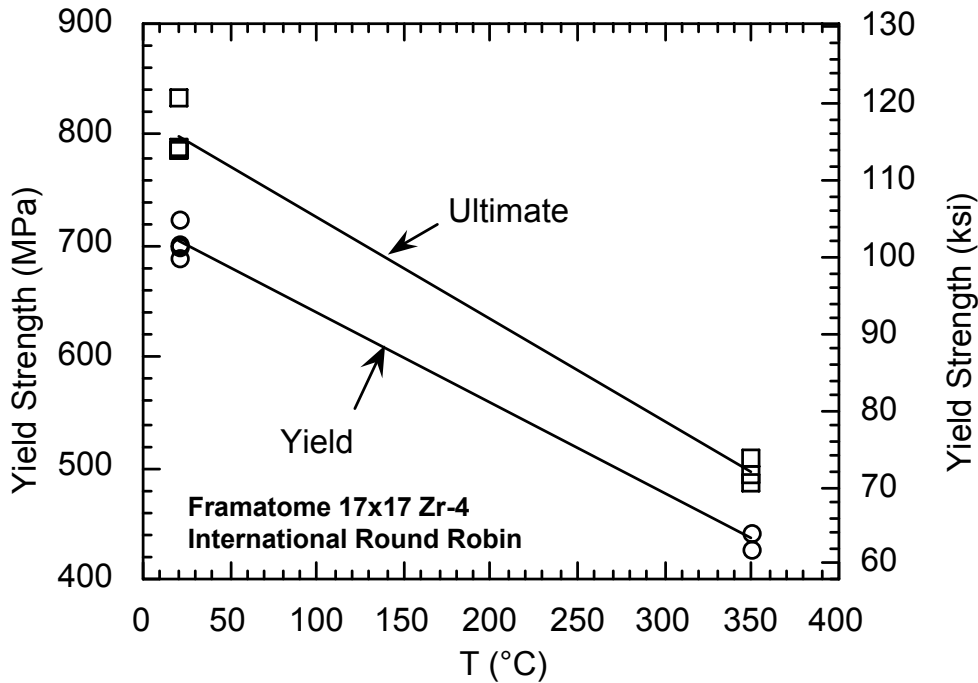
Uniaxial Properties

- Transverse (Hoop) Properties (Finite Element Analysis)



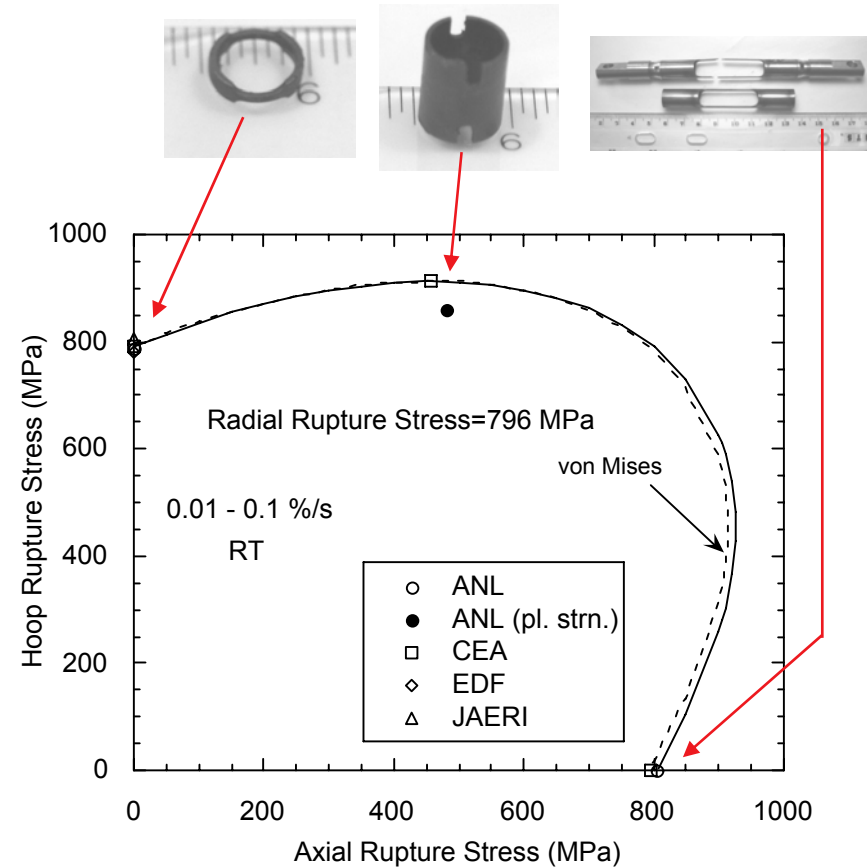
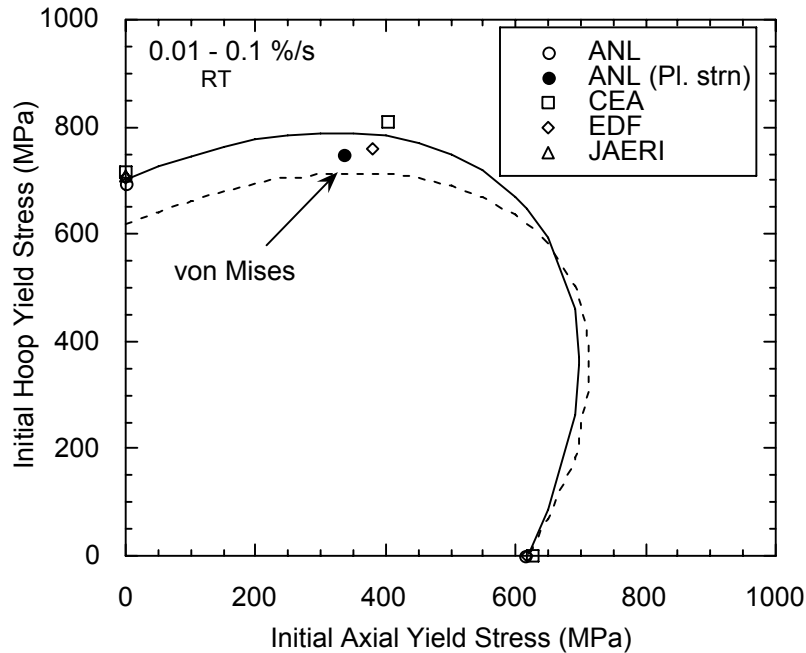
Uniaxial Properties – Zr-4

- Transverse (Hoop) Properties



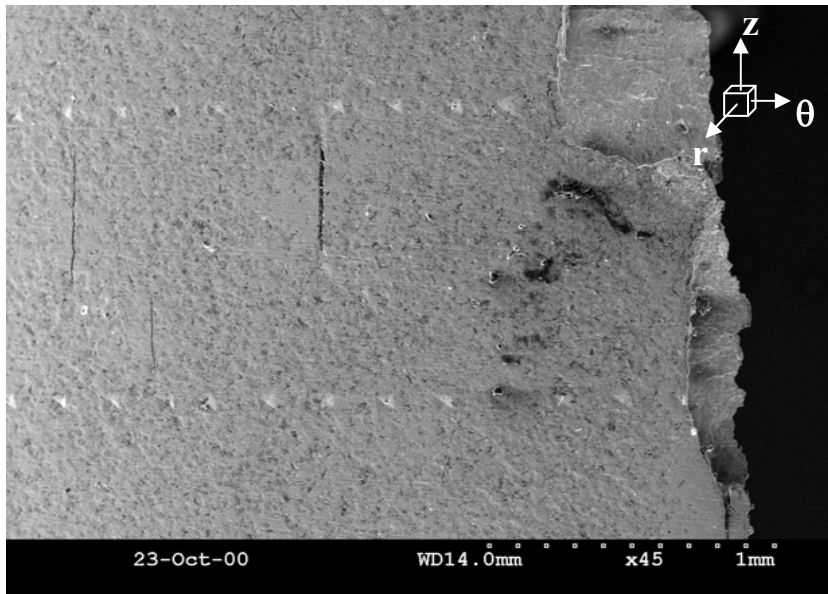
Biaxial Properties – Zr-4

- 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



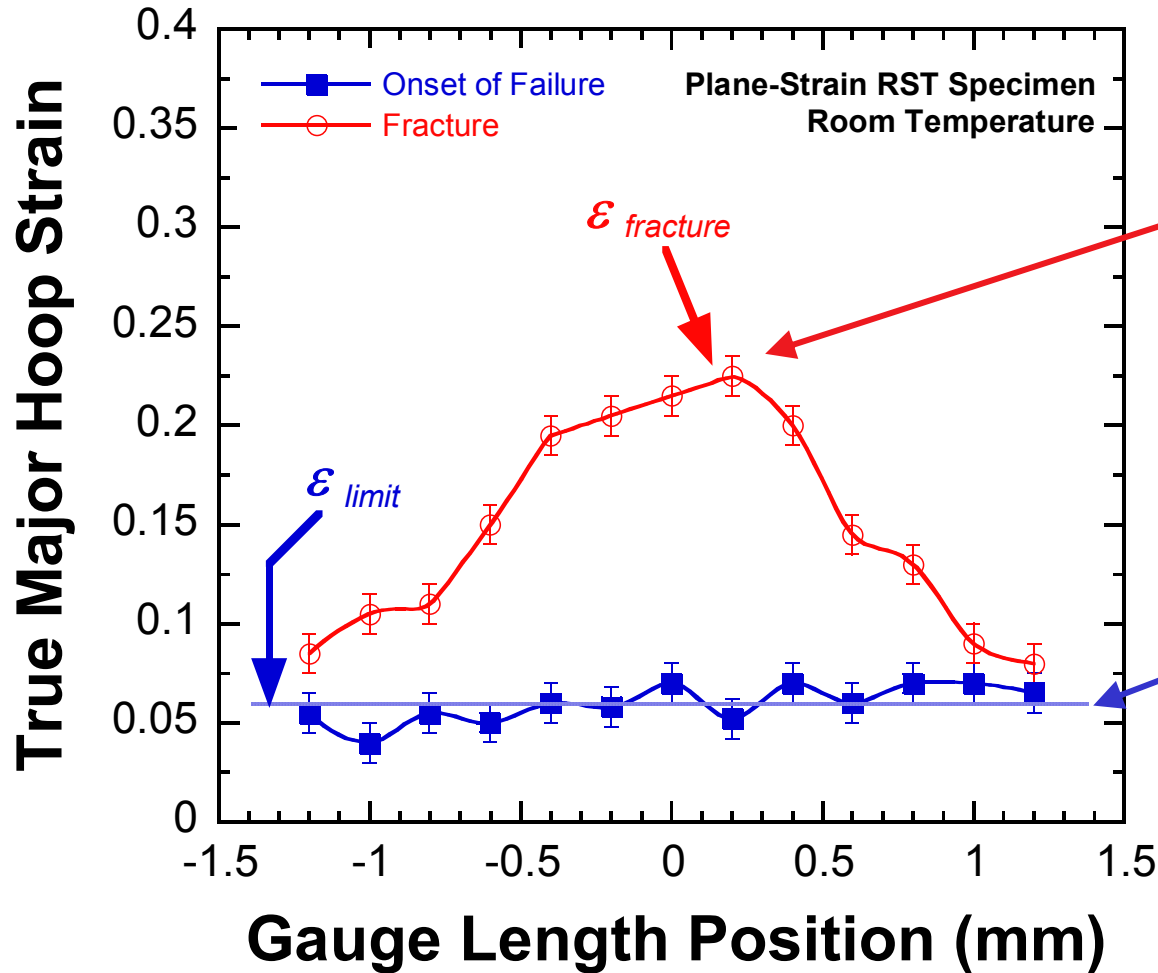
Indent-to-indent spacing measured using x,y stage with resolution of 0.001 mm before & after testing

Optical Axis

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

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

Critical Strain Definitions

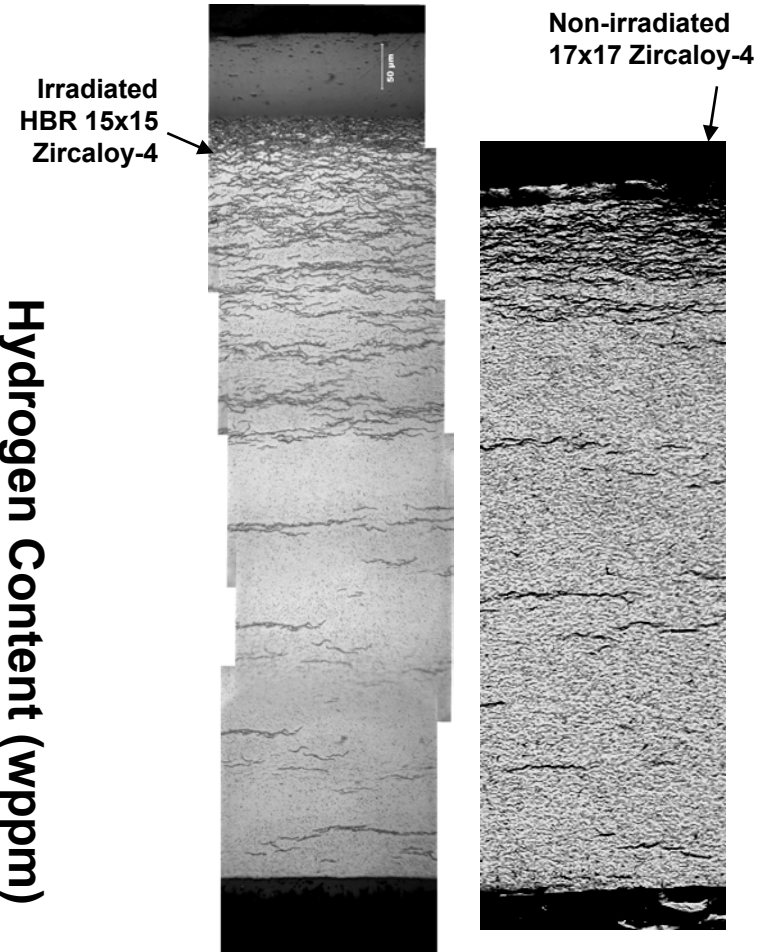
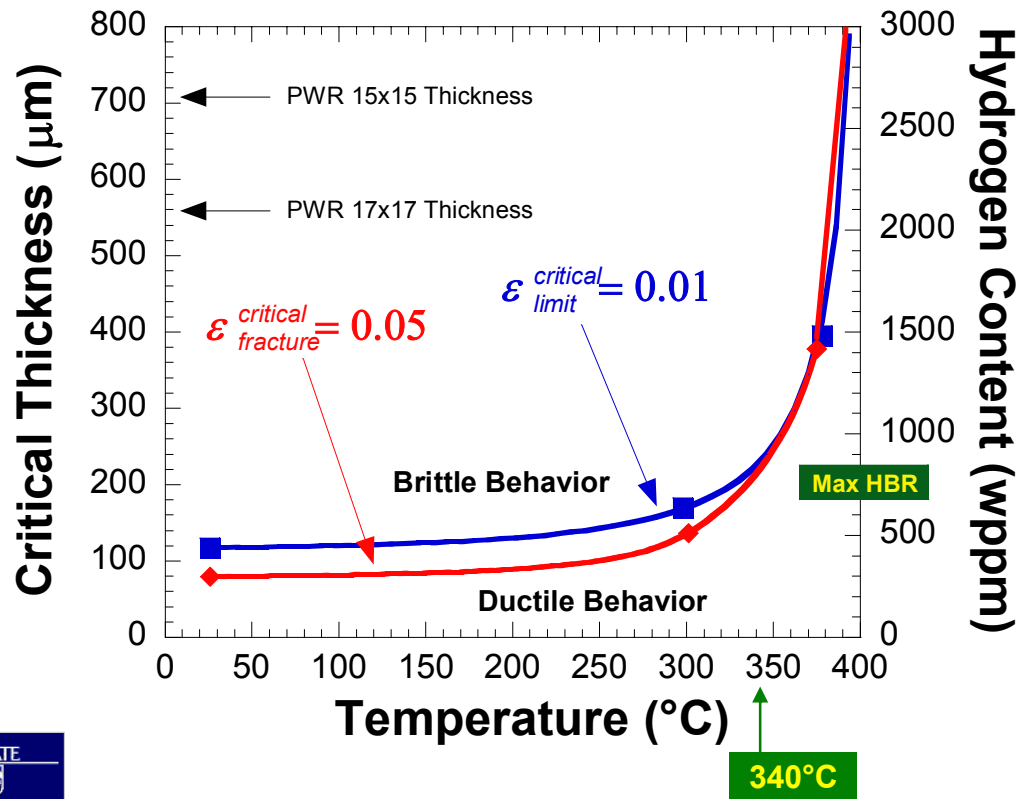


Fracture Strain =
local strain across
fracture surfaces

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.

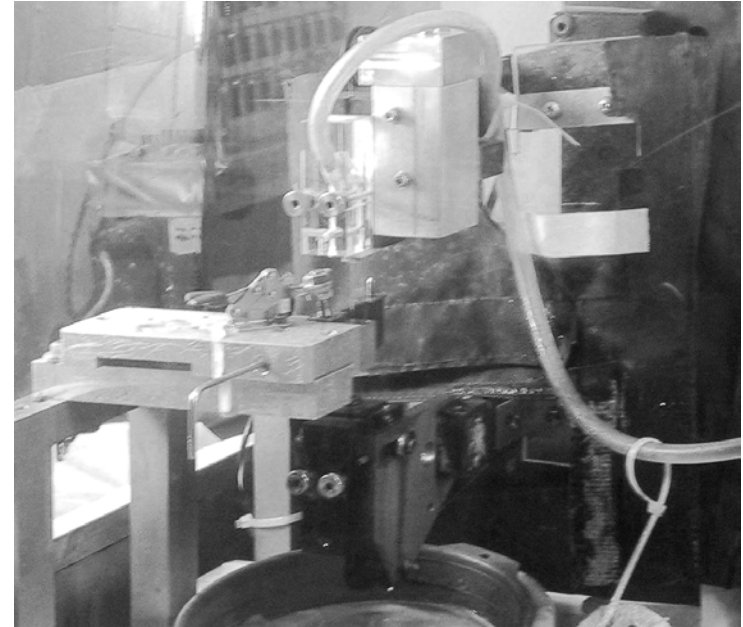


Published in the proceedings of the International Conference on Hydrogen Effects on Material Behavior and Corrosion Deformation Interactions, Moran, WY, September 22-27, 2002

Irradiated Specimen Preparation

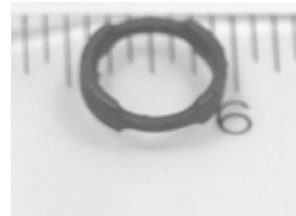
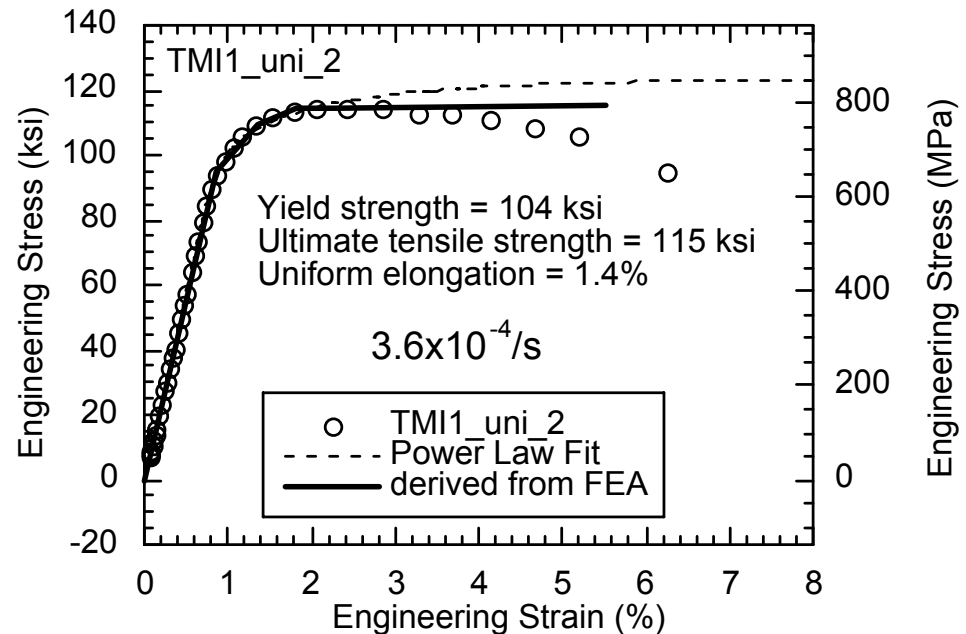
- **Specimen Inventory (End of July 03):**
 - 12 RST and 4 Plane-Strain (TMI-1)
 - 7 Axial (5 – Surry and 2 – HBR)

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**



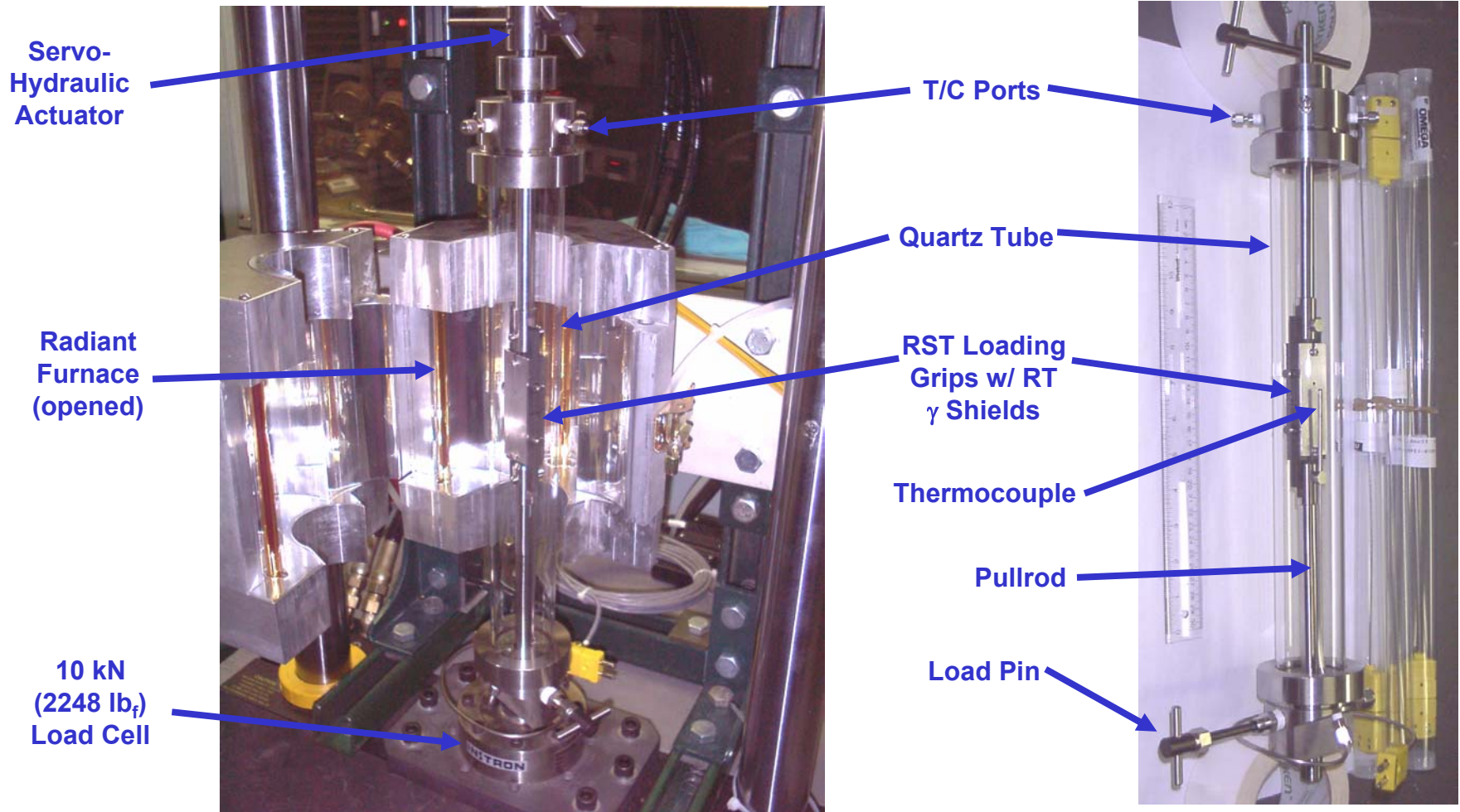
Testing Facility Upgrades

- **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

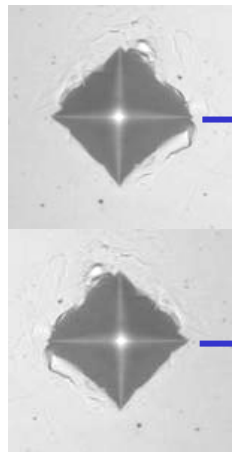


Testing Facility Upgrades



Testing Facility Upgrades

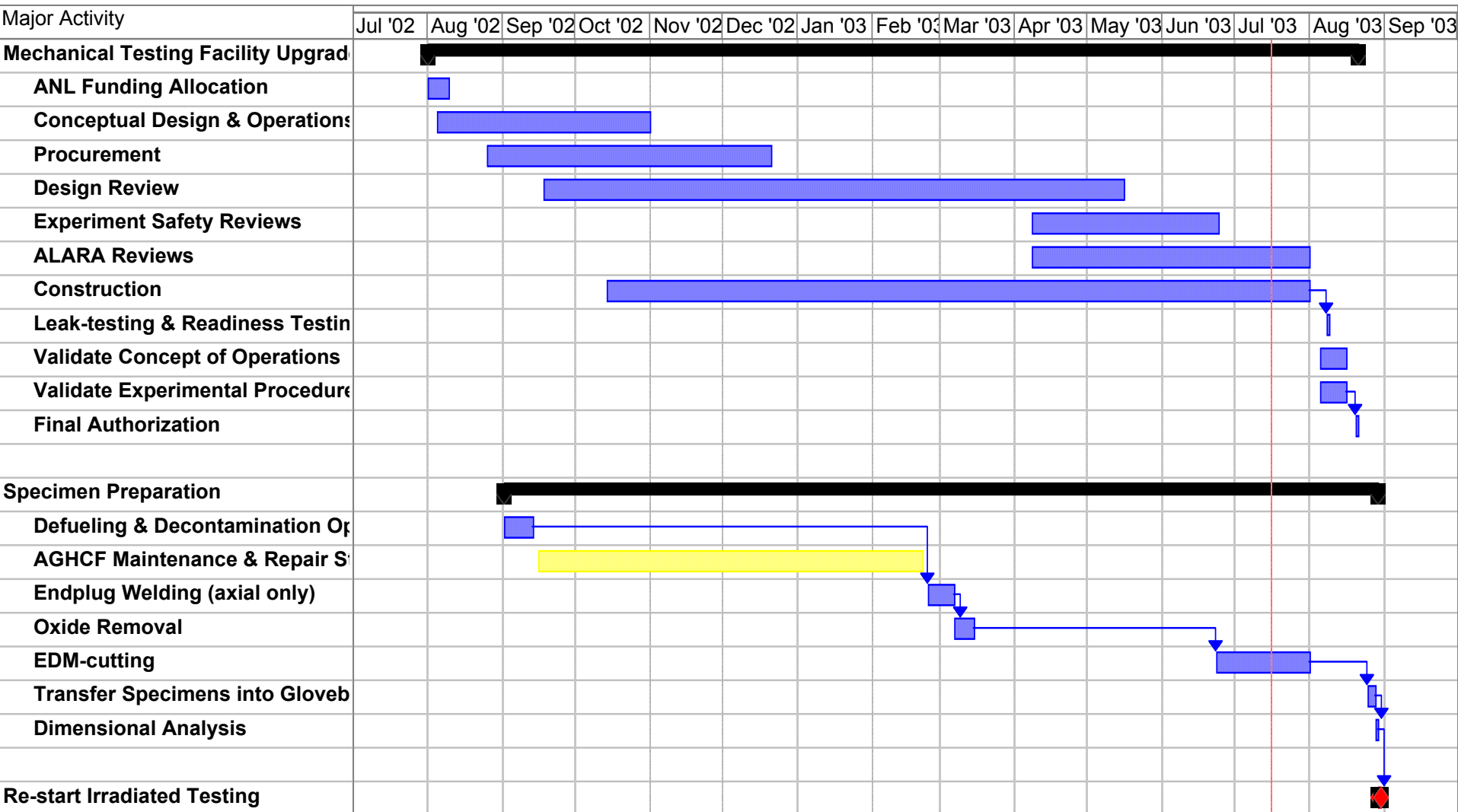
- **Automated Indentation System**
 - Training
 - Modification
 - Installation into glovebox
 - Validate concept of operations
 - Experiment Safety & ALARA Reviews

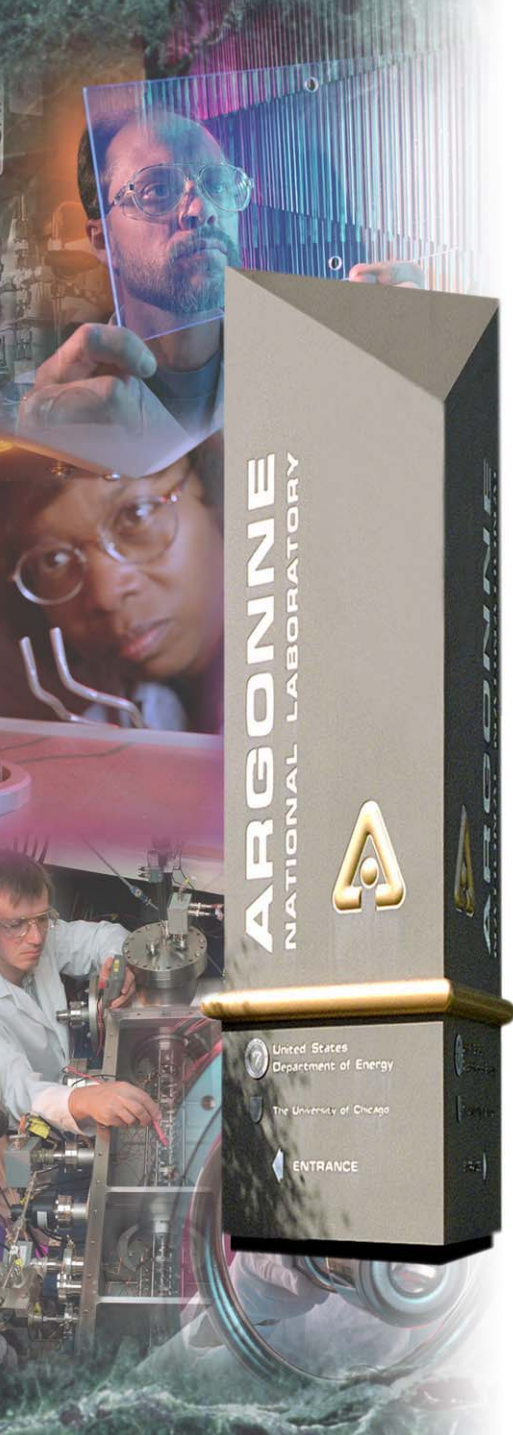


**Measure prior and
after testing**

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

Schedule for Re-starting Irradiated Testing





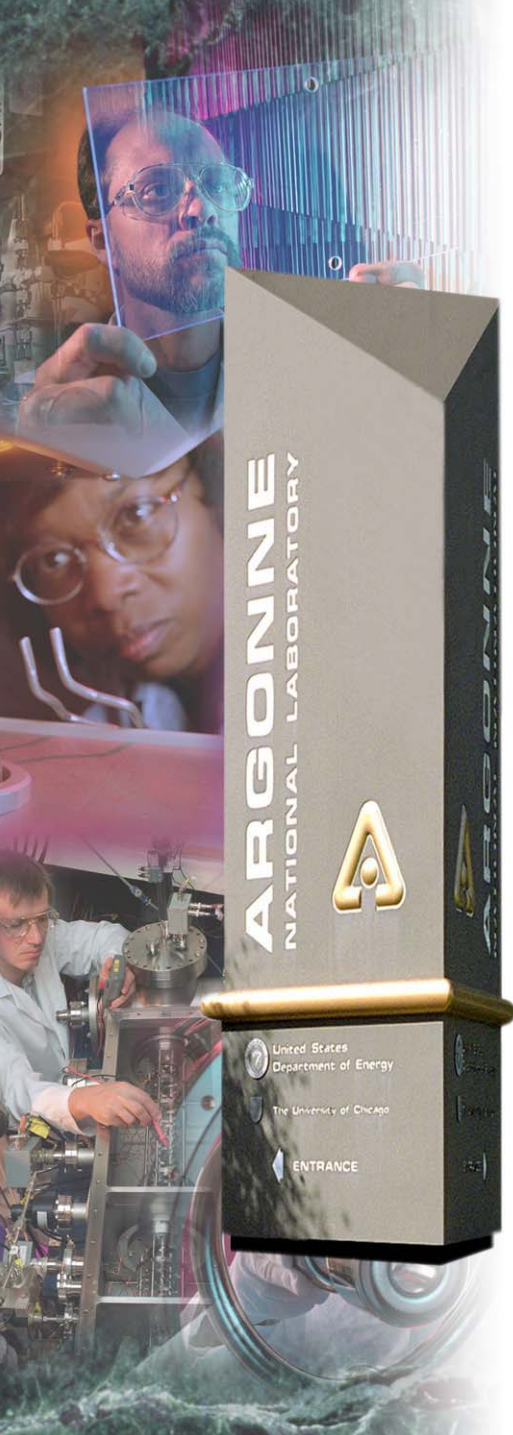
Questions?

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Backup Slides

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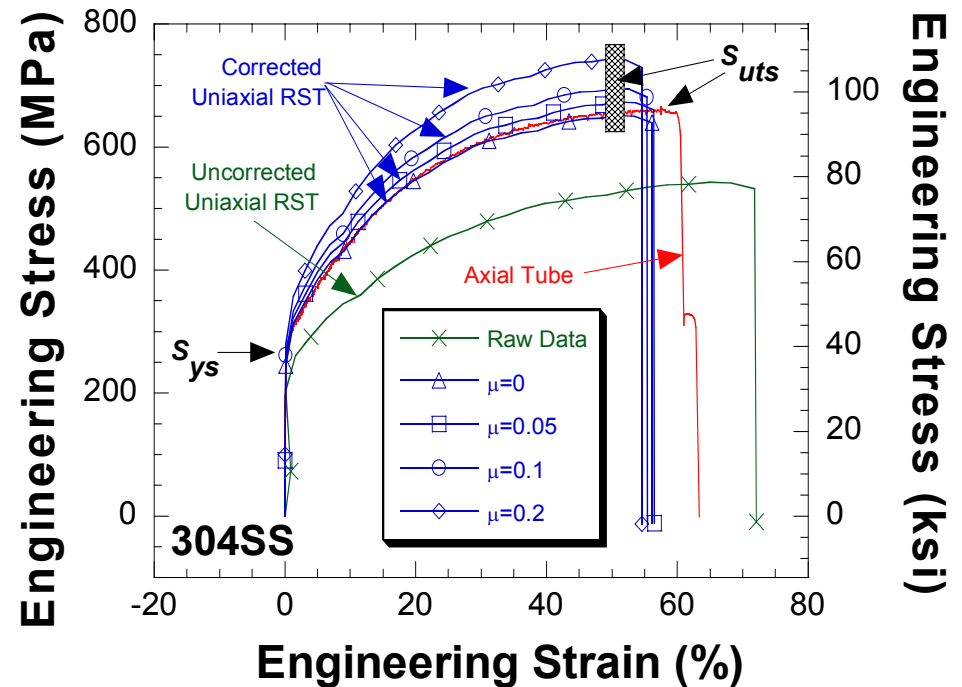


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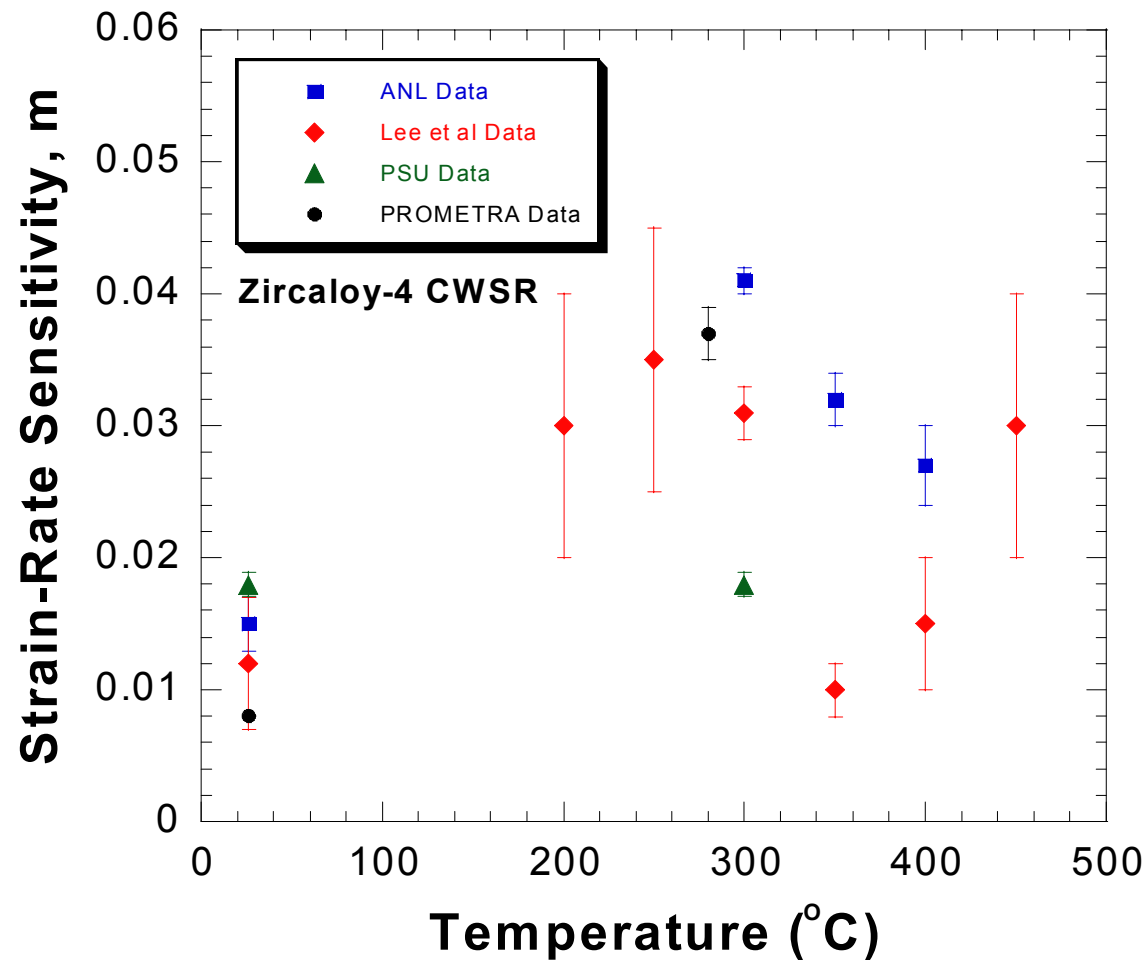


RST Procedure based on 'Isotropic' 304SS

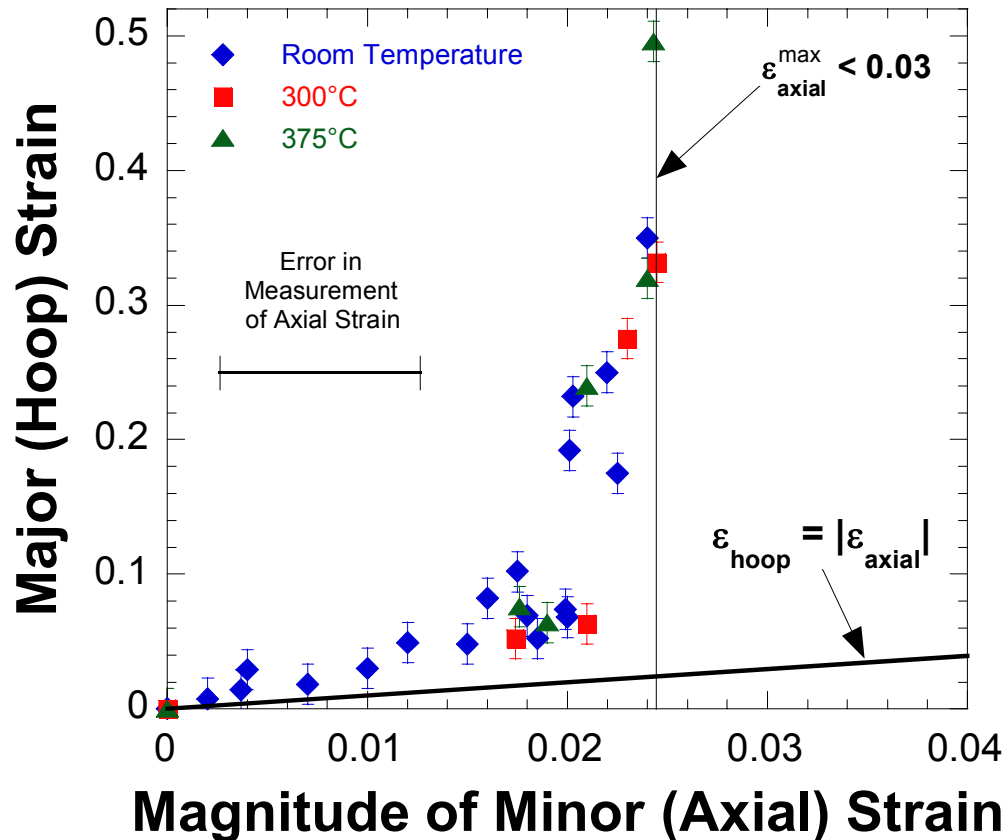
- Assumes isotropic plasticity of 304SS tubing.
- Uniaxial RST data indicates $0 < \mu < 0.05$.
- FEA is used to correct for effects of loading grips & friction, as well as, an “effective” gauge length as a function of plastic displacement.



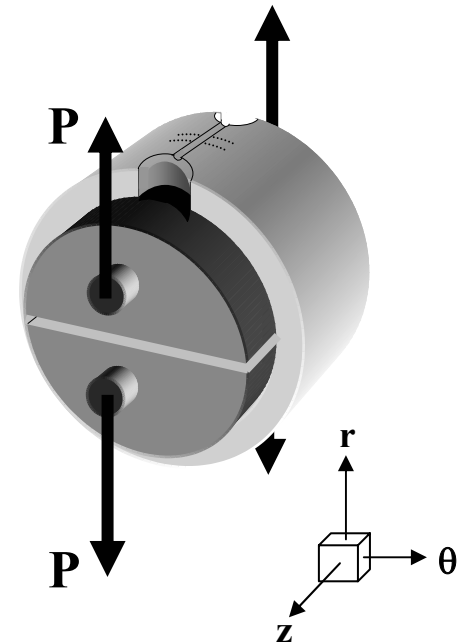
Hoop Strain-rate Sensitivity



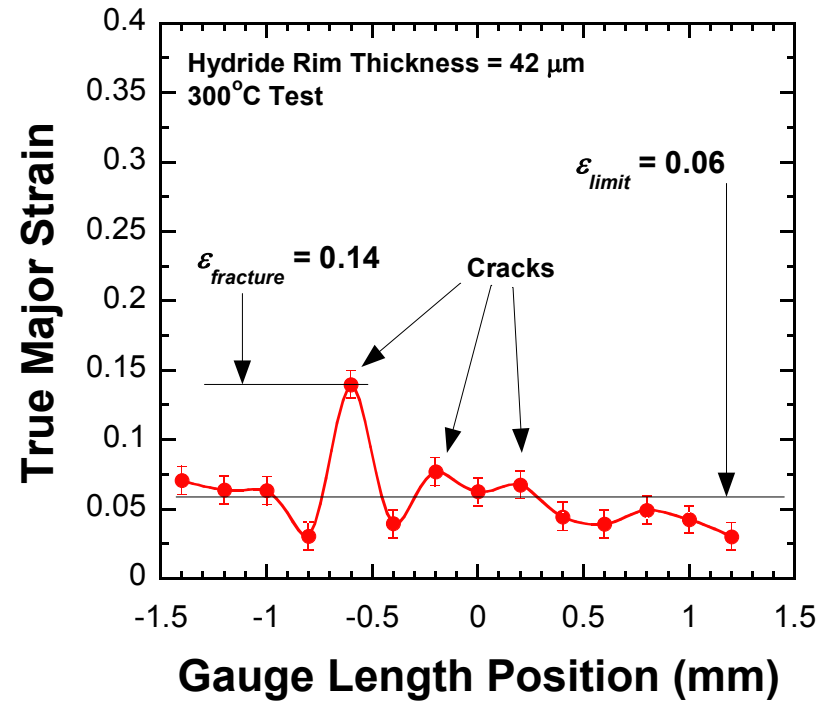
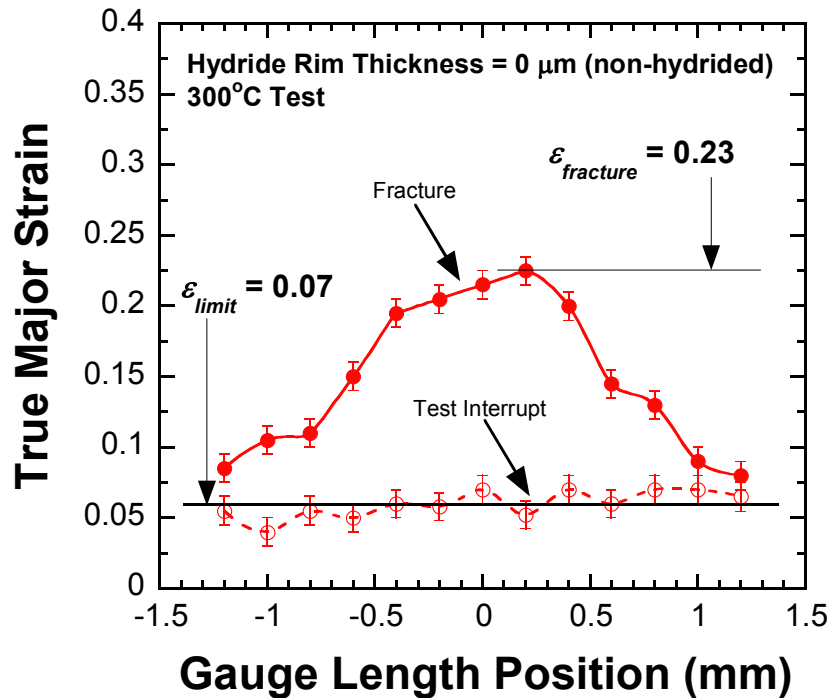
Near Plane-strain Condition



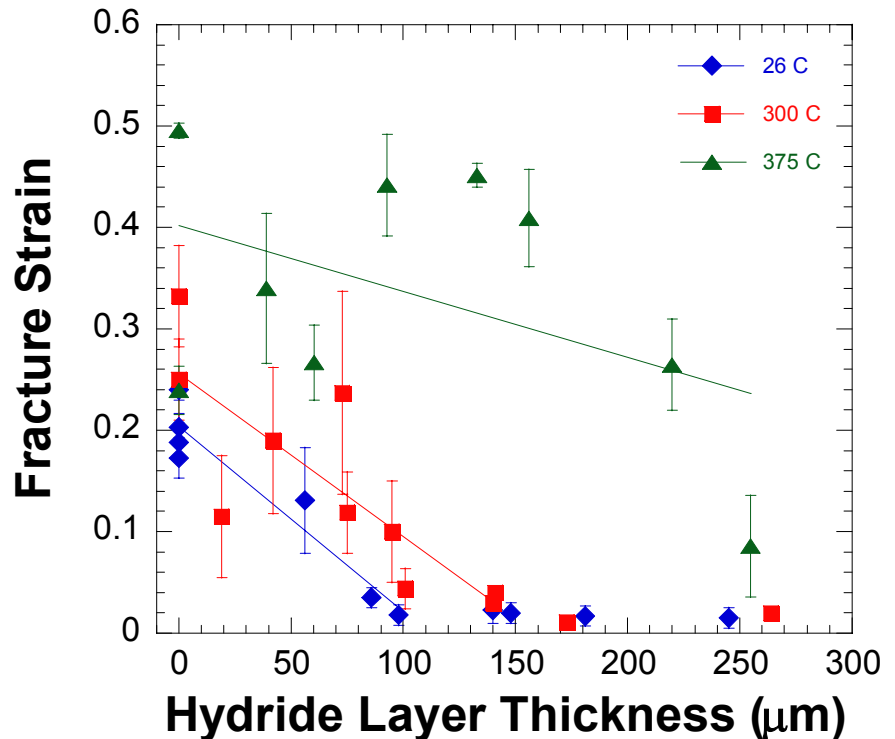
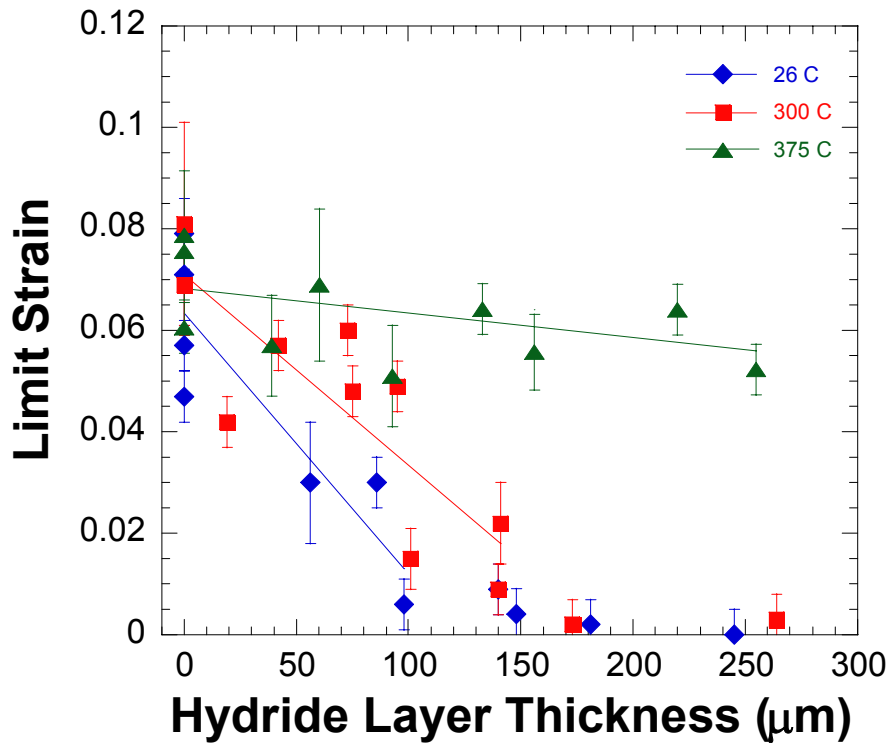
“Near” plane-strain condition is located in center 2-3 mm of gauge section.



Hydrided Specimen Plasticity vs. Cracking

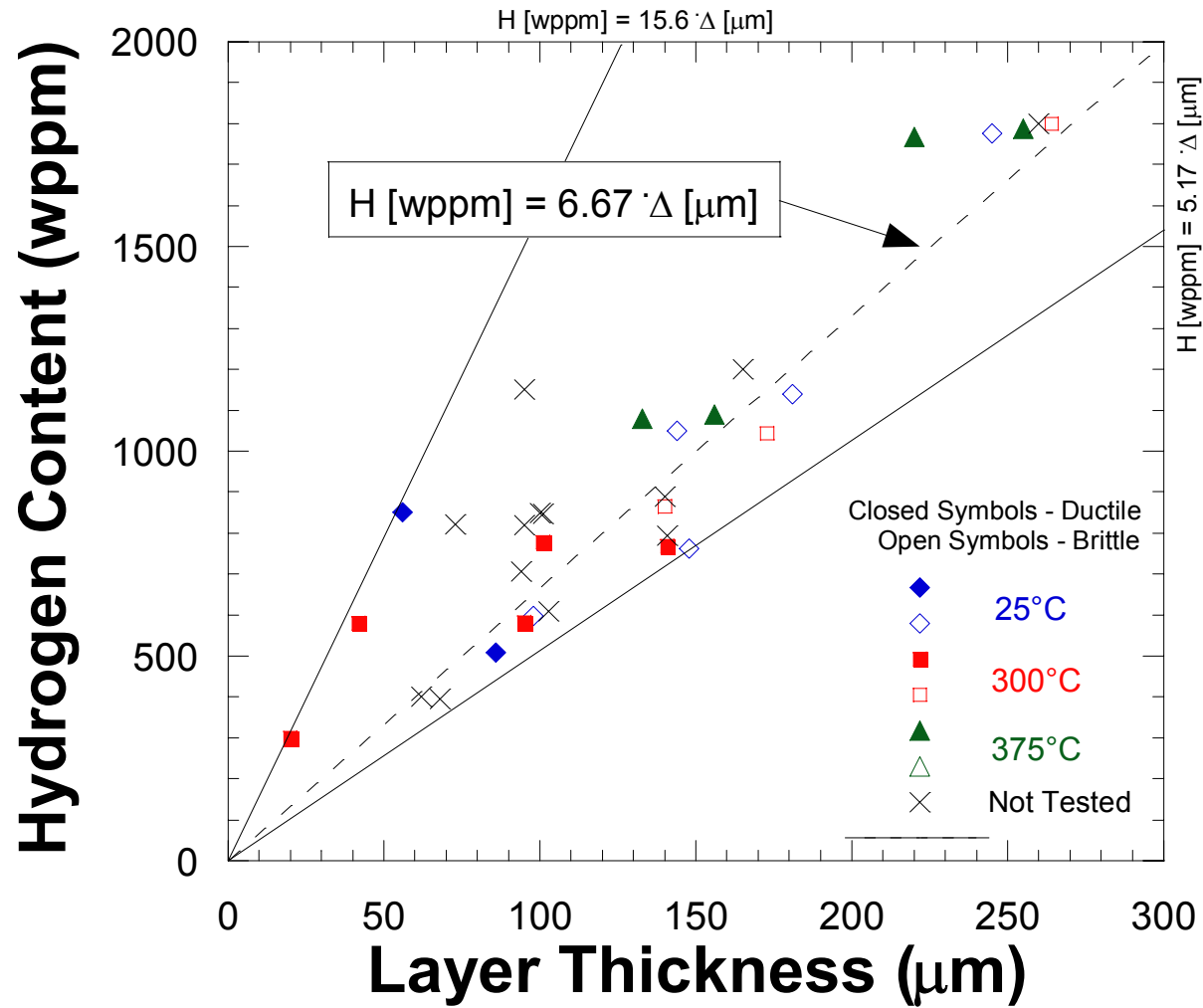


Hydrided Specimen Ductility

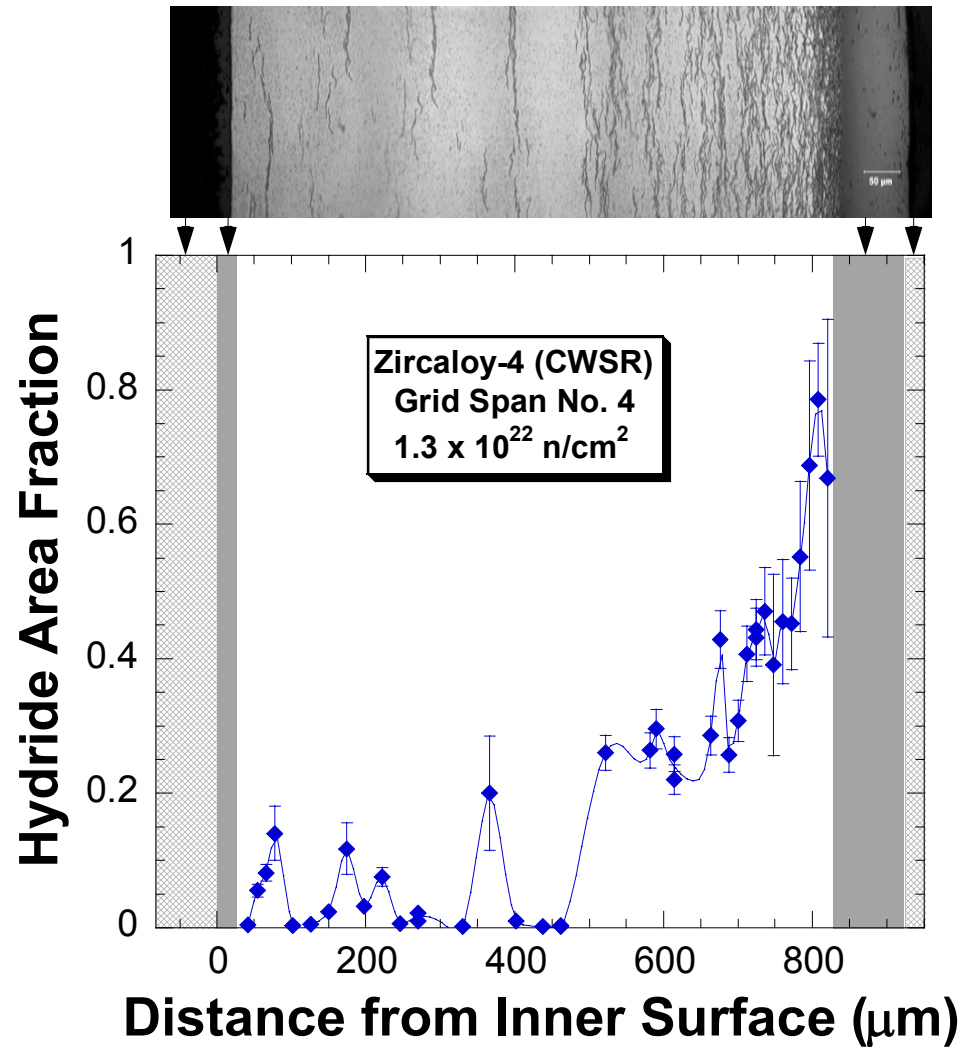


- Ductile-to-brittle transition occurs at approximately:
 - 100 μm for 26°C
 - 140 μm for 300°C
 - >270 μm for 375°C

Correlation of H Content to Hydride Layer

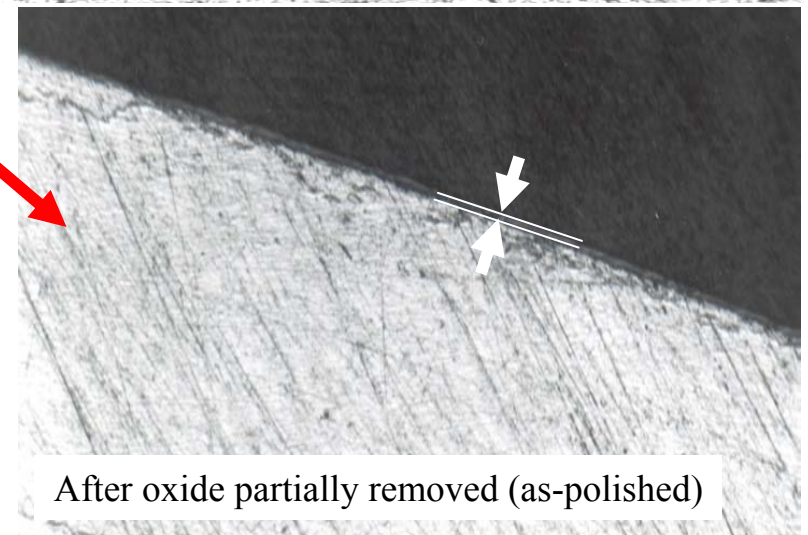
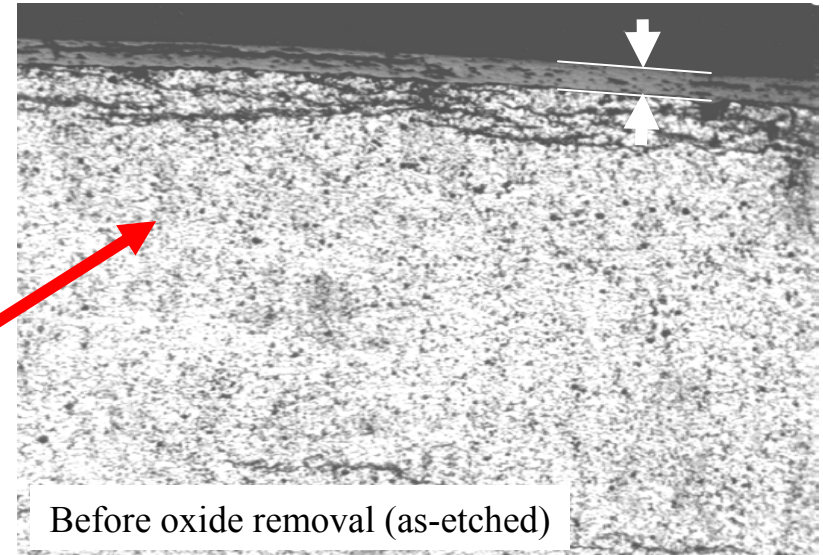


HBR Hydride Distribution

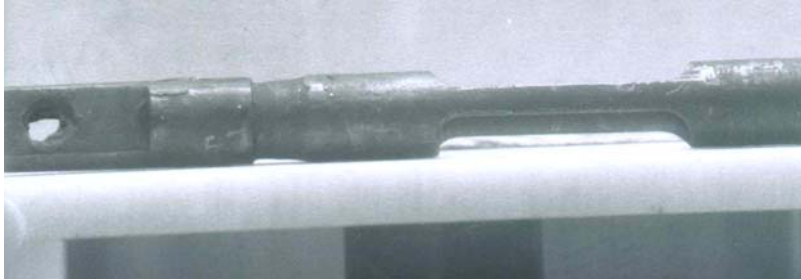


Irradiated Specimen Preparation

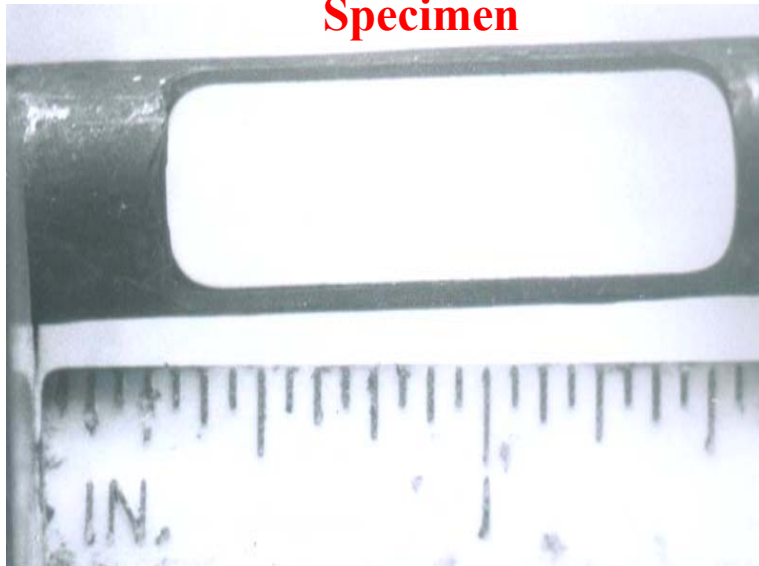
- Sectioning rod into 3 to 6-inch long segments
- Defueling in nitric acid bath
- **Partial removal of OD oxide for electrical continuity**
- Welding endcaps for axial tensile specimens
- Machining of gauge sections using EDM



Irradiated Specimen Preparation



Surry 591C2C Axial Tensile Specimen



TMI 536B3H13 Plane-Strain Specimen



TMI 536B3H5 Type D RST Specimen