Mechanical Property Testing of Fuel Cladding at ANL

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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 highfuel-burnups using ring-stretch, axial, biaxial, bend, and impact specimens relevant to RIA, LOCA, and dry cask storage conditions and transients.
- Develop a database of mechanical properties and limits for inclusion into modeling codes used to analyze high-burnup fuel rods during reactor transients and dry cask storage.

Cladding Type	**Avg. Fast Fluence (E>1 MeV)** **(10^{22} neutrons/cm^2)**	**Rod Avg. Fuel Burnup** (GWd/MTU)	**Max. H Content in Grid Span 4 (wppm)**
Zircaloy-4	0	0	5-10
Surry Zircaloy-4	0.7	36	310
TMI-1 Zircaloy-4	0.9	50	120
HBR Zircaloy-4	1.4	67	750
Zircaloy-2	0	0	5-10
Limerick Zircaloy-2	1.1	57	70

Key Issues to Consider for High-Burnup Cladding

- **Creep Deformation**
  - *Are rupture strains >1%? ANL data indicates 'yes.'*
  - *Does accumulated creep strain decrease additional plastic ductility?*

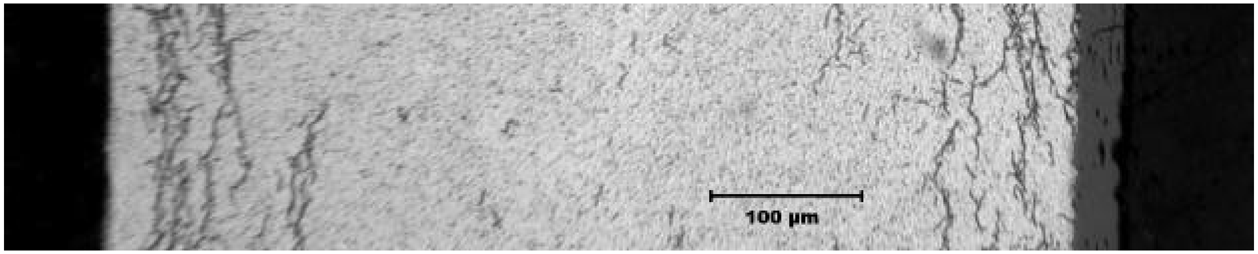
- **Hydrogen Effects**
  - *Do localized hydrides act as crack-initiation sites?*
  - *Does radial reorientation of hydrides increase failure susceptibility?*
  - *Does redistribution of hydrides decrease failure susceptibility?*

- **Accident Loadings**
  - *Which mechanical test? State of Stress? Specimen type?*
  - *Strain rates?*
  - *Temperatures?*

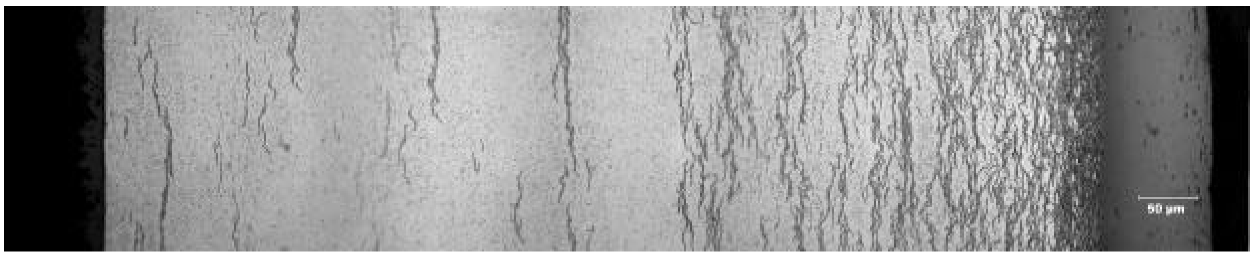
Overview – Focus on Dry Storage Implications

- **Material Characterization (Zircaloy-4)**
- **Mechanical Testing Plans & Procedures**
  - *Testing Plan*
  - *Preparation & Testing Facilities*
- **Evaluation of Testing Techniques**
  - *Descriptions*
  - *Lab-to-Lab Database – An International Perspective*
  - *Relevance to Key Issues*
- **Summary**

Material Characterization (Zircaloy-4)

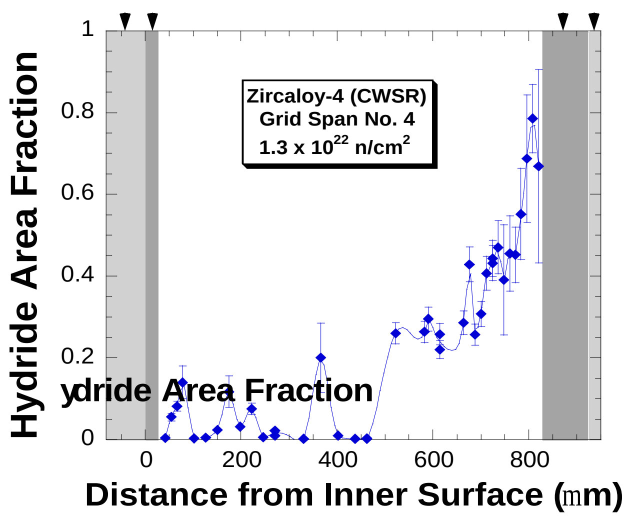


Inner Surface **Outer Surface**



Surry-2
36 GWd/MTU
~ 310 wppm hydrogen (max)
15 years in Castor-V/21

H.B. Robinson
67 GWd/MTU
~ 750 wppm hydrogen (max)

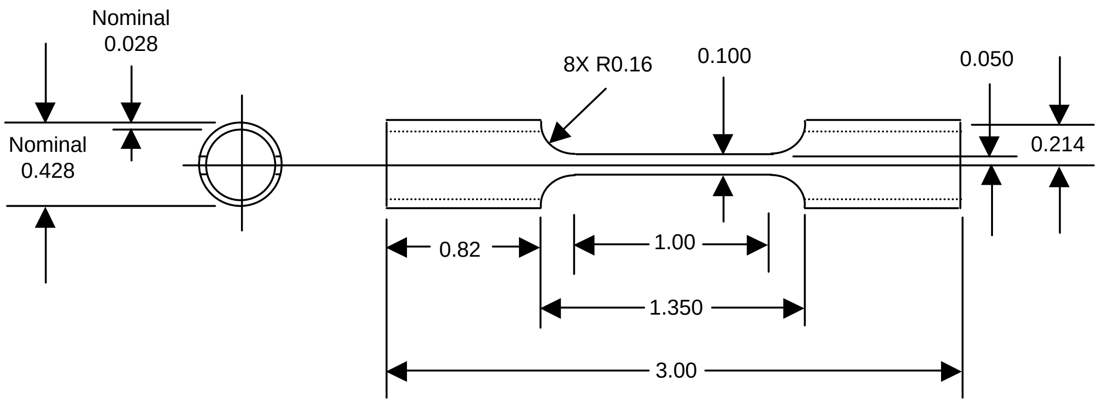


Will redistribution of hydrides occur due to vacuum drying and/or long-term storage?

Will stress-temperature history cause hydride reorientation?
- **» No, Surry-2 after 15 years storage**
- **» Yes, Surry-2 after experiment**

Testing Plan (Zircaloy-4) for Dry Storage

? / T (°C)	0.1%/s		100%/s	
	Non-irradiated	Irradiated	Non-irradiated	Irradiated
25	FRAM-ANP (7A46)	Surry (1C2) HBR (1C13, TBF)	FRAM-ANP (7A47)	Surry (2C6) HBR (2C6, TBF)
200	FRAM-ANP (7A65)	HBR (TBF)	FRAM-ANP (7A66)	HBR (TBF)
300	FRAM-ANP (7A67)	HBR (2C11)	FRAM-ANP (7A68)	HBR (TBF)
350	FRAM-ANP (7A69)	HBR (TBF)	FRAM-ANP (7A71)	HBR (TBF)
400	FRAM-ANP (7A72)	Surry (2C2) HBR (1C18, TBF)	FRAM-ANP (7A73)	Surry (2C14) HBR (2C8, TBF)



GREEN – Specimen ID (Test Completed)

BLUE – Specimen ID
(Complete & Ready to Test)

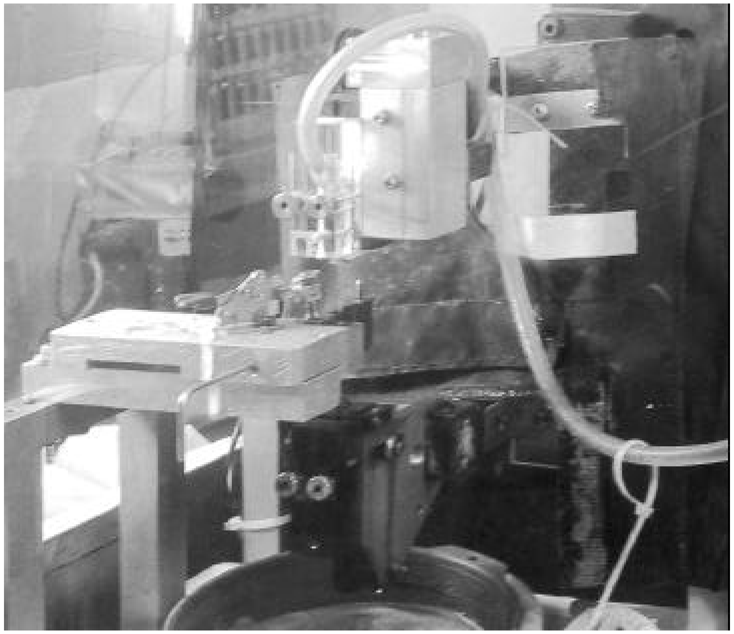
RED – Specimen ID or 'To Be Fabricated (TBF)' & Tested

Irradiated Specimen Preparation

- **Specimen Inventory:**
  - 6 axial specimens complete & ready for testing (4 – Surry and 2 – HBR)
  - Currently, preparing 3 more HBR axial specimens, along with ring-stretch specimens for LOCA/RIA program

Sectioning	**Completed**
Defueling	**Completed**
Oxide Removal	**Completed**
Endcap Welding	**Completed**
EDM	**Completed**
Glovebox Workup & Furnace Calibration	**On-going**
Measure & Testing	**Not Complete**
Post-test Analysis	**Not Complete**

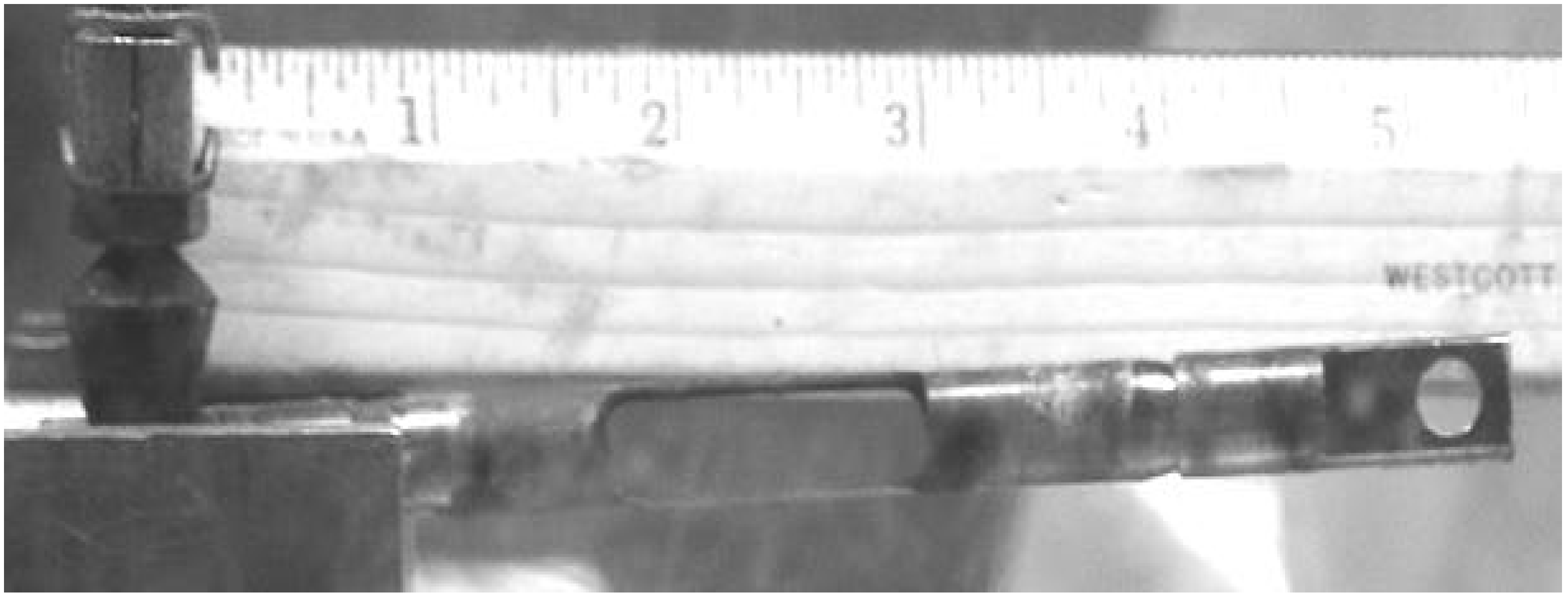
Computer-Controlled, Traveling-Wire Electro-Discharge Machine (EDM) in Hotcell



Irradiated Specimen Preparation

HBR Specimen ID 1C13

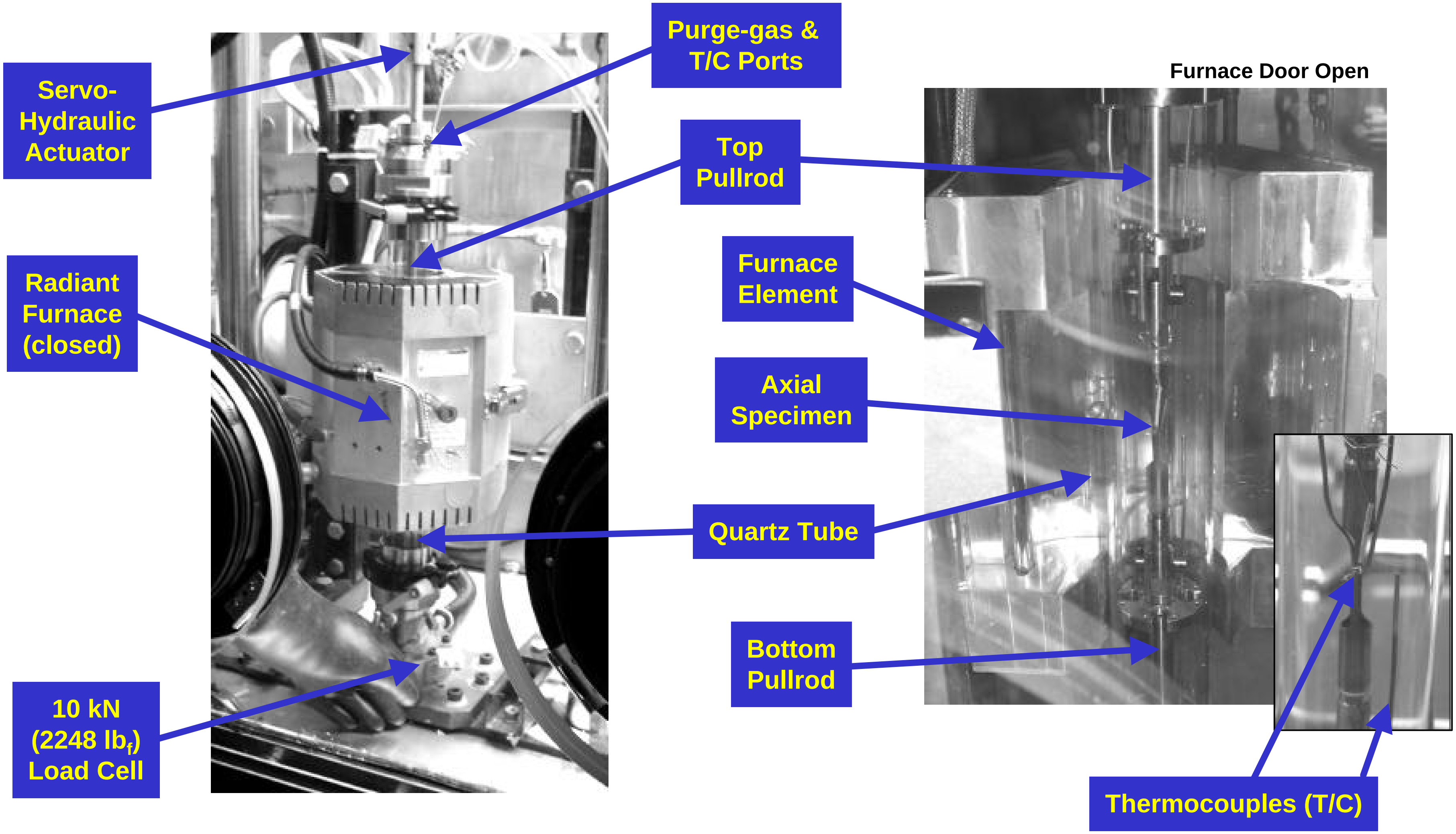
(Ready to Measure & Test)



Testing Facility Upgrades

- **Radiological Glovebox**
  - Primary purpose is contamination control
  - Leaded glass & structure provides γ shielding
  - Experimental Equipment
    - Instron Model 8511 mechanical testing system with infrared furnace
    - Struers Model Duramin-20 imaging and microhardness testing system
  - Awaiting final Design & Safety Verification Reviews

Testing Facility Upgrades



Evaluation of Testing Techniques

- **Pressurized-tube Creep Test –** ***STEADY-STATE STORAGE***

- **Microhardness -** ***MECHANICAL PROPERTIES***

- **Uniaxial Tensile Test (*z* and *q*) –** ***MECHANICAL PROPERTIES***
  - Yield Stress (*YS*), Ultimate Stress (*UTS*), & Uniform Elongation (*UE*)
  - Total elongation (*TE*) is used for comparative purposes
  - Can use results to determine Strain Energy Density (*SED*)

- **Biaxial Tension Test (1 £ *q*/*z* £ 2) –** ***MECHANICAL PROPERTIES***
  - Plane-strain ring specimen for relative ductility, *YS*, *UTS*, & *SED*
  - Tube burst specimen for *YS*, *UTS*, *SED*, & relative ductility

- **Ring Compression Test –** ***MECHANICAL PROPERTIES***
  - Relative ductility

Evaluation of Testing Techniques (cont'd)

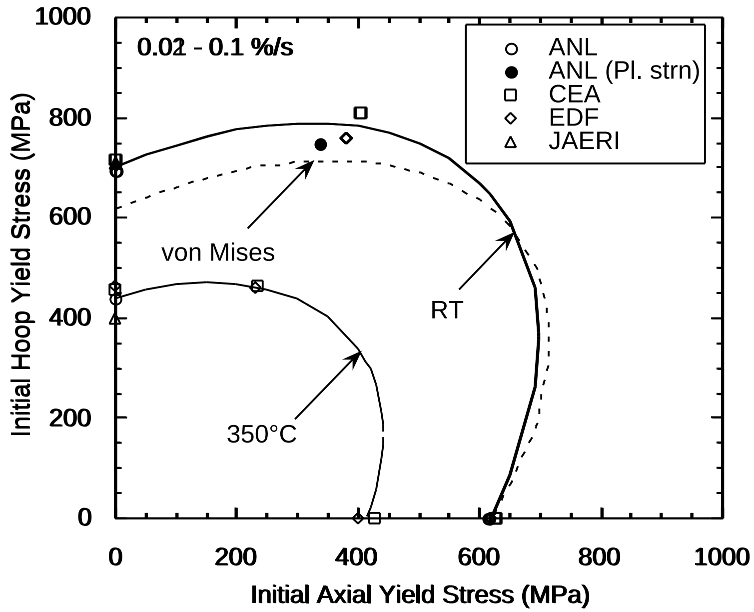
- **3- or 4-Point Bending Test (*UE* < 1%) – *MECHANICAL PROPERTIES*, *HANDLING & ACCIDENT***
  - Fueled pre-creep samples (76-100 mm)
  - Defueled post-creep samples (76-100 mm)
  - Determine effective elastic stiffness for code input
  - Determine failure Bending Moment M_f, axial stress (s_f) & strain (e_f), *SED*

- **Impact Tests – *HANDLING & ACCIDENT***
  - High-*?* deformation modes
  - Relative impact energy

Evaluation of Testing Techniques (cont'd)

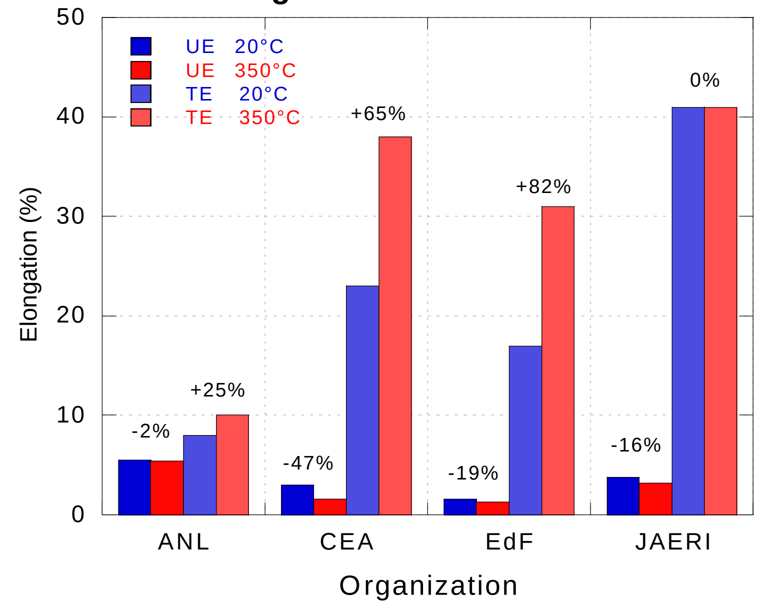
- **Lab-to-Lab Variation (*International Round Robin*) for testing identical material**
  - Differences in specimen design and test procedures

Mechanical Strength – good agreement



Ductility – "relative" agreement

% Change between 20 and 350°C



Evaluation of Testing Techniques (cont'd)

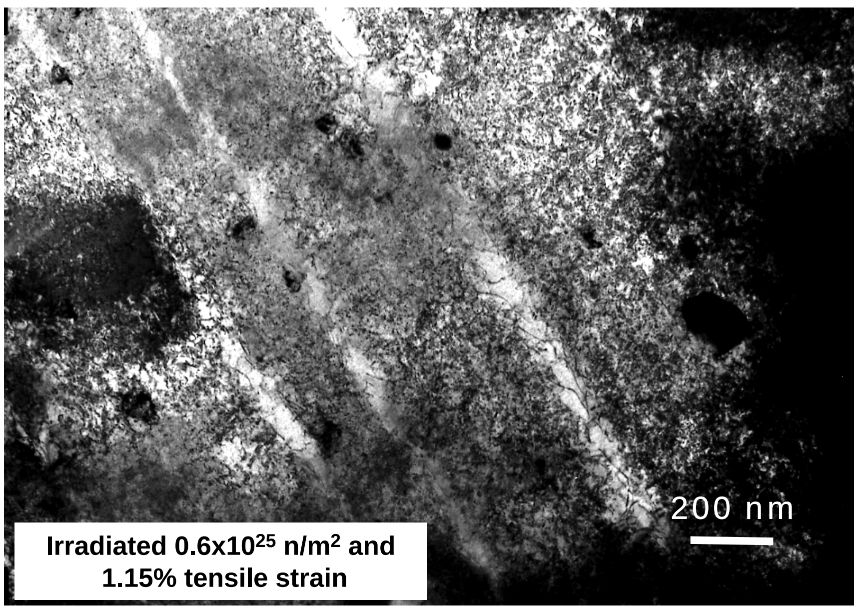
Dry Cask License Renewal Criteria

Testing Technique	Primary Relevance	ANL Capable
Pressurized-tube Creep Test	STEADY-STATE STORAGE	yes
Microhardness	*MECHANICAL PROPERTIES*	yes
Axial (*z*) Tensile Test (uniaxial)	*MECHANICAL PROPERTIES*	yes
Hoop (*q*) Tensile Test (uniaxial)	*MECHANICAL PROPERTIES*	yes
Plane-strain Tensile Test (biaxial)	*MECHANICAL PROPERTIES*	yes
Tube Burst Tensile Test (biaxial)	*MECHANICAL PROPERTIES*	no
Ring Compression Test	*MECHANICAL PROPERTIES*	yes
3- and 4-point Bend Test	*MECHANICAL PROPERTIES* *HANDLING & ACCIDENT*	yes
Impact Test	*HANDLING & ACCIDENT*	yes

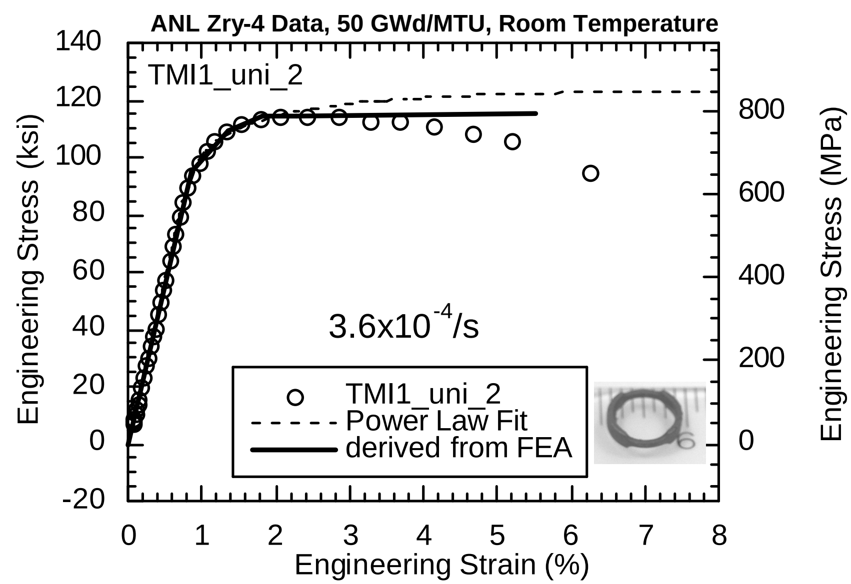
Evaluation of Testing Techniques (cont'd)

- **Relevance to Key Issues – *Creep Deformation***
  - Additional decrease in strain-hardening properties due to increase in creep-induced defect density

C. Regnard, et al., "Activated Slip Systems and Localized Straining Of Irradiated Zr Alloys in Circumferential Loading," Zr in the Nuclear Industry: 13th Inter. Symposium, ASTM STP 1423, pp. 384-399.



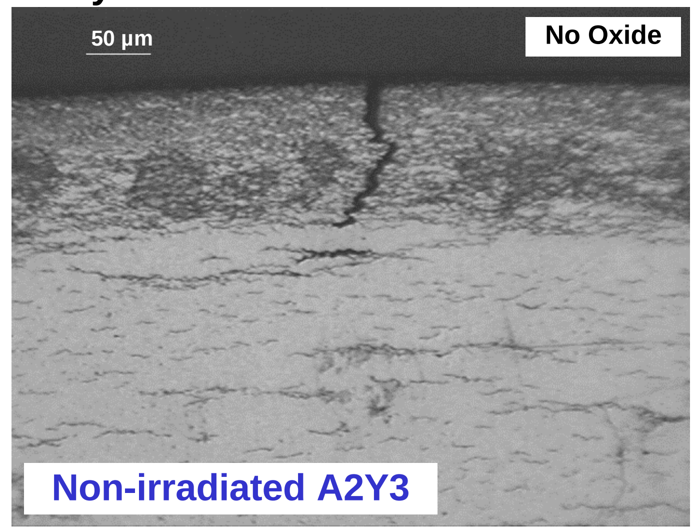
Irradiated 0.6x10^{25} n/m^2 and 1.15% tensile strain

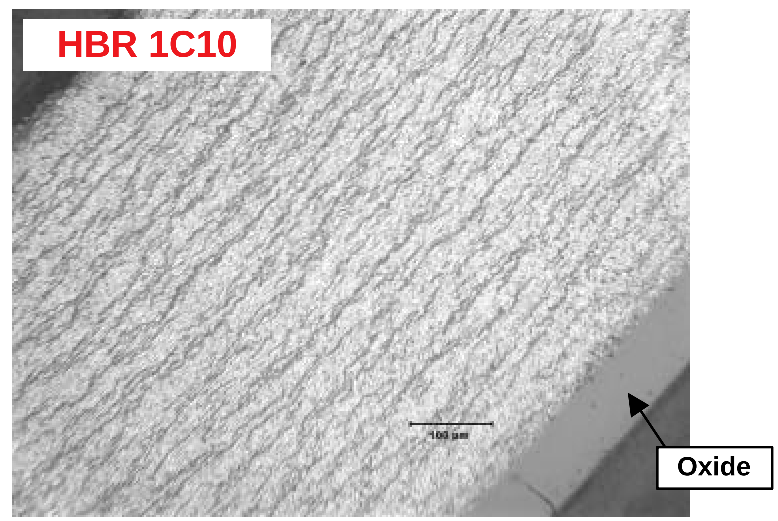


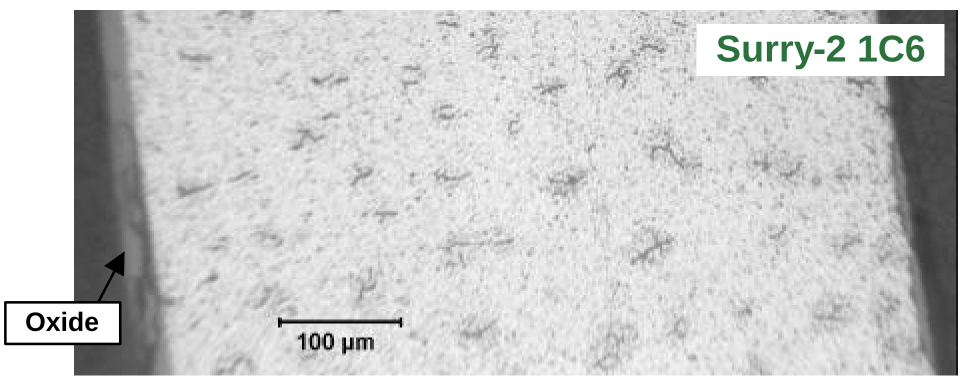
Evaluation of Testing Techniques (cont'd)

- **Relevance to Key Issues – *Hydrogen Effects***
  - **Hydride layer causes flaw initiation at outer surface**
  - **Re-distribution of hydrides to a more uniform**
  - **Re-orientation of hydrides to a more radial orientation**

Dry Cask License Renewal Criteria







Evaluation of Testing Techniques (cont'd)

- **Recall Key Issues – *Accident Loadings***
  - **Temperatures 200-400°C per ISG-11**
  - **Strain rates**
    - ***0.1 and 100%/s for MECHANICAL PROPERTIES***
    - ***>100%/s for HANDLING & ACCIDENTS***
  - **Proper selection of pre- and post-creep specimen to represent deformation modes**

F. Yunchang and D.A. Koss, "The Influence of Multiaxial States of Stress on the Hydrogen Embrittlement of Zirconium Alloy Sheet," Metallurgical Transactions A, 16A, April 1985, pp. 675-681.

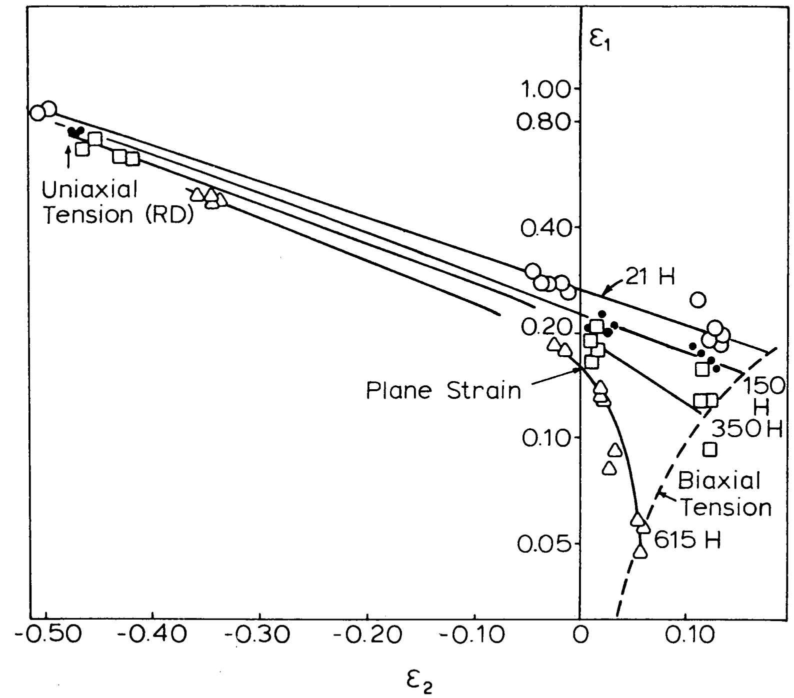


Fig. 3—A fracture limit diagram for ZIRCALOY-2 sheet at four levels of hydrogen. The major ε_1 and minor ε_2 principal strains in the plane of the sheet at fracture are shown.

Evaluation of Testing Techniques (cont'd)

	Pre-creep Specimens		**Post-creep Specimens**
Mechanical Properties	**Microhardness** **Axial Tensile Specimen** **Low strain-rate Bend Specimen** ***Biaxial Specimen***	⟷	**Microhardness** **Axial Tensile Specimen** **Low strain-rate Bend Specimen** ***Biaxial Specimen***
		Relative assessment of properties pre- and post-creep	
Handling & Accidents	**High strain-rate Bend & Impact**	⟷	**High strain-rate Bend & Impact**

Summary

- **Mechanical Properties of Zircaloy-4 cladding from Surry-2 (36 GWd/MTU after 15 years of dry storage) and H.B. Robinson (67 GWd/MTU) for code development and licensing input**
  - Fluence, storage history, and hydrogen effects
  - Initial testing of axial-tensile specimens to commence in Nov. 2003

- **Interpretation of irradiated properties database should be more *relative* than *absolute* to account for lab-to-lab and material-to-material variations.**

- **Pre- and post-creep testing must account for:**
  - Possible, reduction in strain-hardening
  - Hydrogen-induced cracking, hydride re-distribution and re-orientation
  - State of stress relevant to storage handling and accidents