Thermal Creep of Dry-Cask-Stored PWR Cladding and High-Burnup PWR Cladding

Hanchung Tsai (htsai@anl.gov)

Review of
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Thermal Creep Tests

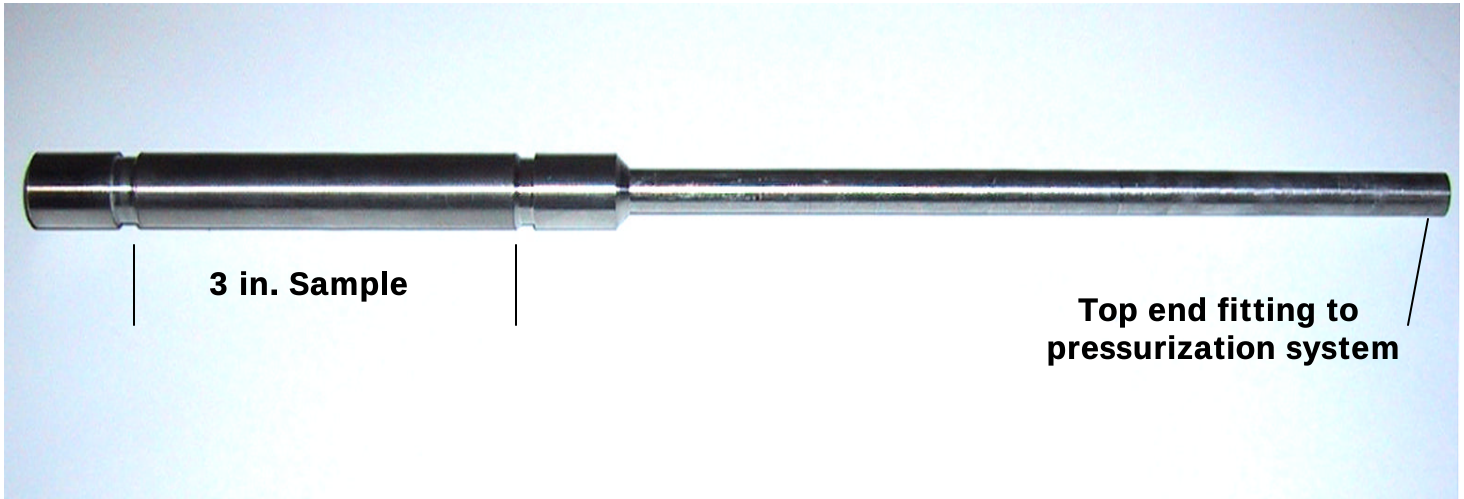
- **Presentation Outline**
  - **Creep testing methodology**
  - **Creep test results**
    - ***Dry-cask-stored Surry***
    - ***High-burnup H. B. Robinson (vis-à-vis Surry to explore burnup and hydrogen effects)***
  - **Summary and Conclusions**

Thermal Creep Tests

- **Why studying creep?**
  - **Creep is the dominant cladding deformation mechanism under normal conditions of dry storage. The core issue, however, is cladding integrity.**
- **Test objectives**
  - **Determining creep ductility and steady-state creep rate**
  - **Generating samples to study hydride reorientation and post-creep mechanical properties**

Thermal Creep Tests

- **Creep Test Specimen**
  - 76-mm-long segments of defueled cladding
  - Cavity filled with Zr-702 pellets to reduce stored energy
  - Welded end fittings – no mechanical connection to pressure line in heated zone



Thermal Creep Tests

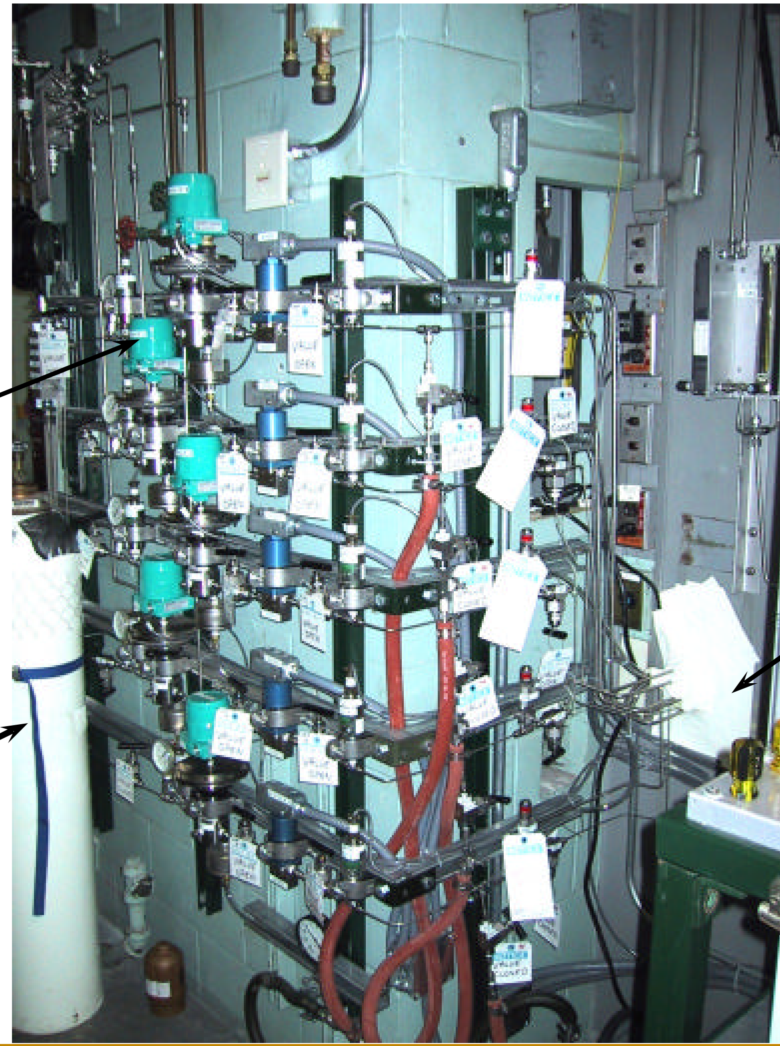
- **Test Chamber**
  - **Inert-gas purged to preclude sample oxidation during test**

Thermal Creep Tests

- **Pressurization Systems**
  - **Specimens pressurized with argon gas from 6000-psi cylinders (˜ 270 MPa hoop stress max.)**
  - **No pumps.**
    - **Improved safety, costs, and space utilization.**
  - **Pressures regulated with individual microprocessor-controlled regulators, to <±10 psi (0.5 MPa hoop).**
  - **Five systems for concurrent testing.**

Thermal Creep Tests

- **Pressurization Systems (5)**



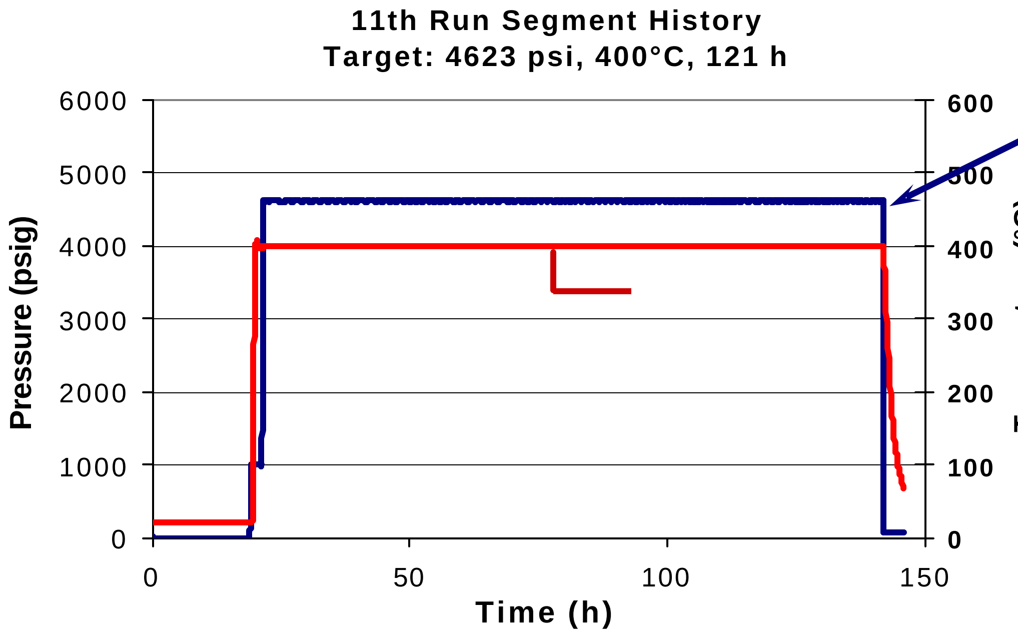
CPU-based Pressure Controllers

Penetration into Cell

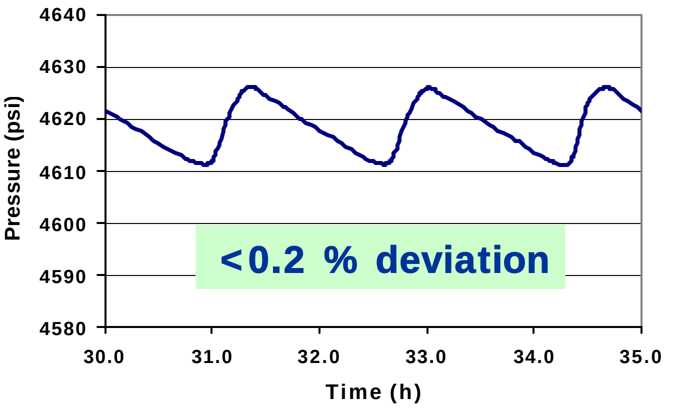
Gas Cylinders

Thermal Creep Tests –Typical Performance

- Good pressure and temperature control
- Periodic shutdowns for dimensional measurements



Depressurized first to preclude hydride reorientation



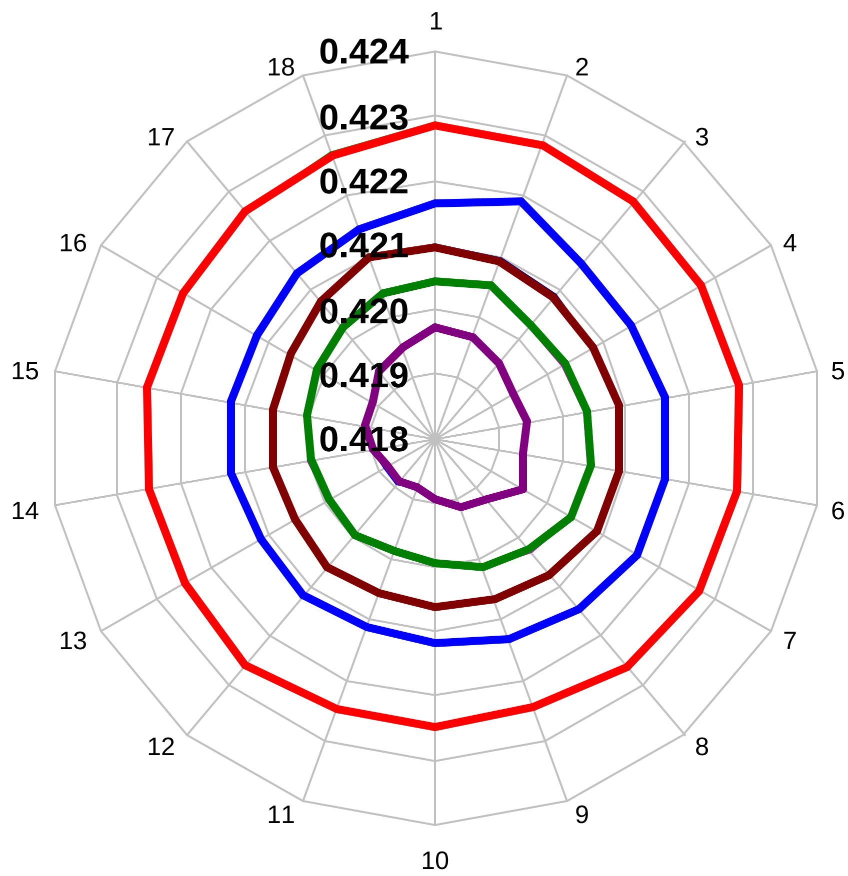
Thermal Creep Tests

- **Laser Profilometry**
  - **Measurements made off-line at room temperature**
  - **Diameters measured at multiple axial and azimuthal locations to within ±2x10^{-5} in. (0.005% strain)**
  - **Length measured to ±10^{-3} in. to evaluate creep anisotropy.**

Thermal Creep Tests

Laser Profilometry – Typical Results

- **Midplane cross-sectional profiles of a sample at 0, 335, 671, 1028, and 1820 h.** **(Dimensions in inches.)**



Thermal Creep of Post-Storage Surry Cladding

Surry Test Matrix

	Sample	Temp. (°C)	Stress (MPa)	Purpose
Completed	C3	360	220	Primary/secondary creep
Completed	C6	380	190	Primary/secondary creep
Completed	C8	380	220	Residual creep strain
Completed	C9	400	190/ 250	Residual creep strain
On-going	2-C9	400	160	Primary/secondary creep, ISG-11(Rev. 2)
To be initiated	*C10*	*400*	*220*	*Residual creep strain, ISG-11(Rev. 2)*

Thermal Creep of Post-Storage Surry Cladding

Surry Summary Results

Sample	Temp. (°C)	Stress (MPa)	At End of Test			Sample Disposition
			Hours	Avg. e	Intact?	
C3	360	220	3305	0.22	Yes	DE(1)
C6	380	190	2348	0.35	Yes	DE(1)
C8	380	220	2180	1.10	Yes	Bend Test
C9	400	190 250	1873 693(2)	1.03 5.83	Yes Yes	-- Bend Test
2-C9	400	160	286(3)	0.22	Yes	tbd

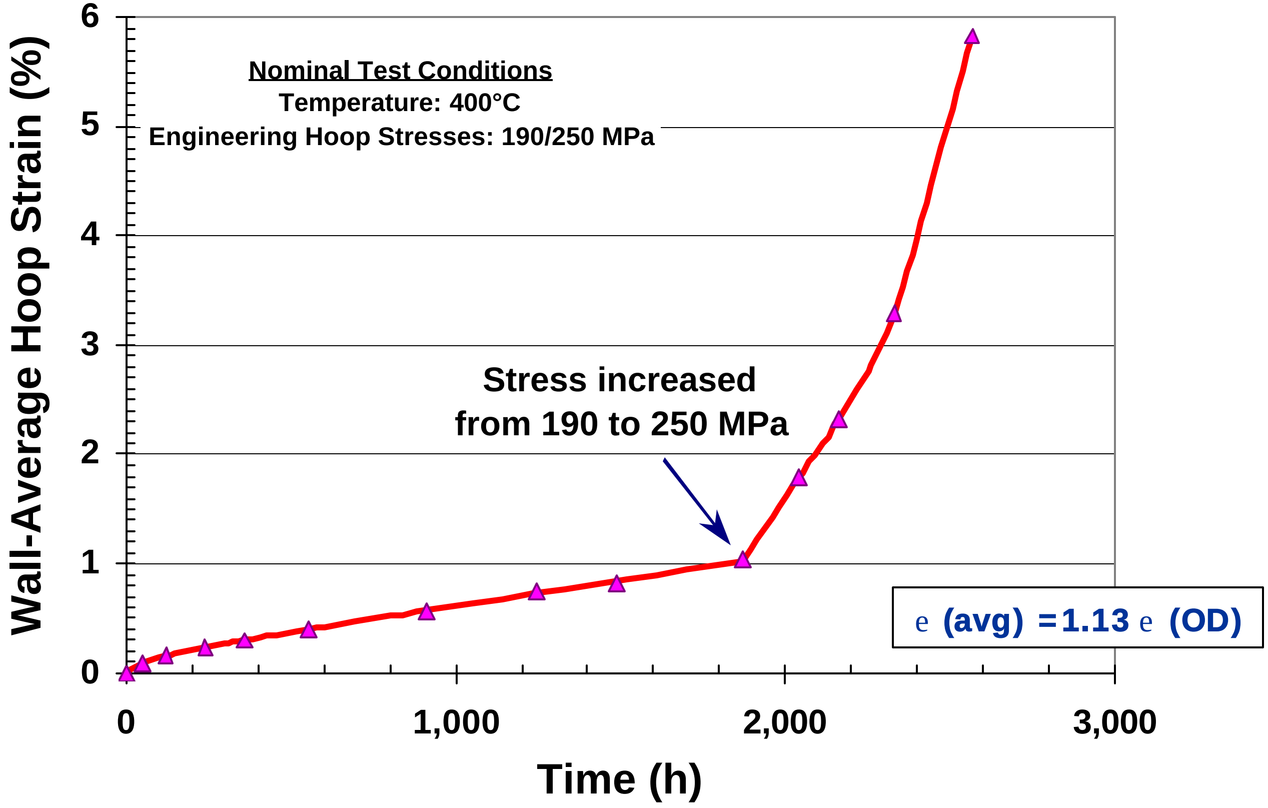
(1) DE: Destructive examination, for hydride orientation determination. For this, the final shutdown was done with sample pressurized.

(2) Incremental hours

(3) On-going

Thermal Creep Tests – Surry C9

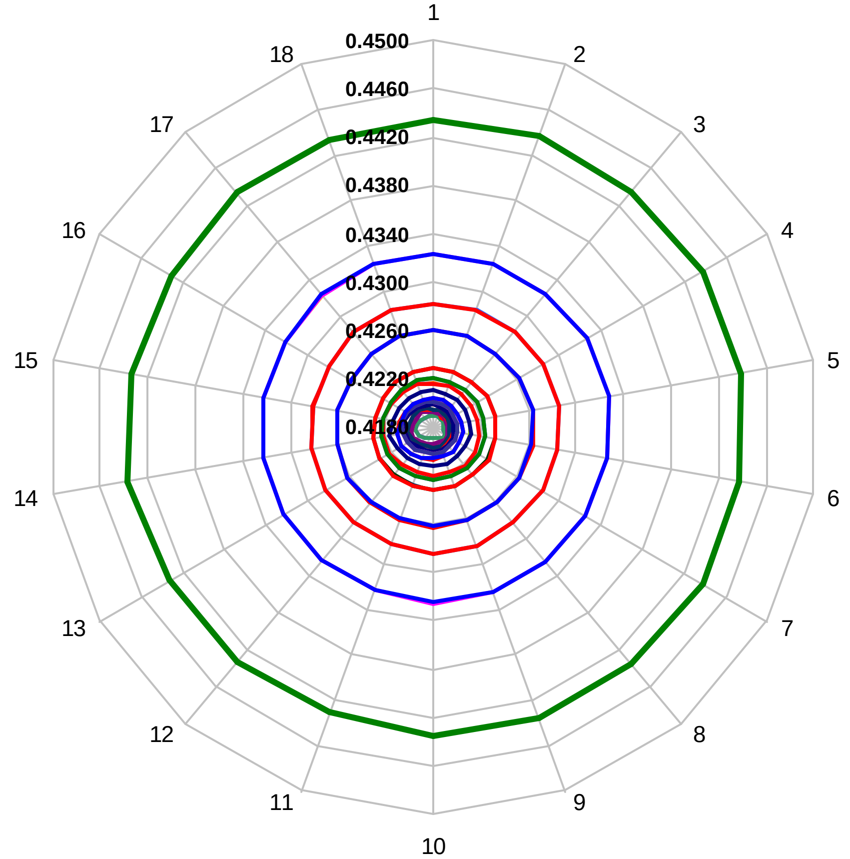
- 400°C, 190/250 MPa engineering hoop stress, 2566 h
- 5.8% average hoop strain, no rupture



Thermal Creep Tests – Surry C9

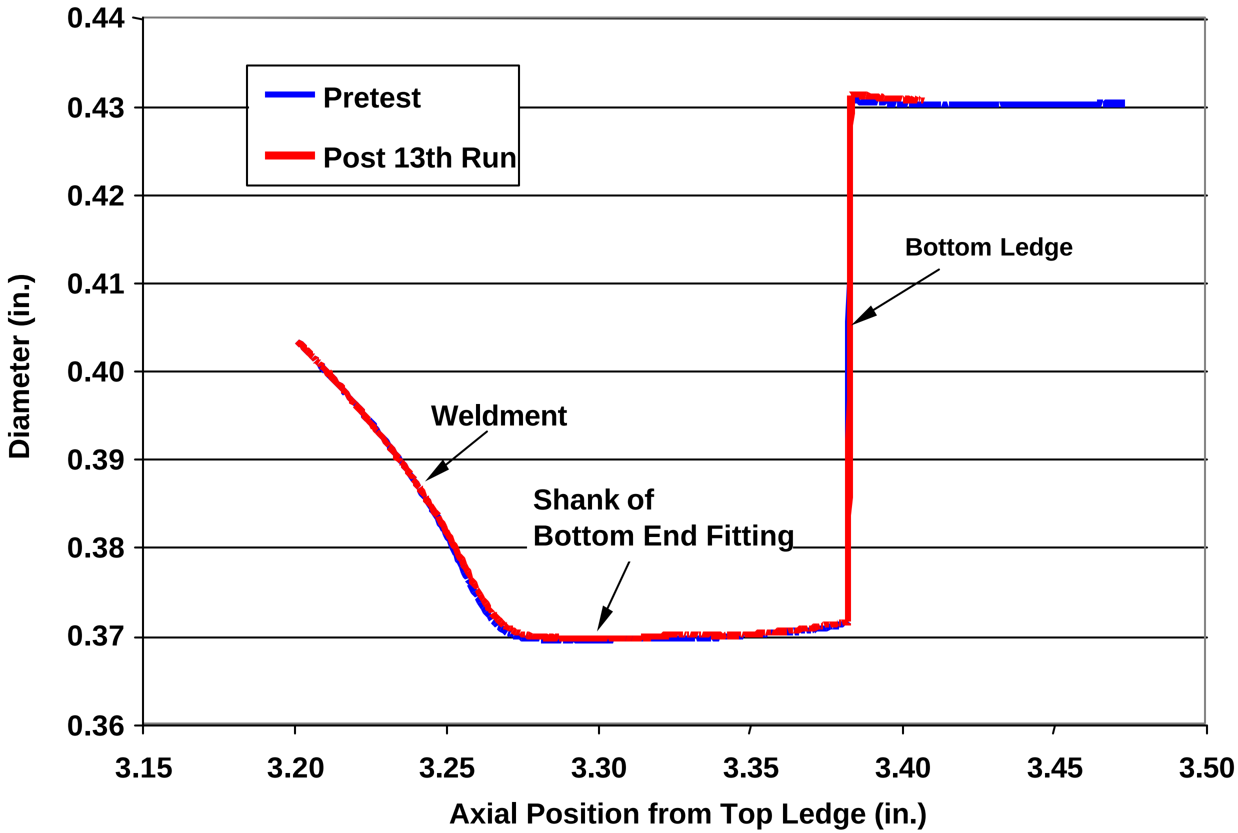
- **Deformation uniform even at high strain (5.8 %)**
- **No signs of imminent failure**
- **Additional creep ductility likely**

Run-by-Run Cross Sectional Profiles of C9 (Dimension in inches)



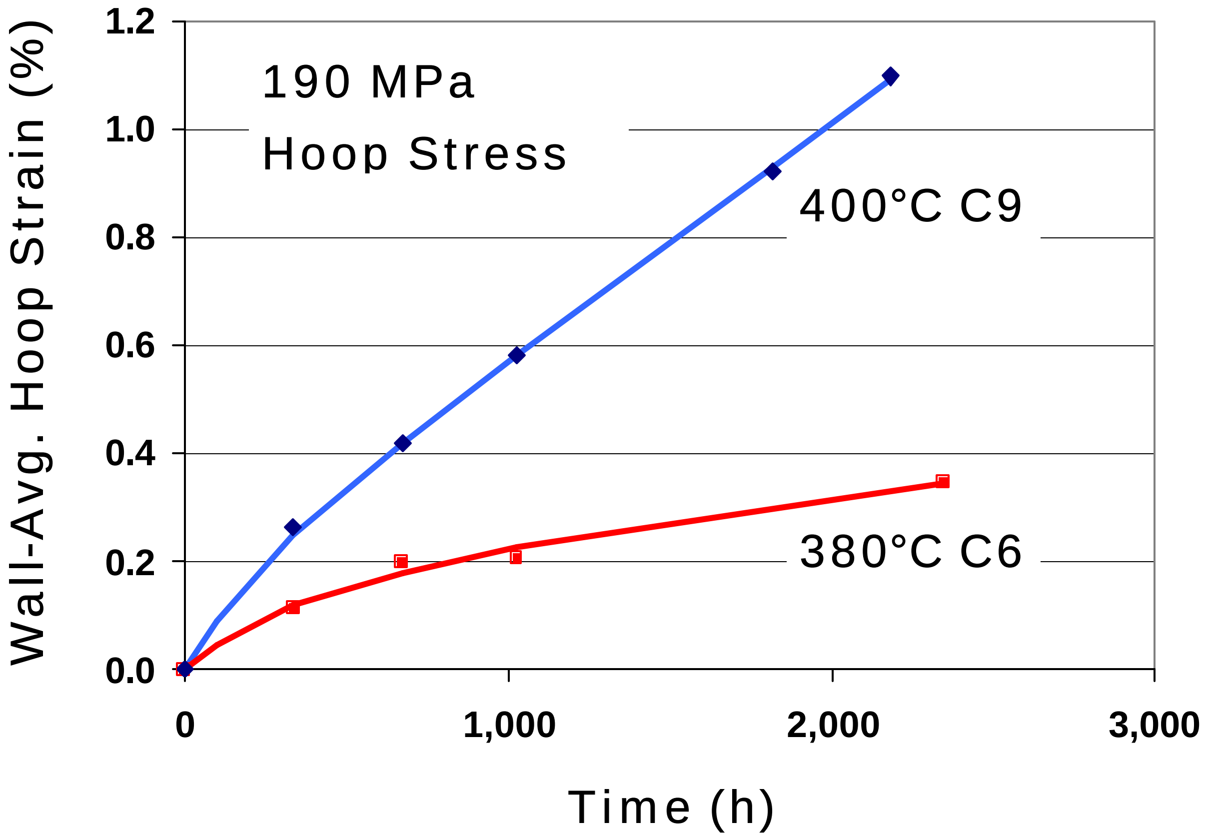
Thermal Creep Tests – Surry C9

- **No apparent creep anisotropy based on sample length measurements**



Thermal Creep of Post-Storage Surry Cladding

- **Temperature Dependency**



Thermal Creep of Post-Storage Surry Cladding

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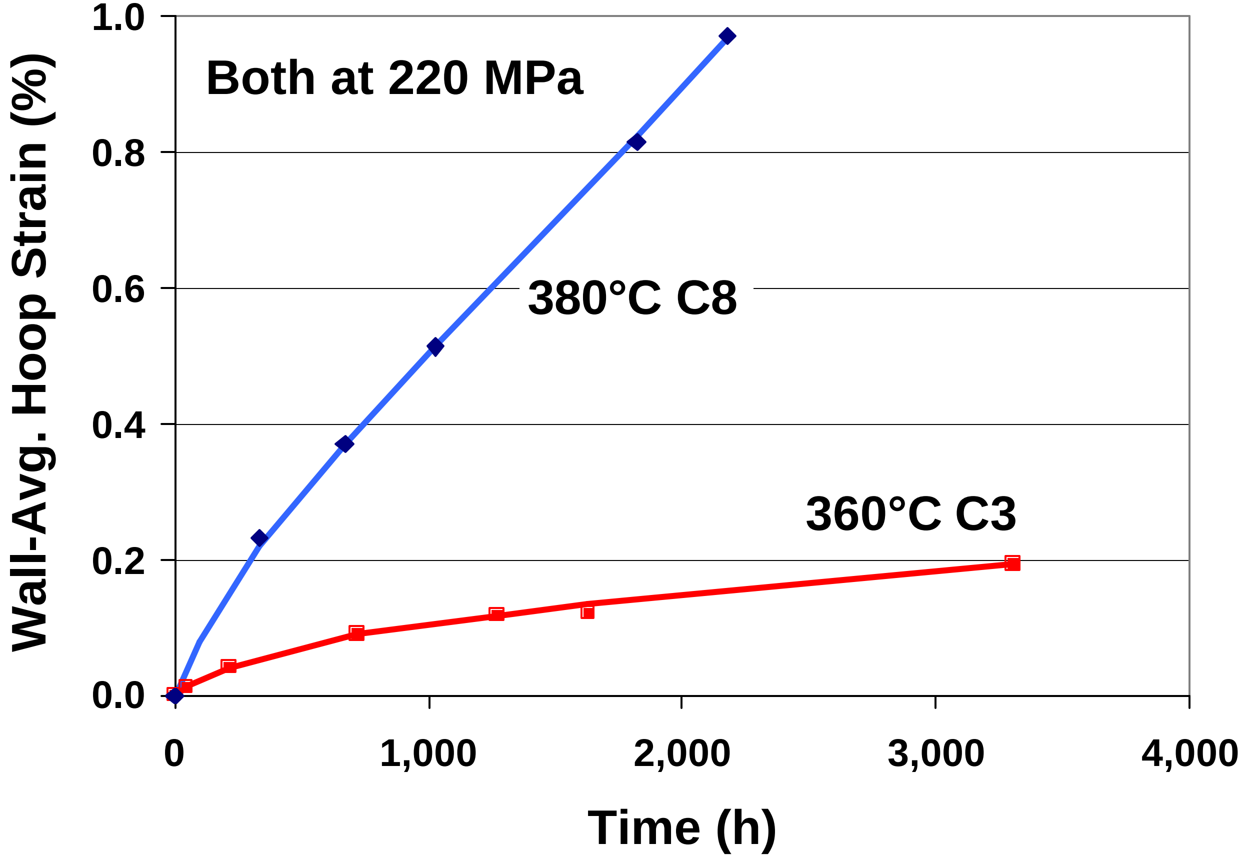
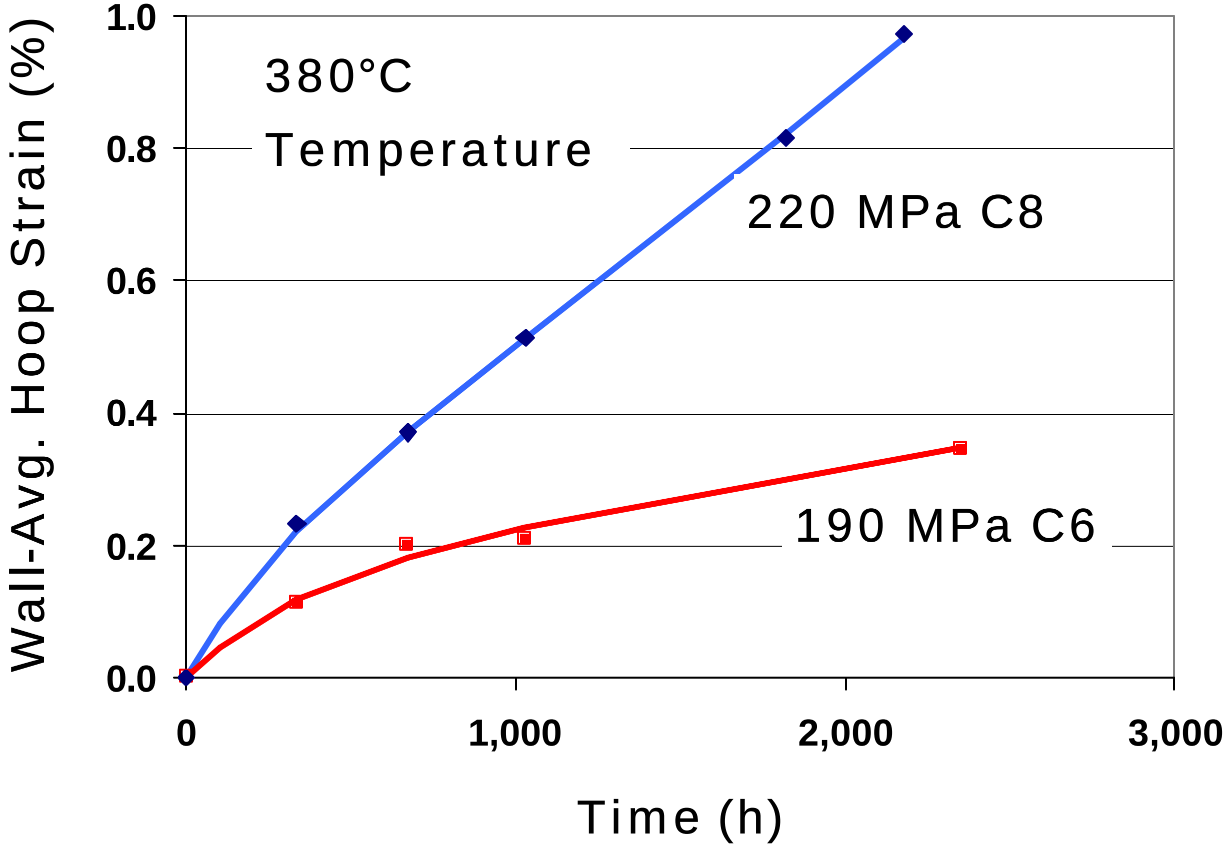


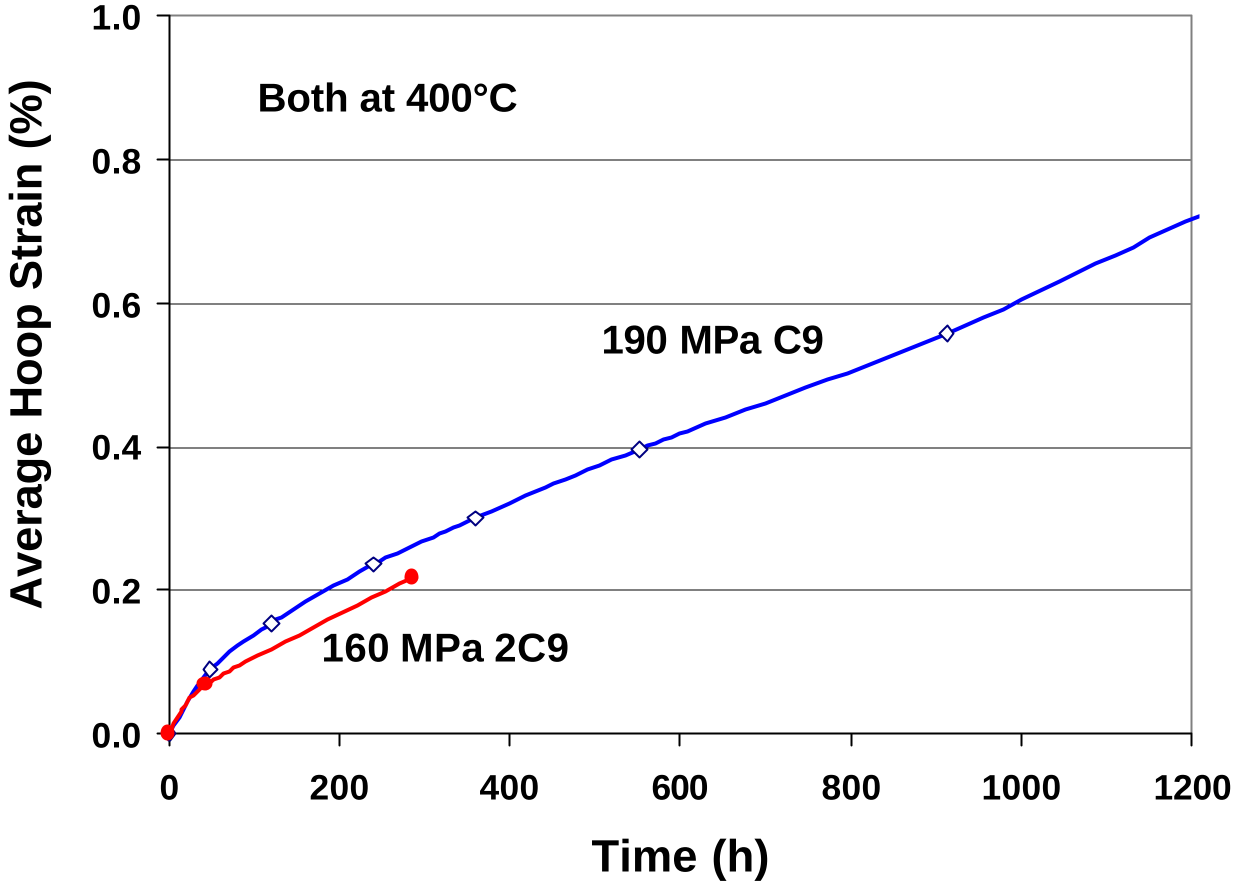
Thermal Creep of Post-Storage Surry Cladding

- **Stress Dependency at 380°C**



Thermal Creep of Post-Storage Surry Cladding

- **Stress Dependency at 400°C**



Thermal Creep of Post-Storage Surry Cladding

Secondary Creep Rates

Test Purpose	Sample	Temp. (°C)	Stress (MPa)	SS $\Delta\varepsilon/\Delta t$ [1] (% / h)
PSC	C3	360	220	$\sim 1.6 \times 10^{-5}$
PSC	C6	380	190	$\sim 8.6 \times 10^{-5}$
RCS	C8	380	220	$\sim 4.6 \times 10^{-4}$
RCS	C9	400	190 250	$\sim 4.9 \times 10^{-4}$ $\sim 4.9 \times 10^{-3}$

(1) ε (avg). Values are approximates. Effects of wall thinning and diameter increase on hoop stress not included.

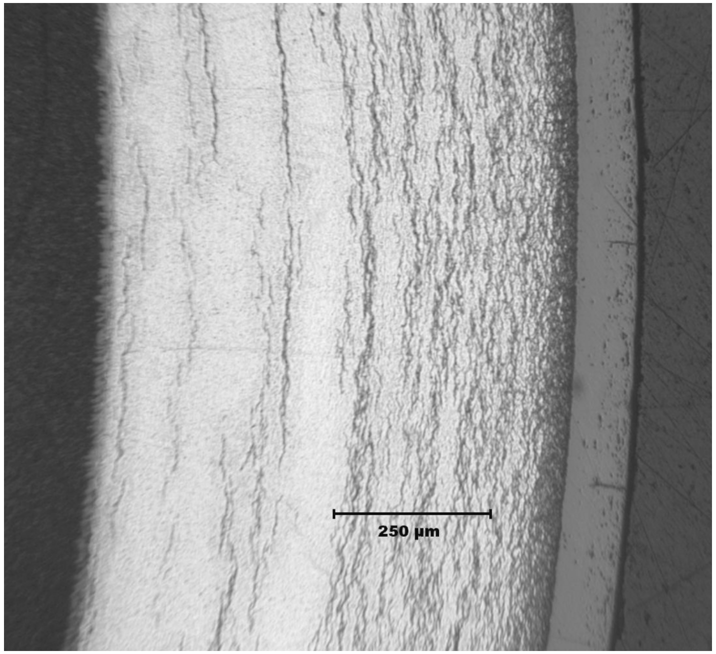
Thermal Creep Tests – H. B. Robinson

Robinson Test Matrix (6/03)

		Stress (MPa)				
		100	160	190	220	250
Temp. (°C)	420		1			
	400		1	C14 C15	1	
	380		1	C16	C17	
	360			1	1	
	320					

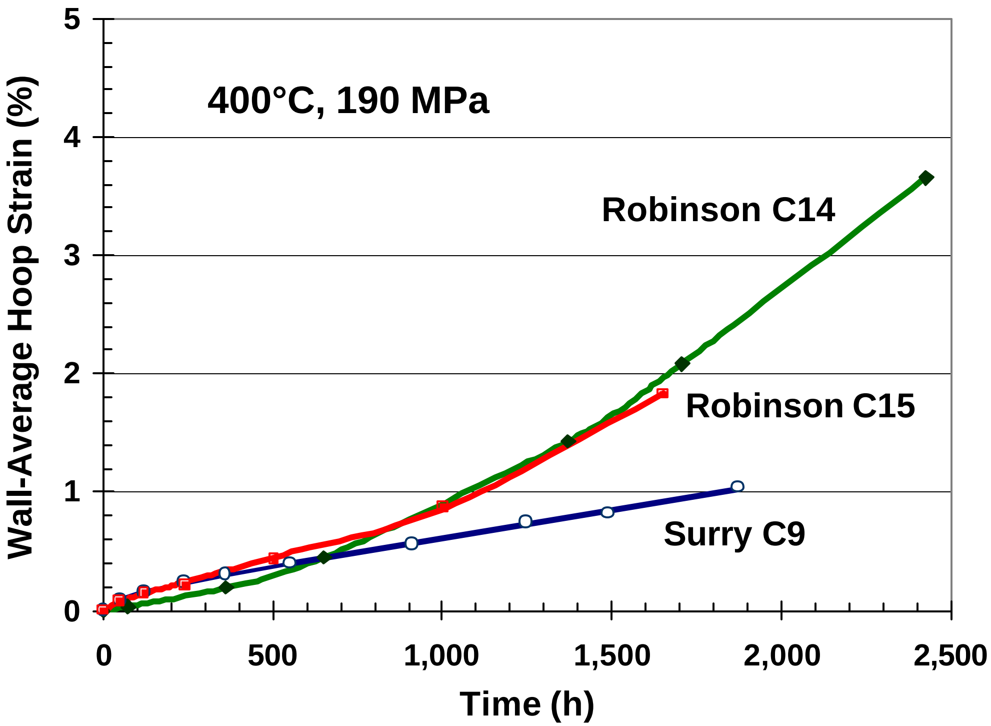
H. B. Robinson Cladding

- **Significant corrosion and H uptake from extended operation to high burnup**
  - **Oxide thickness:** ***~100 μm max.***
  - **Hydrogen uptake:** ***~800 wppm max.***
  - **Hydrides:** ***circumferentially oriented***
- **What are the effects of increased hydrogen and radiation damage on creep?**



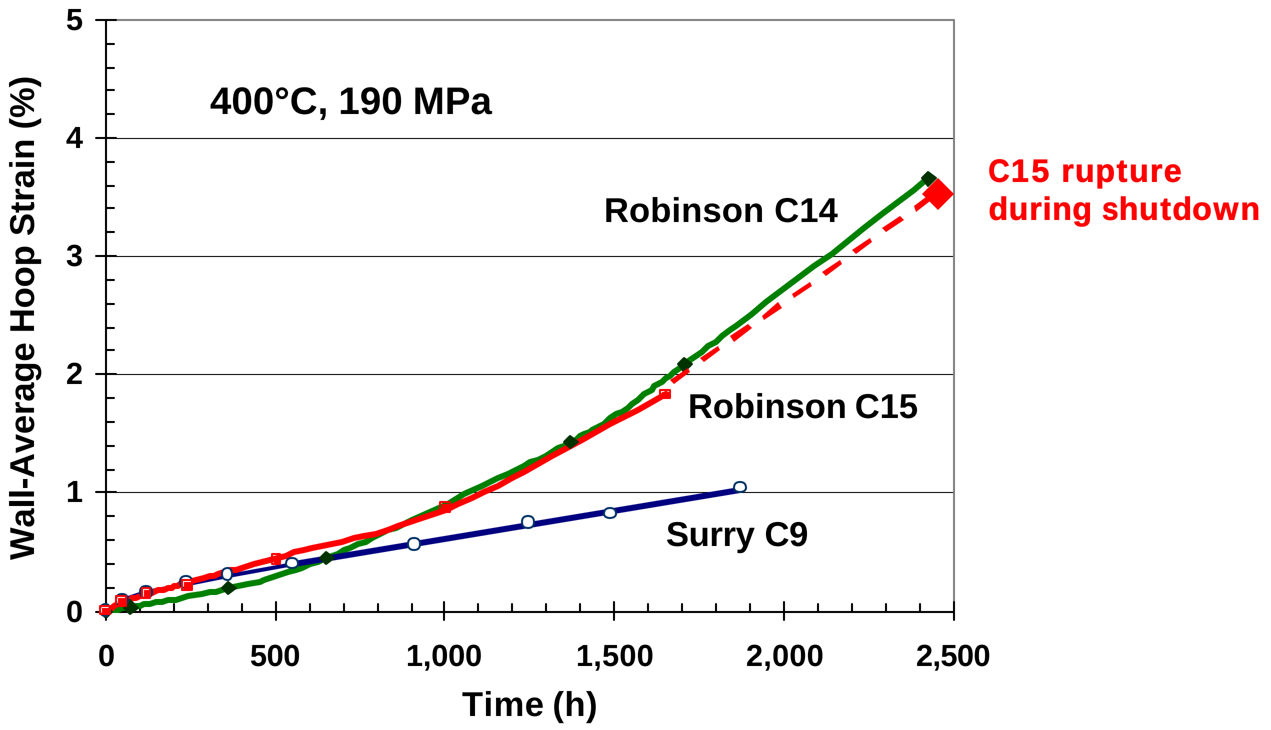
Thermal Creep Tests – H. B. Robinson

- **At 400°C, secondary creep rate of H. B. Robinson appears to be comparable to that of Surry at the onset of test. Rate appears to be greater afterwards.**
- **C14 was terminated at 2450 h at 3.6% e.**



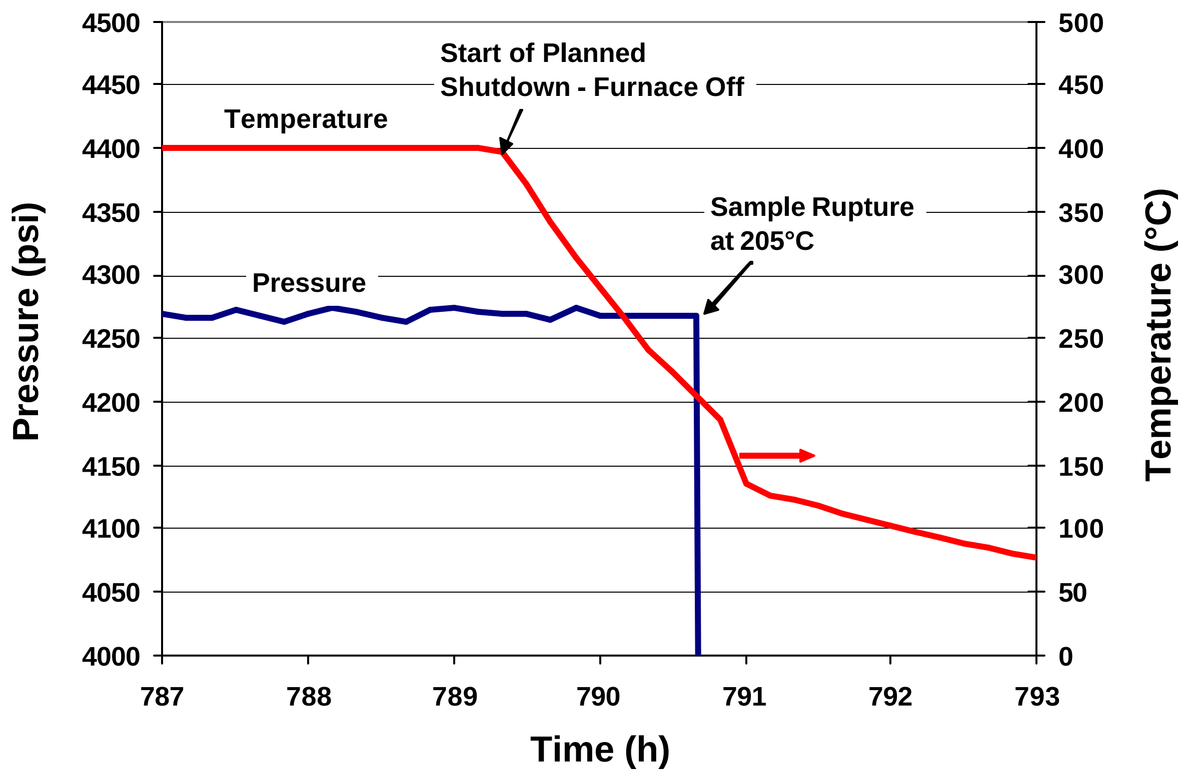
Thermal Creep Tests – H. B. Robinson

- C15 developed a rupture during the final shutdown, which stipulated cool-down first before depressurization to study hydride reorientation. (In comparison, C14 was depressurized first in the final shutdown.)



Thermal Creep Tests – H. B. Robinson

- **Shutdown history of C15**
  - **Sample intact at the end of run at 400°C.**
  - **Rupture occurred when temperature decreased to 205°C.**



Thermal Creep Tests – H. B. Robinson

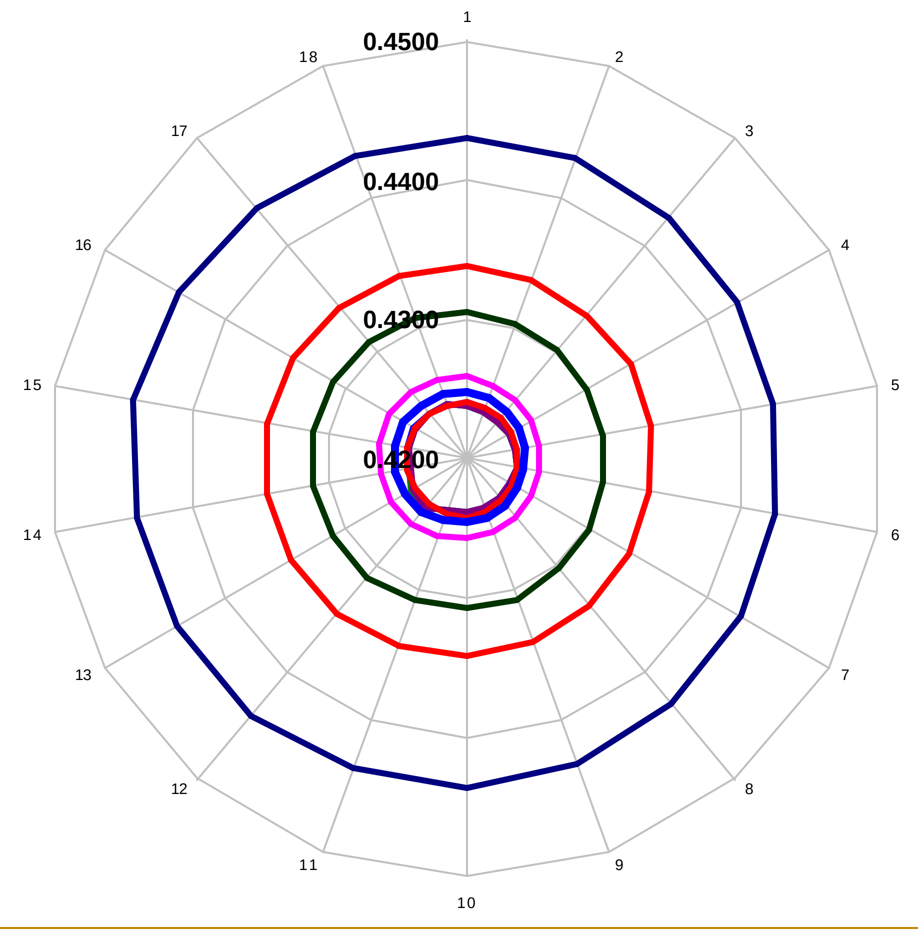
- **Status of C15**
  - The rupture caused substantial contamination of the hot cell in spite of the following provisions:
    - Sample defueled (by acid dissolution) and filled with Zr pellets
    - In-line pin hole in the pressurization system to restrict flow
    - Solenoid valve to shut off pressure
    - Down-stream HEPA filter.
  - Condition of the sample could not be readily determined until the cell is cleaned up.
    - End-plug weld failure or rupture due to hydride reorientation are two possible causes.
    - If latter, extensive examination will be conducted to characterize the hydride effects.

Thermal Creep Tests – H. B. Robinson

Robinson C14 Sample shows good creep ductility: >3.6 % at 400°C and 190 MPa.

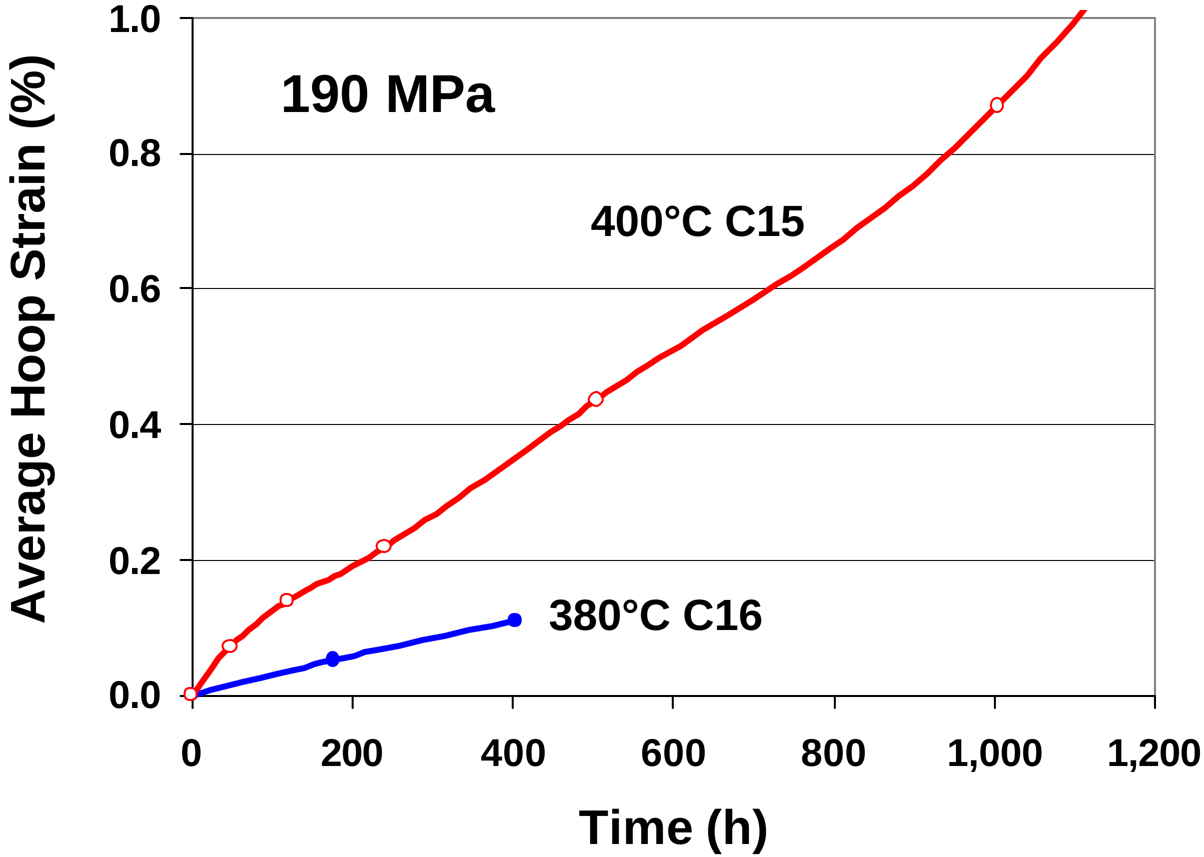
- **Deformation still azimuthally uniform at end of test**
- **Additional creep life likely**

Cross Sectional Profile
HBR A/G611C14 at 2.1 in. from top



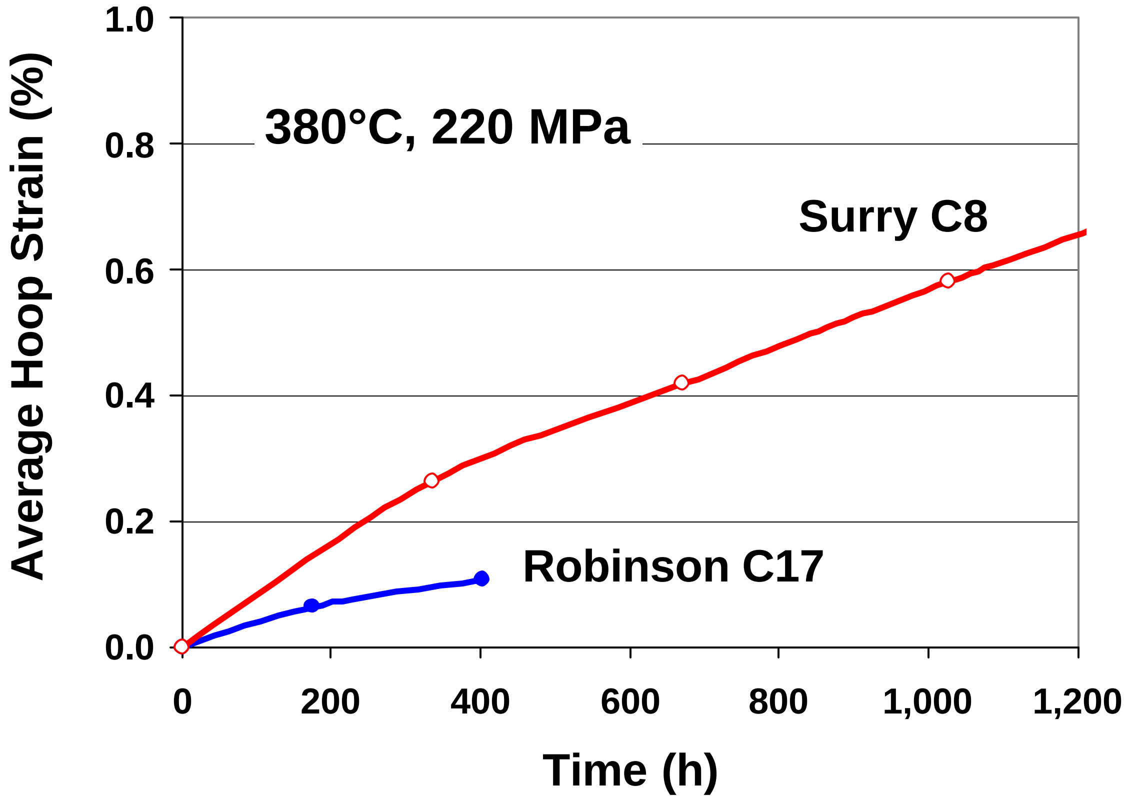
Thermal Creep Tests – H. B. Robinson

- **Temperature Dependency**



Thermal Creep Tests – H. B. Robinson

- **Creep rate of H. B. Robinson appears to be smaller than that of Surry at the lower temperature of 380°C.**



Summary and Conclusions

- **Significant residual creep ductility has been demonstrated for Surry cladding (36 GWd/MTU) after 15 years of dry-cask storage**
  - **No hydride reorientation in storage.**
  - **Findings support NRC ISG-11 (Rev. 2)**
- **Steady-state creep rates of Surry cladding show strong temperature and stress dependency in the regime tested**
  - **Useful for model development and code benchmarking**
- **Early data on Robinson cladding suggest creep rate at 400°C to be comparable to that of Surry**
  - **Because radiation damage has saturated? Annealing/recovering during tests? Negligible H effect as long as there is no reorientation? Fundamental differences in materials?**

Summary and Conclusions (cont'd)

- **Unexpected rupture of the H. B. Robinson C15 sample during the final shutdown (under pressure) requires further investigation**
  - **Was hydride reorientation the cause?**
  - **If yes, could it occur in real fuel rods? (Note: C15 with full pressure was a significant over-test for actual fuel rods.)**
- **Post-creep characterization to be performed**
  - **Hydride morphology/hydrogen migration**
  - **Bend or other mechanical tests.**