

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

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**Argonne National Laboratory**



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Office of Science Laboratory  
Operated by The University of Chicago



# *Thermal Creep Tests*

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- **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*

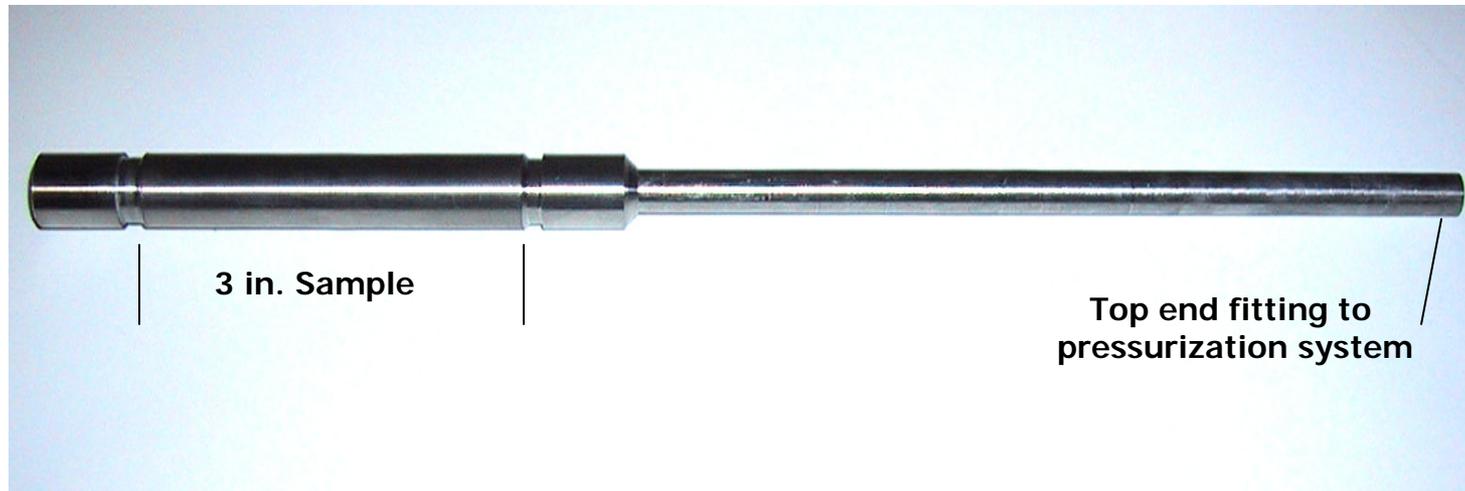
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- **Why studying creep?**
  - Creep is the dominant cladding deformation mechanism under normal conditions of dry storage. The core issue, however, is cladding integrity.
- **Test objectives**
  - Determining creep ductility and steady-state creep 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*

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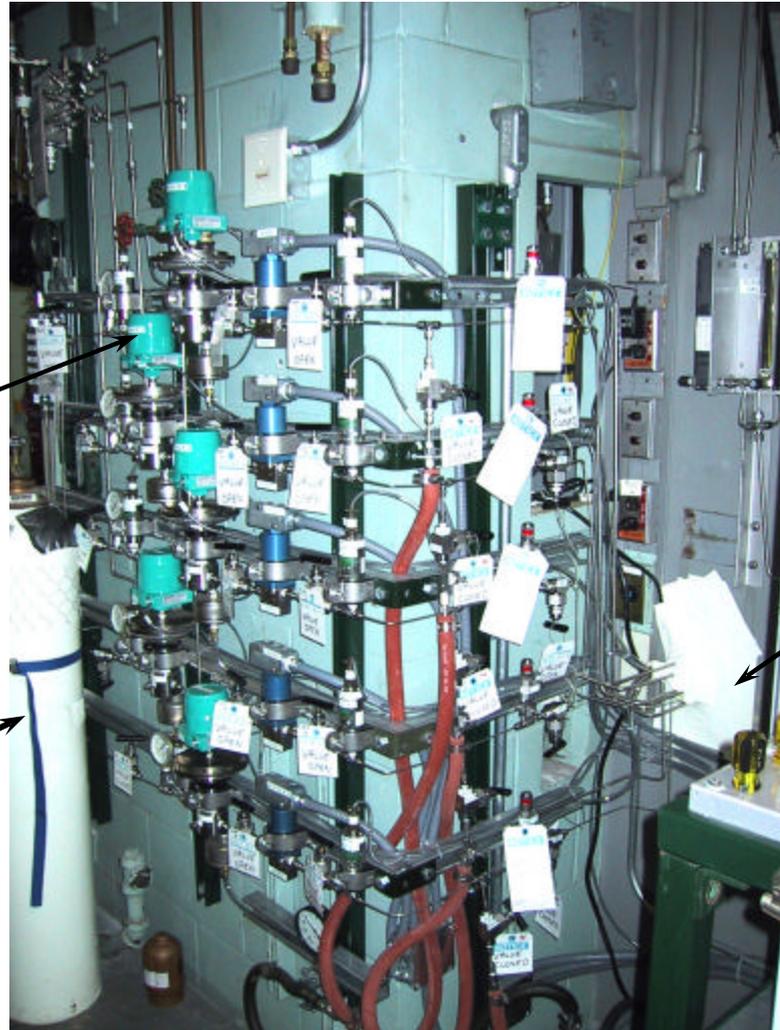
- **Pressurization Systems**
  - Specimens pressurized with argon gas from 6000-psi cylinders (~ 270 MPa hoop stress max.)
  - No pumps.
    - Improved safety, costs, and space utilization.
  - Pressures regulated with individual microprocessor-controlled regulators, to  $< \pm 10$  psi (0.5 MPa hoop).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

# Thermal Creep Tests

- Pressurization Systems (5)

CPU-based  
Pressure  
Controllers

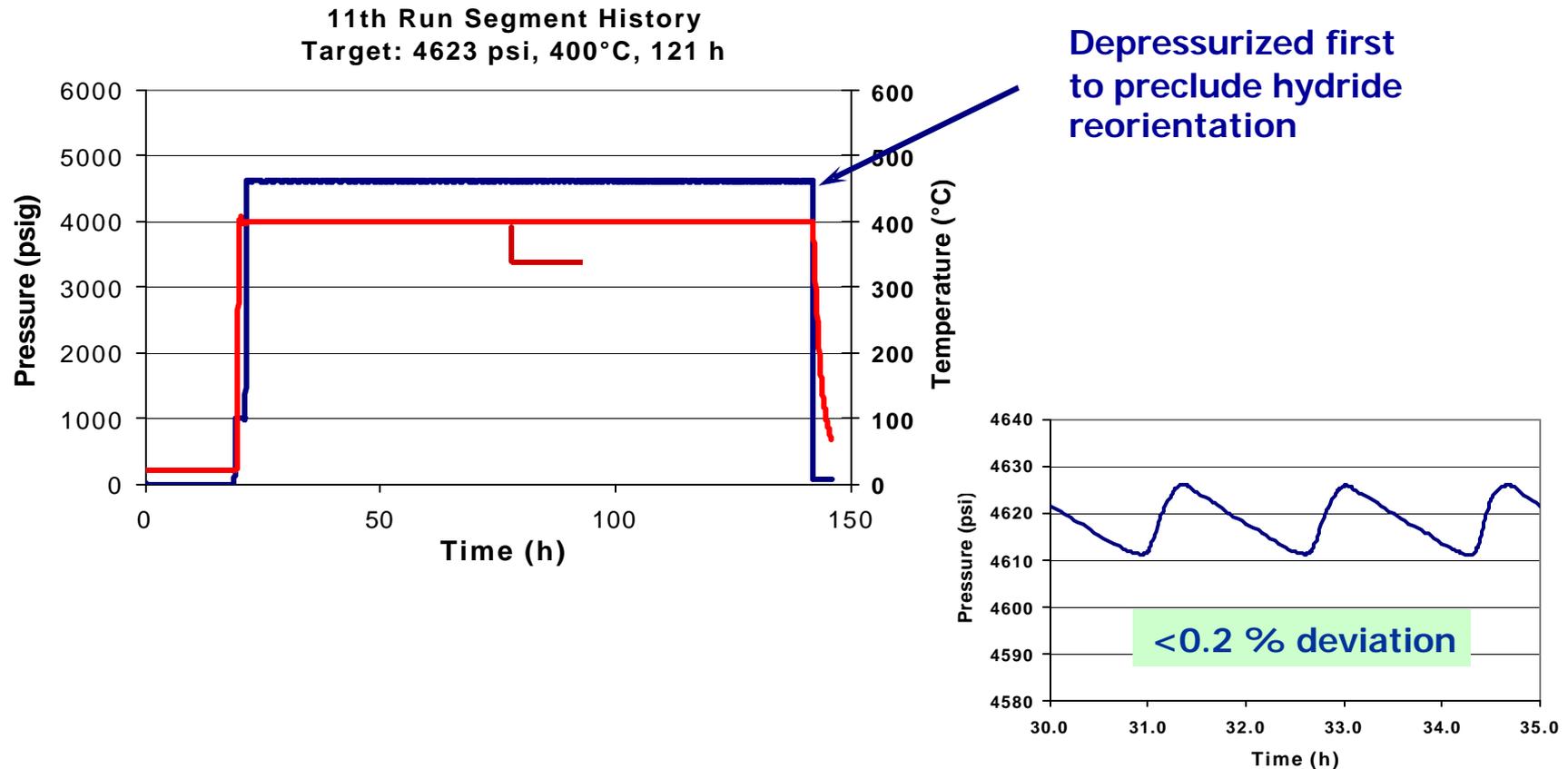
Gas Cylinders



Penetration  
into Cell

# Thermal Creep Tests – Typical Performance

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



# Thermal Creep Tests

- **Laser Profilometry**

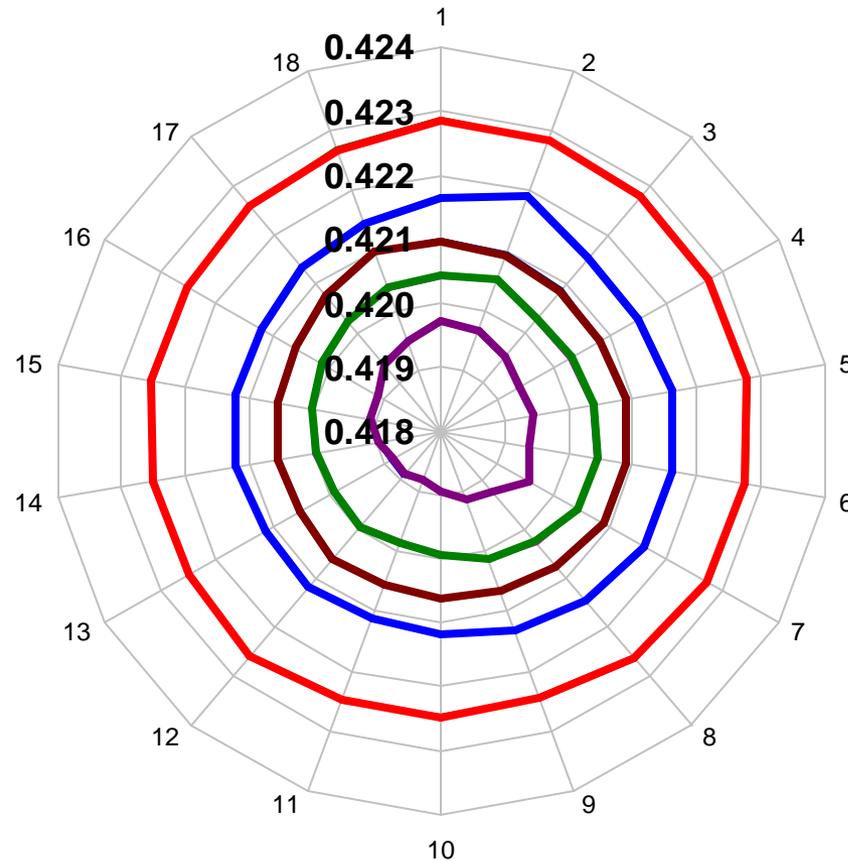
- Measurements made off-line at room temperature
- Diameters measured at multiple axial and azimuthal locations to within  $\pm 2 \times 10^{-5}$  in. (0.005% strain)
- Length measured to  $\pm 10^{-3}$  in. to evaluate creep anisotropy.



# 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)
<i>To be initiated</i>	<i>C10</i>	<i>400</i>	<i>220</i>	<i>Residual creep strain, ISG-11(Rev. 2)</i>

# Thermal Creep of Post-Storage Surry Cladding

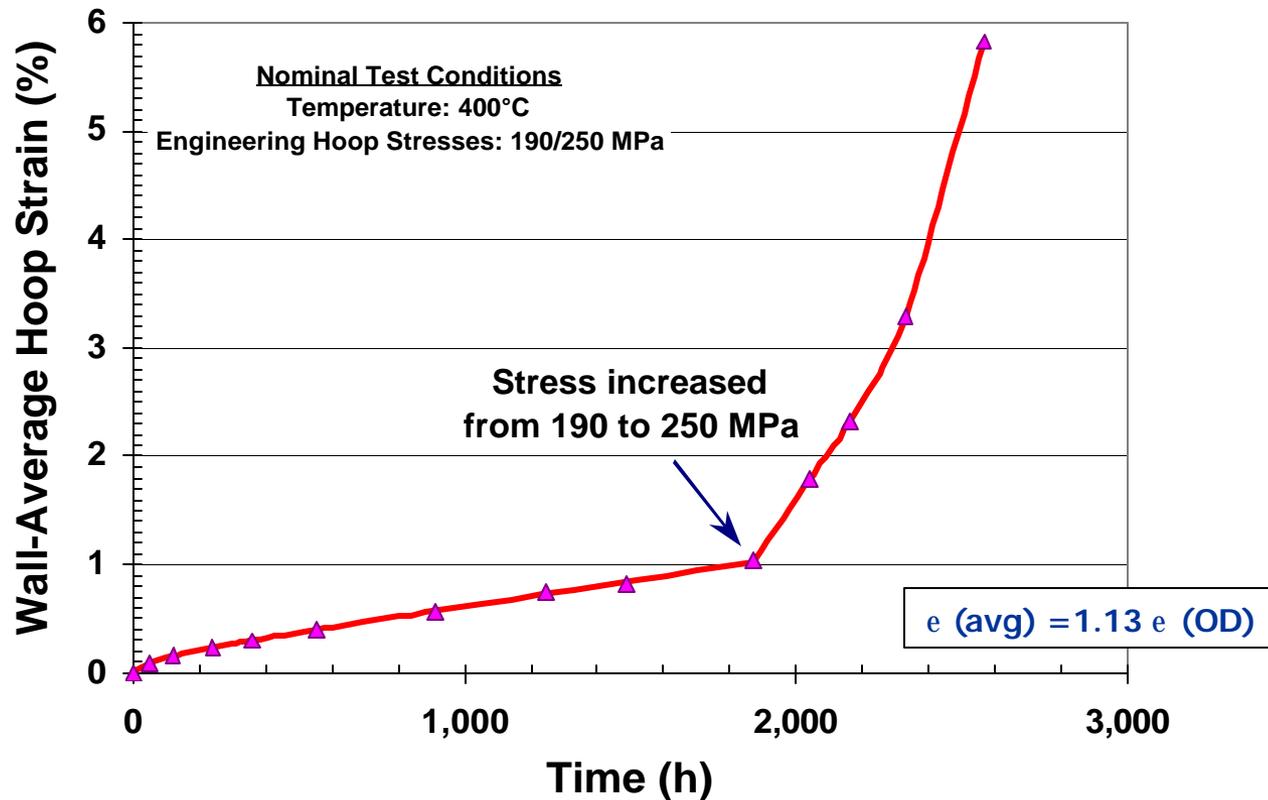
## Surry Summary Results

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

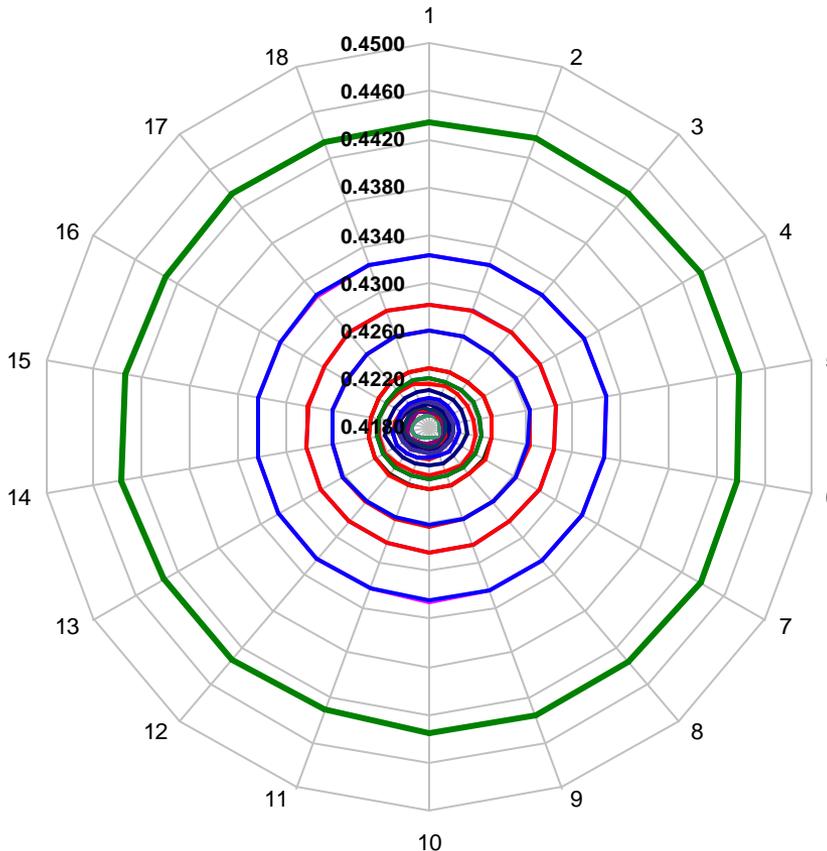
- 400°C, 190/250 MPa engineering hoop stress, 2566 h
- 5.8% average hoop strain, no rupture



# Thermal Creep Tests – Surry C9

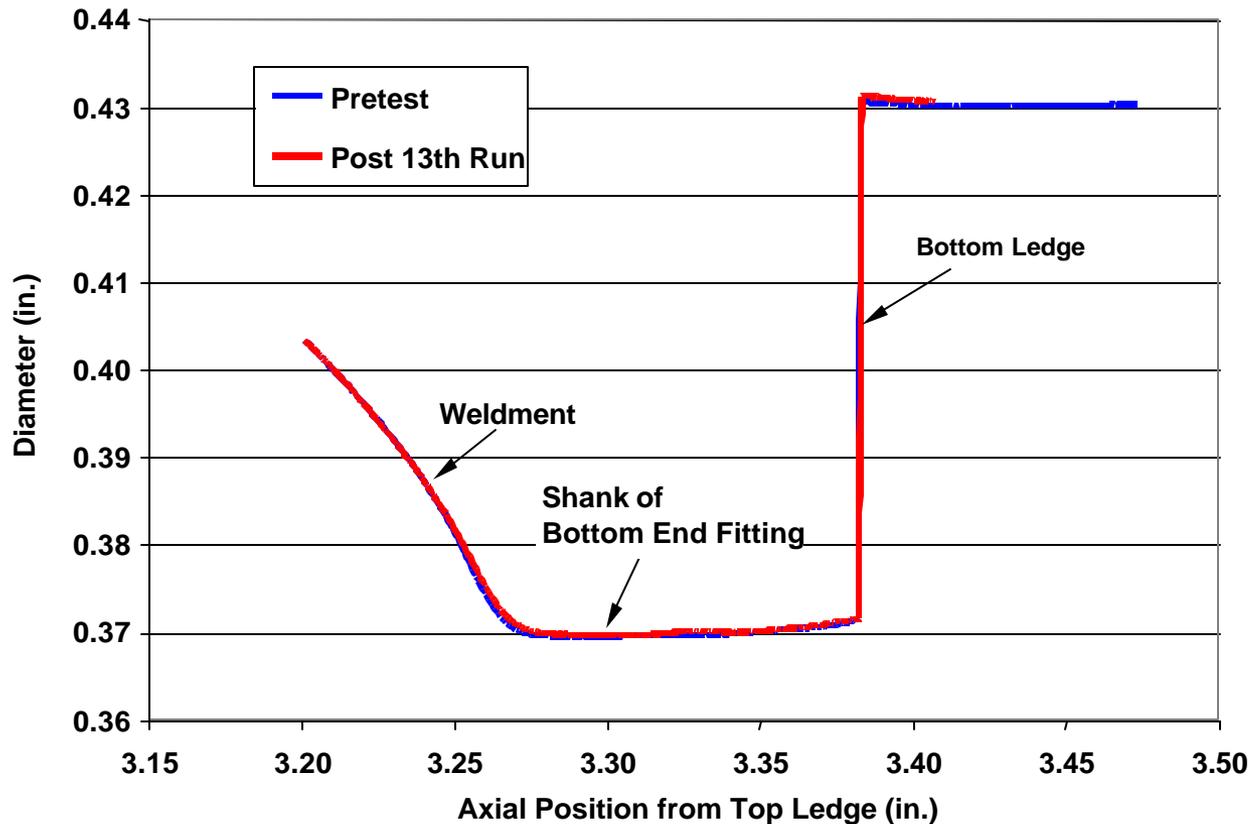
- Deformation uniform even at high strain (5.8%)
- No signs of imminent failure
- Additional creep ductility likely

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



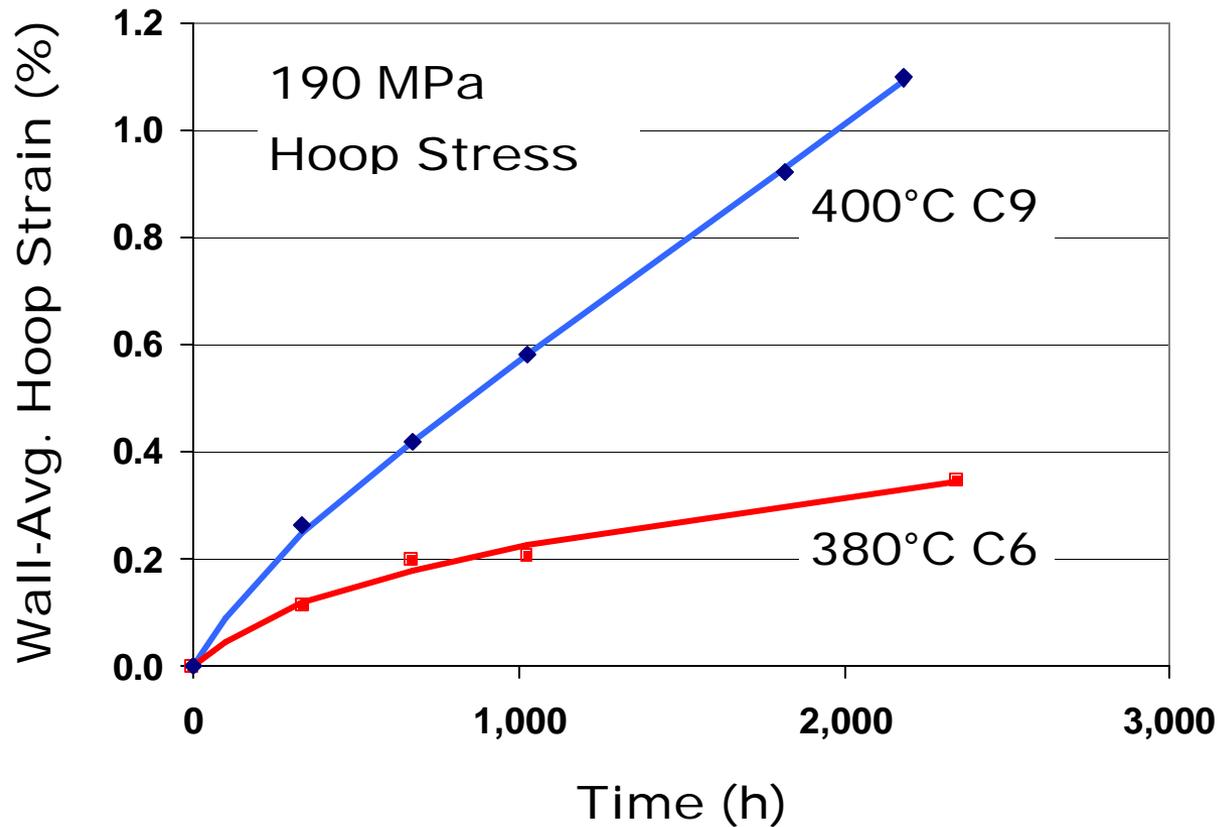
# Thermal Creep Tests – Surry C9

- No apparent creep anisotropy based on sample length measurements



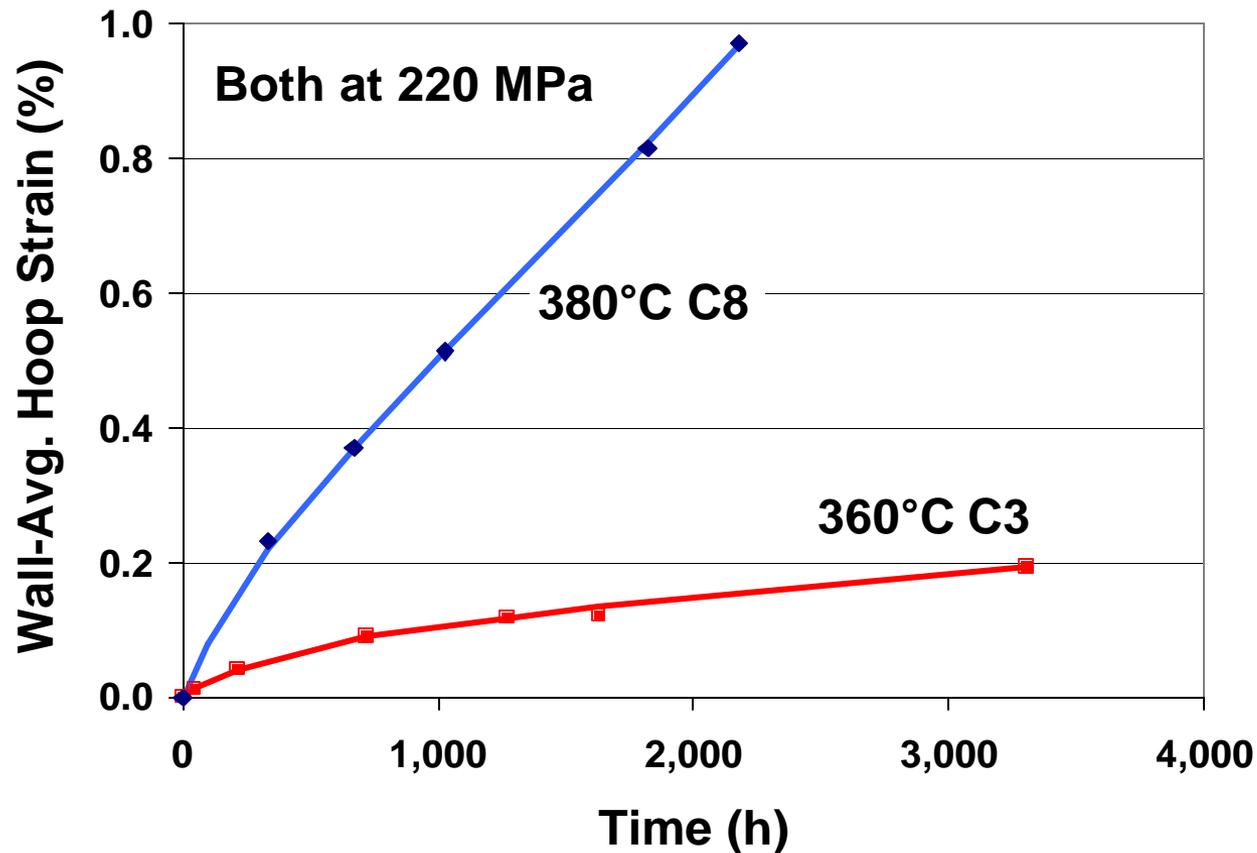
# Thermal Creep of Post-Storage Surry Cladding

## - Temperature Dependency



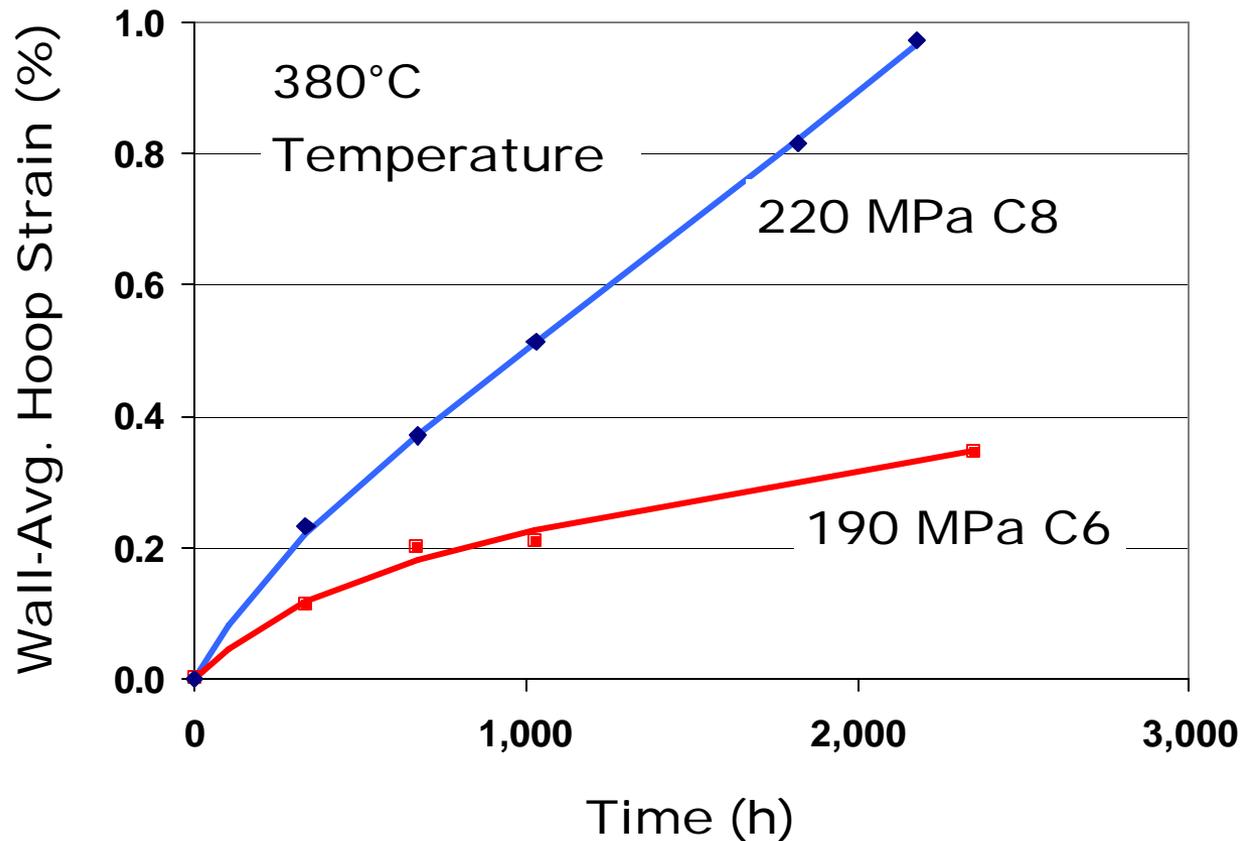
# Thermal Creep of Post-Storage Surry Cladding

## - Temperature Dependency



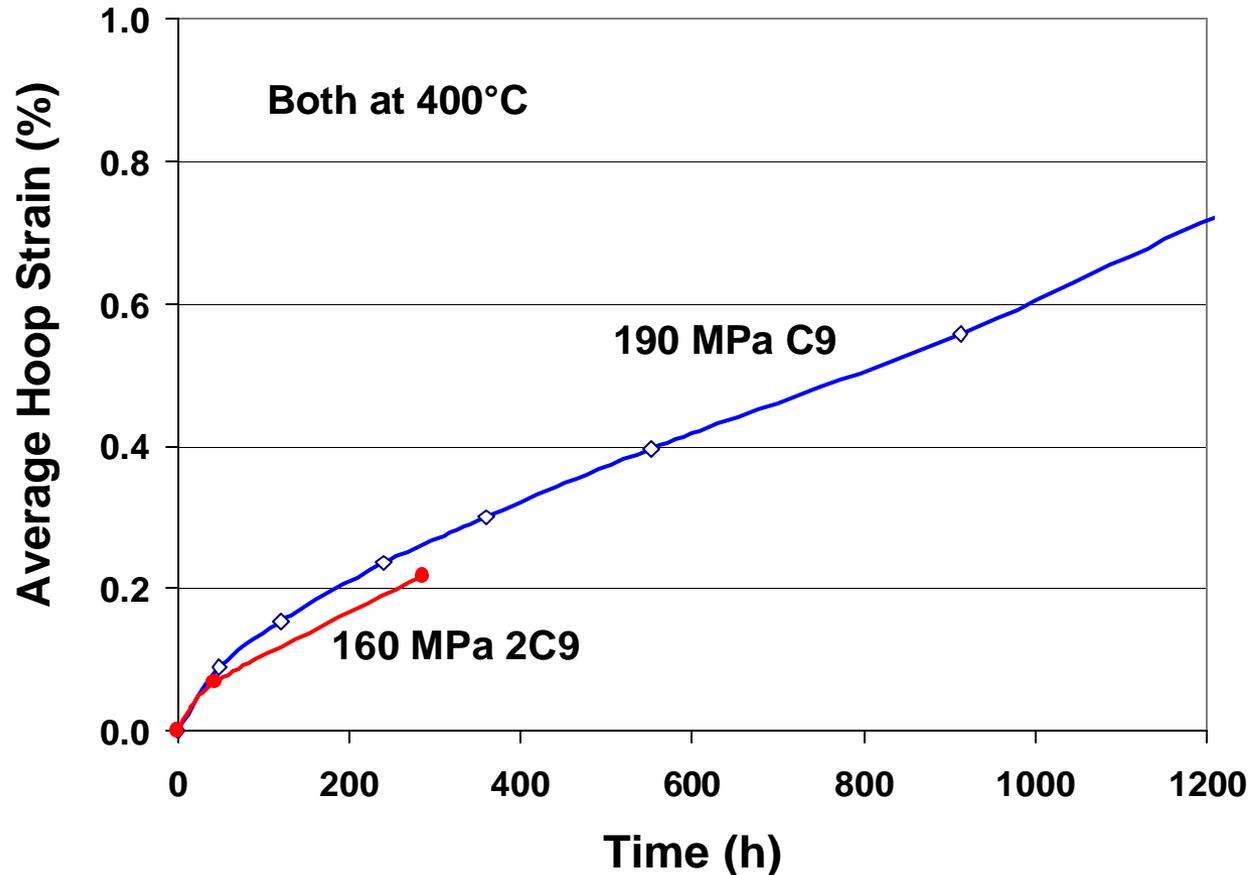
# Thermal Creep of Post-Storage Surry Cladding

## - 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 $\epsilon/Dt^{(1)}$ (%/h)
PSC	C3	360	220	$\sim 1.6 \cdot 10^{-5}$
PSC	C6	380	190	$\sim 8.6 \cdot 10^{-5}$
RCS	C8	380	220	$\sim 4.6 \cdot 10^{-4}$
RCS	C9	400	190 250	$\sim 4.9 \cdot 10^{-4}$ $\sim 4.9 \cdot 10^{-3}$

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

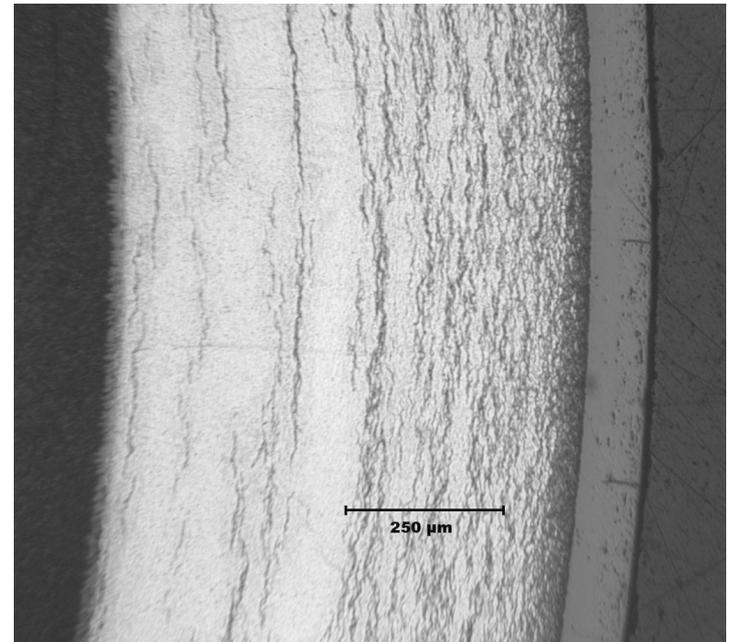
# Thermal Creep Tests – H. B. Robinson

## 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					

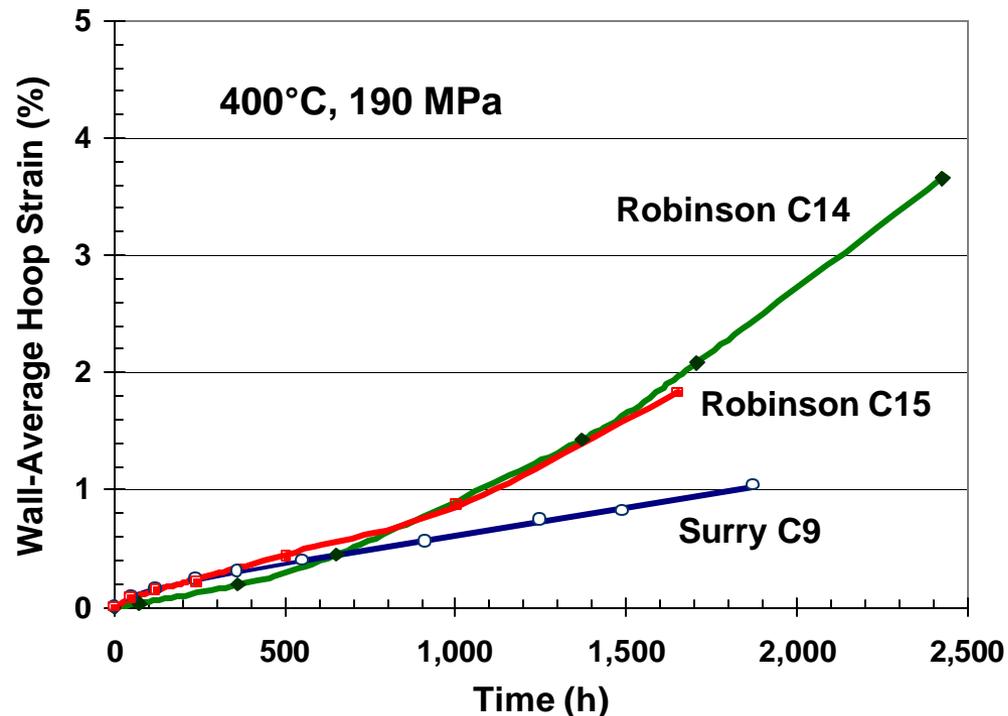
# H. B. Robinson Cladding

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



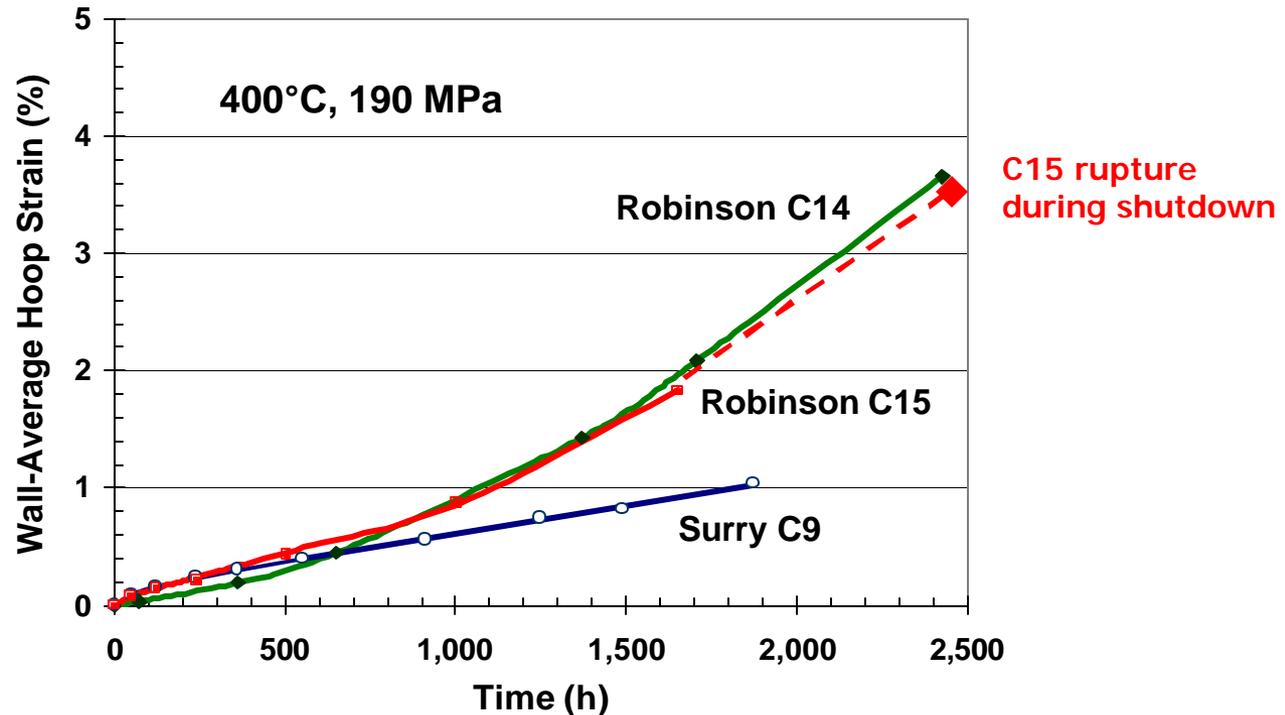
# Thermal Creep Tests – H. B. Robinson

- 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

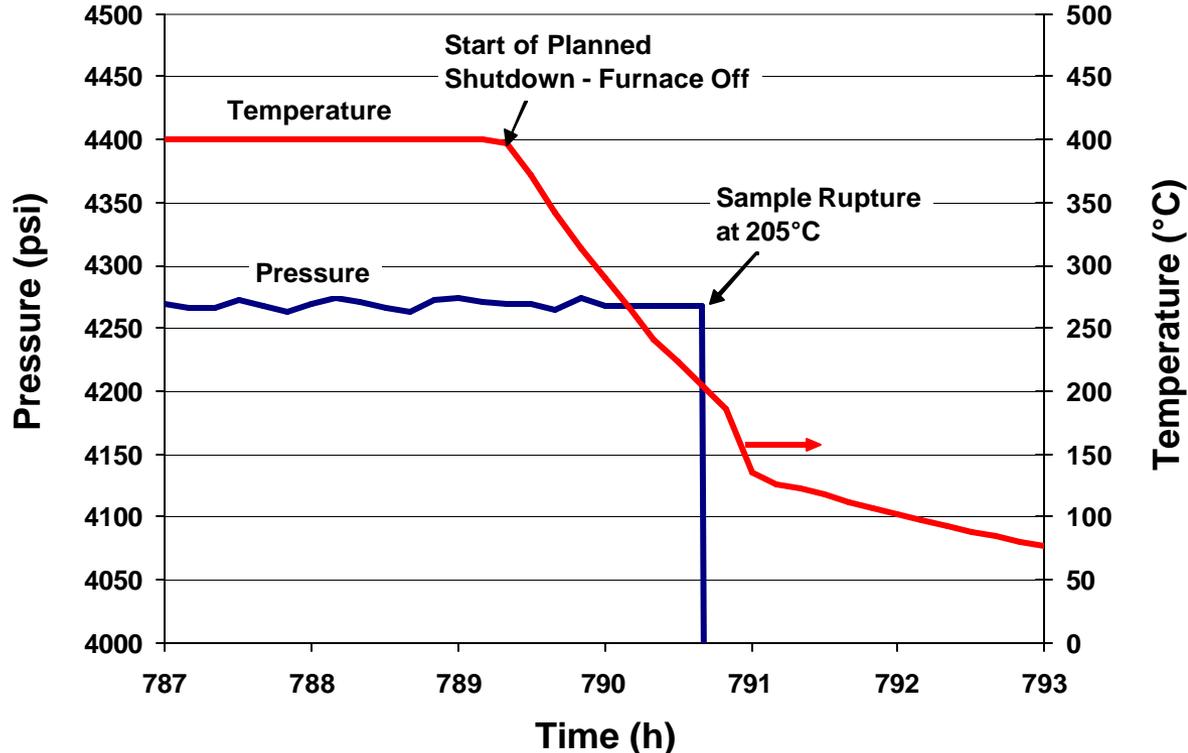
- C15 developed a rupture during the final shutdown, which stipulated cool-down first before depressurization to study hydride reorientation. (In comparison, C14 was depressurized first in the final shutdown.)



# 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*

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- **Status of C15**

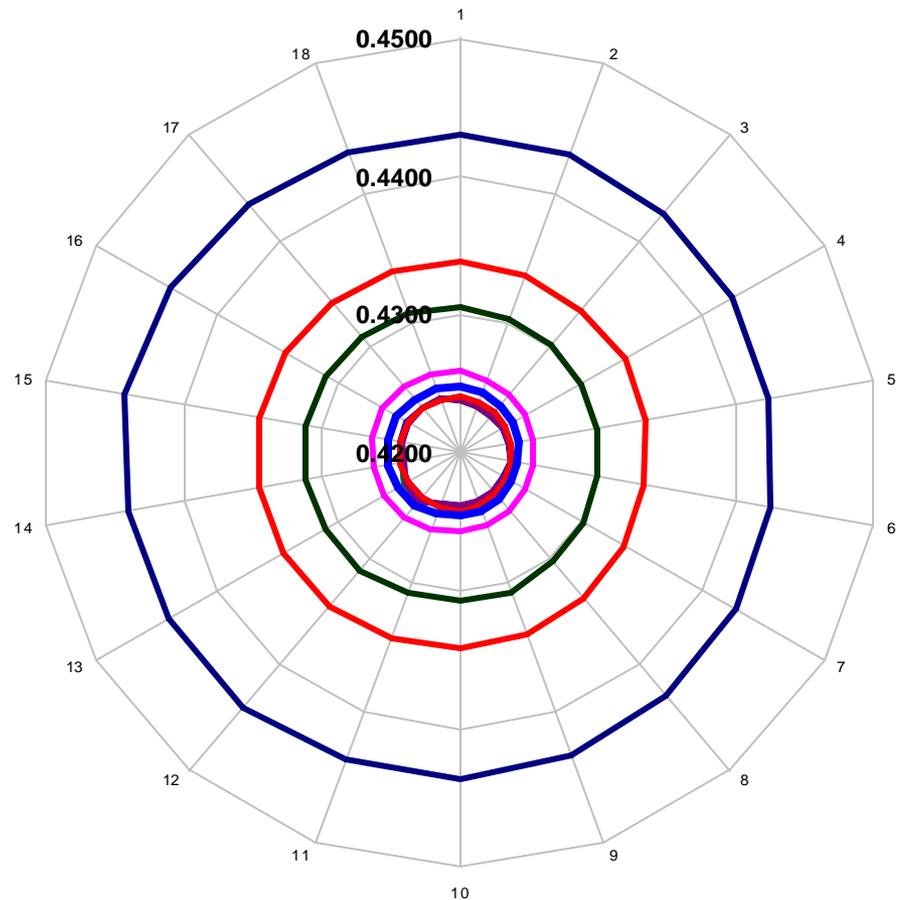
- **The rupture caused substantial contamination of the hot cell in spite of the following provisions:**
  - **Sample defueled (by acid dissolution) and filled with Zr pellets**
  - **In-line pin hole in the pressurization system to restrict flow**
  - **Solenoid valve to shut off pressure**
  - **Down-stream 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  $400^{\circ}\text{C}$  and  $190\text{ MPa}$ .

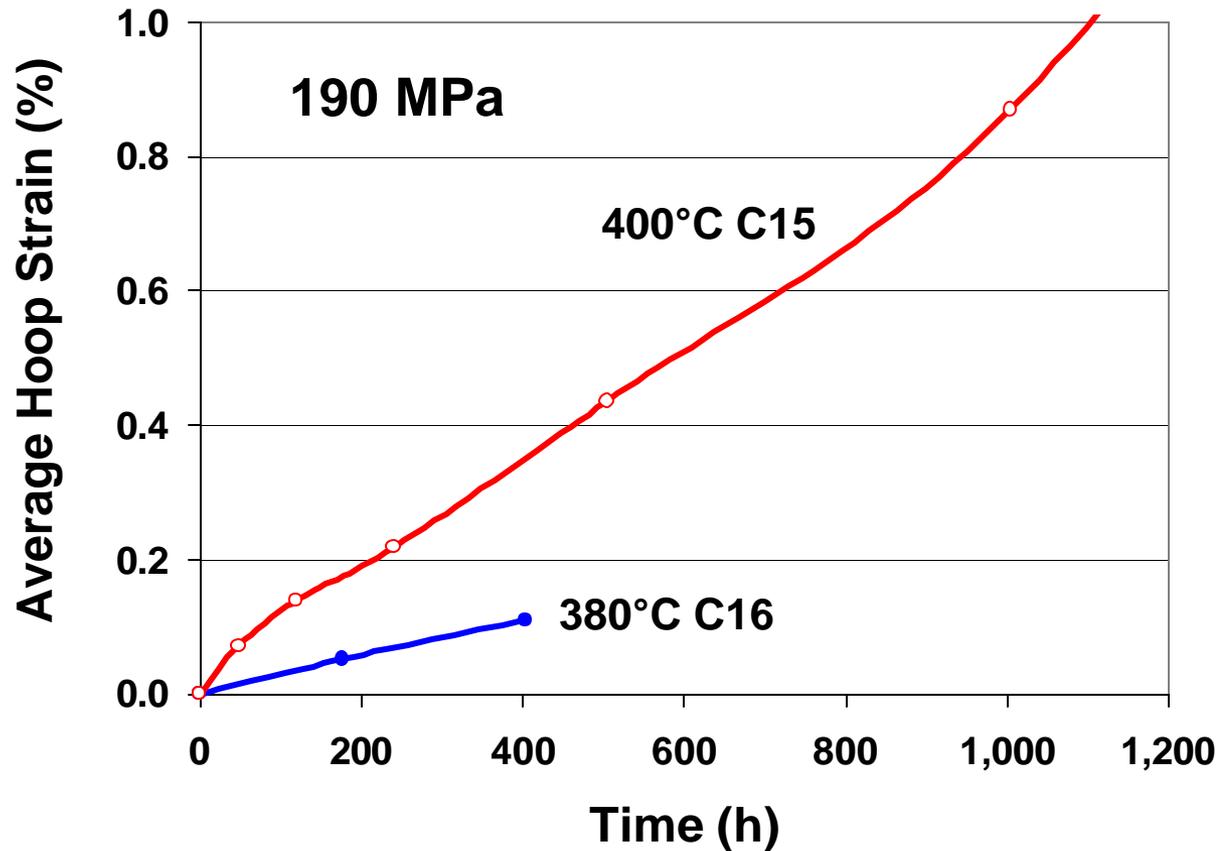
- Deformation still azimuthally uniform at end of test
- Additional creep life likely

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



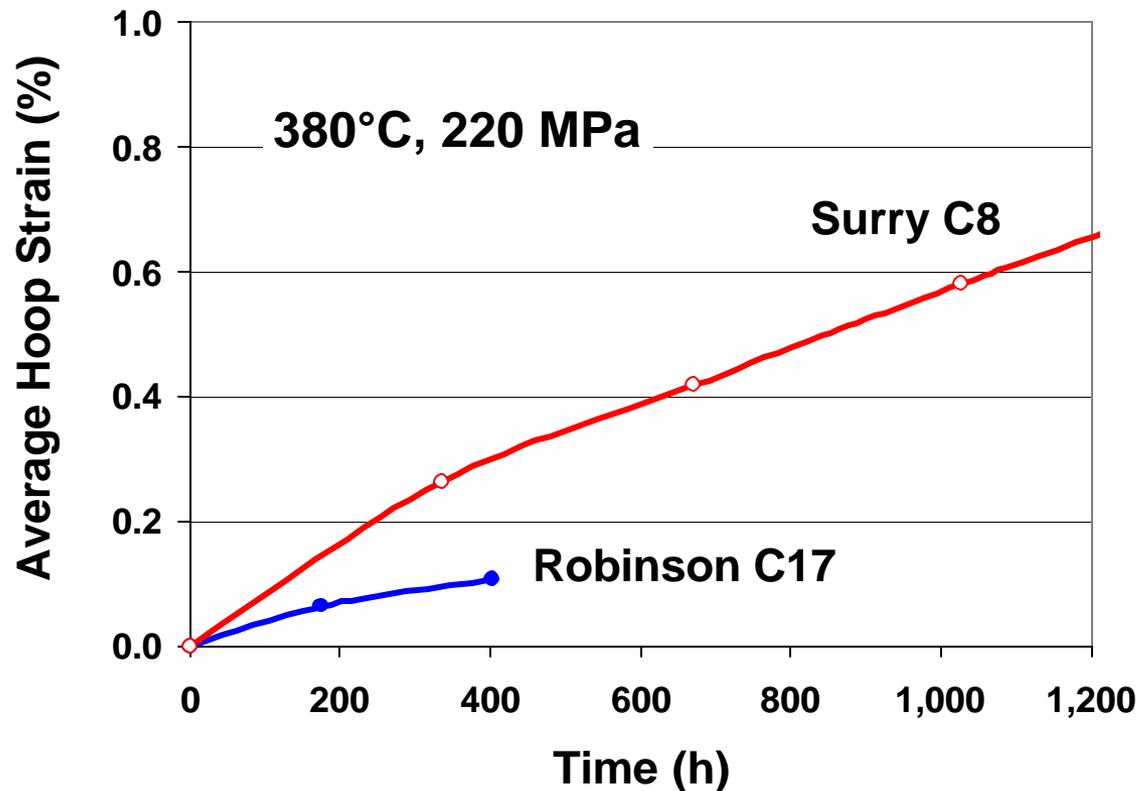
# Thermal Creep Tests – H. B. Robinson

## - 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

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- **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)

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- **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.