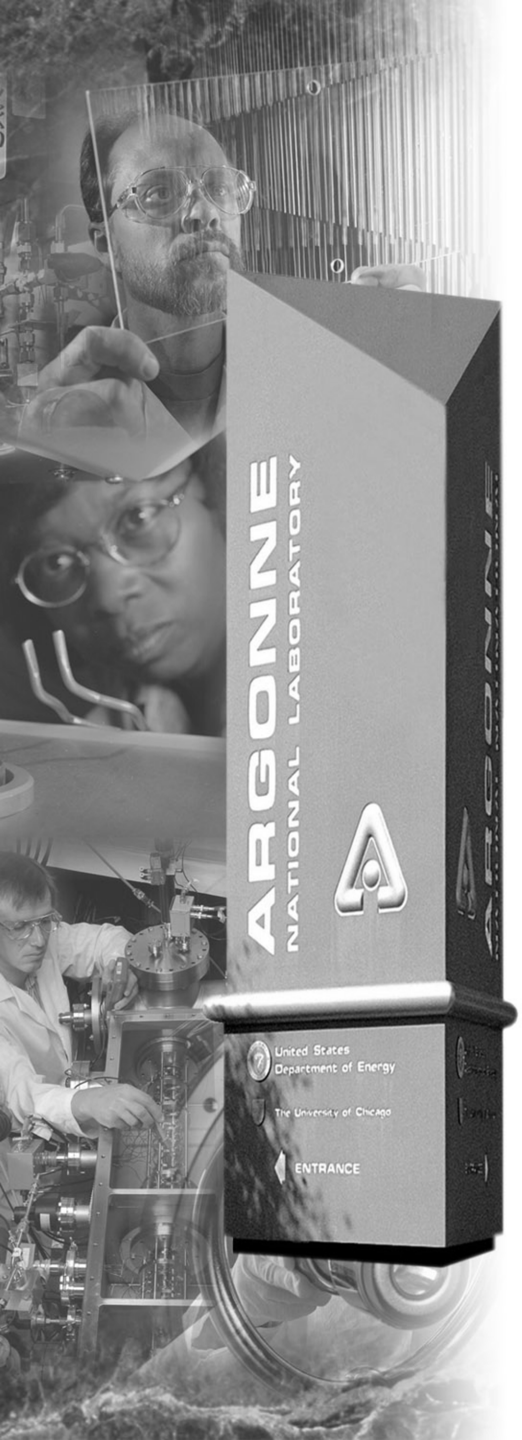

Cladding Behavior during Dry Cask Handling and Storage

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Office of Science
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Cladding Behavior during Dry Cask Handling and Storage

- **Maintaining SNF cladding integrity is important for cask performance**
  - **Fuel retrievability, cask surface dose rate, criticality.**
- **Factors that may affect cladding behavior include**
  - **Thermal creep**
  - **Hydrogen in cladding – hydride redistribution under the influence of temperature and stress.**
- **Objective of our work is to provide data to support**
  - **Extending storage time (>20 years), and**
  - **Extending burnup (>45 GWd/MTU).**

Cladding Behavior during Dry Cask Handling and Storage

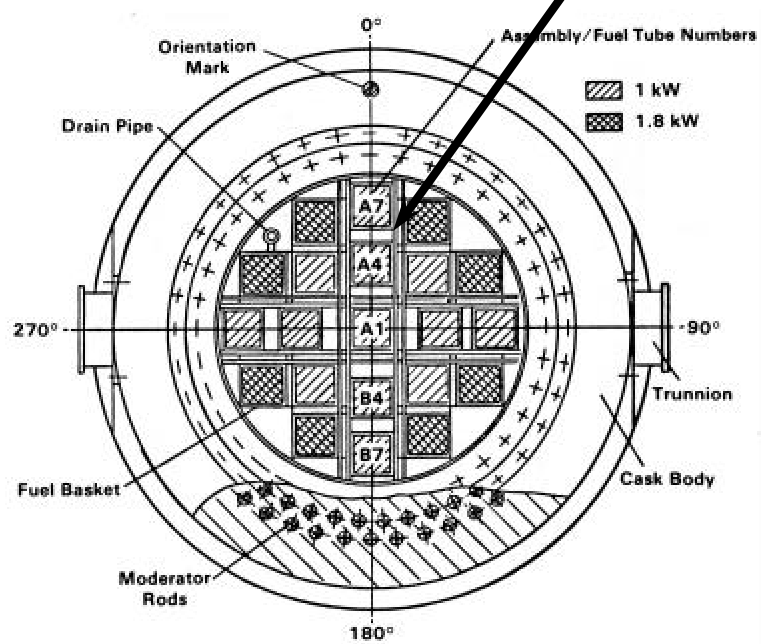
We have performed the following:

- Characterization of medium-burnup (36 GWd/MTU) Surry PWR rods after 15 y-storage in a Castor-V/21 dry cask
  - Extensive in-cask thermal benchmark tests, some emulated vacuum drying.
- Isothermal annealing of cladding from high-burnup (67 GWd/MTU) H. B. Robinson rods
  - Conditions relevant to vacuum drying (420-500°C, 2-72 h).
  - Post-annealing microhardness and hydride morphology determinations.
- Thermal creep tests of both Surry and Robinson cladding
  - Creep ductility and hydride reorientation.

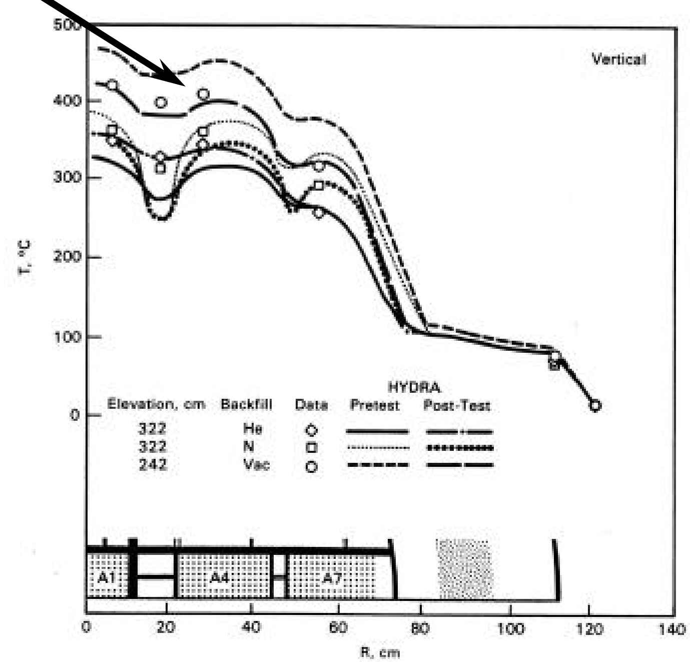
Effects of 15-y Dry Cask Storage (and thermal benchmark tests) on Surry Rods

Surry Rods (Assembly T11) in Castor-V/21

Assembly T11



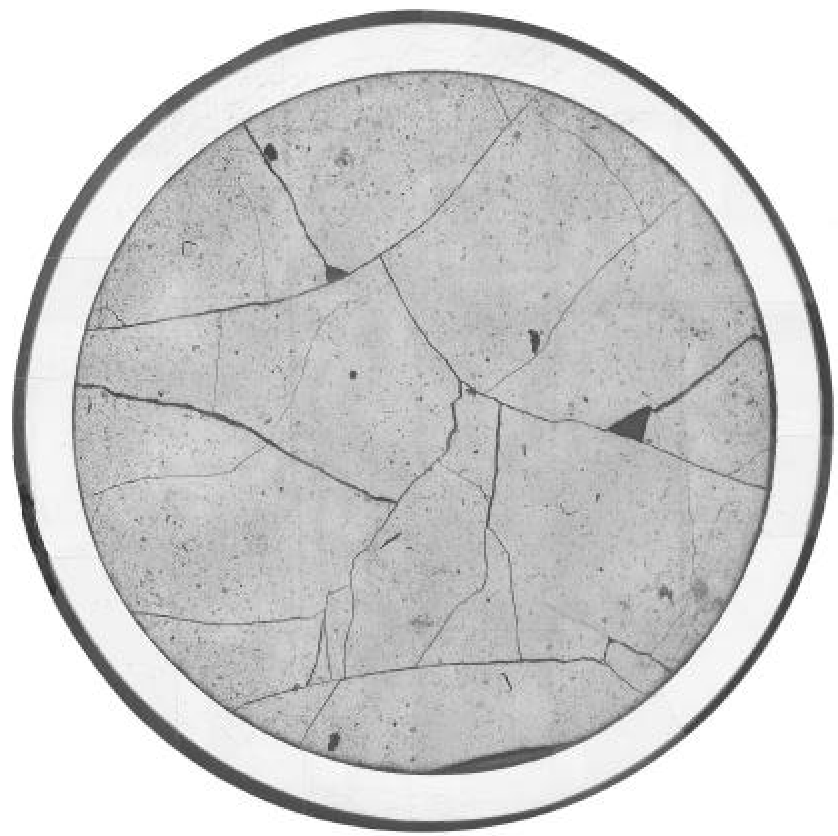
Location of source rods in the Caster-V/21 cask



Peak cladding temperature ~ 415°C for 3 days when the cask was in vacuum. Cladding hoop stress was, however, low, <70 MPa.

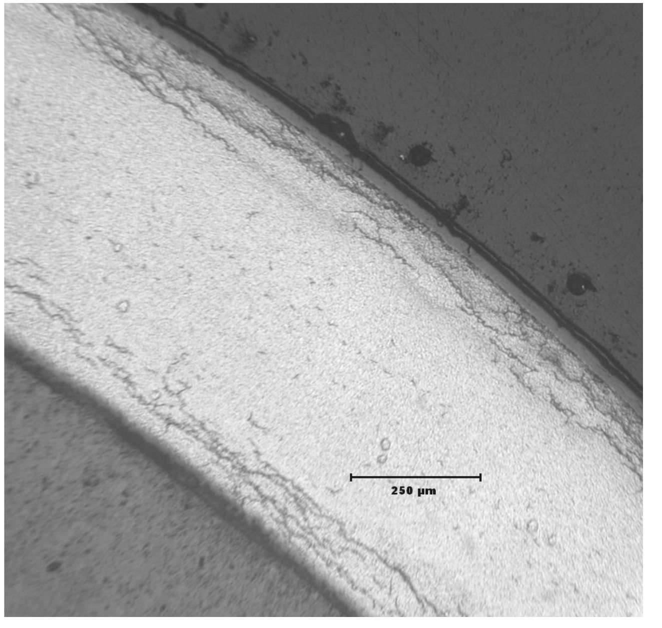
Surry Post-Storage Characterization

- **Effect of 15-y storage is benign**
  - **Gas release: ~ 0.5-1.0 %**
    - **No additional release**
  - **Fuel microstructure**
    - **No obvious changes**
  - **$\Delta D / D_{as\text{-}built}$: ~ -0.6 %**
    - **Little or no in-storage creep**



Surry Post-Storage Characterization *(cont'd)*

- **Effect of 15-y storage is benign.**
  - **Cladding microhardness: 235-240 DPH**
    - **No apparent annealing in storage**
  - **OD oxide thickness**
    - **Normal (~ 24-33 µm)**
  - **Cladding hydrogen content**
    - **Normal (~ 250-300 wppm)**
    - **Axial migration - tbd**
  - **Hydride reorientation**
    - **None observed**



Surry Post-Storage Characterization (cont'd)

- **Summary**
  - **15-y dry-cask storage (with extensive in-cask thermal benchmark tests) produced no apparent deleterious effects on the Surry rods.**
  - **Segments of Surry cladding were prepared for post-storage thermal creep and tensile tests.**

Cladding Annealing Tests and Hydride Reorientation

Robinson Cladding Annealing Tests

- **During vacuum drying, cladding temperature may be raised to >˜ 400°C for hours to days. Will this alleviate radiation hardening in the cladding? What effect it has on hydrogen distribution?**
  - **Figure of merit: cladding microhardness**
  - **Test samples: short segments of defueled cladding from center of rod (11.3 x 10^{21} n/cm^2, E>1 MeV, ˜ 600 wppm H)**
  - **Corollary objective: study hydride redistribution under stress-free conditions**
  - **Test environment: high-purity argon**

Robinson Cladding Annealing Tests

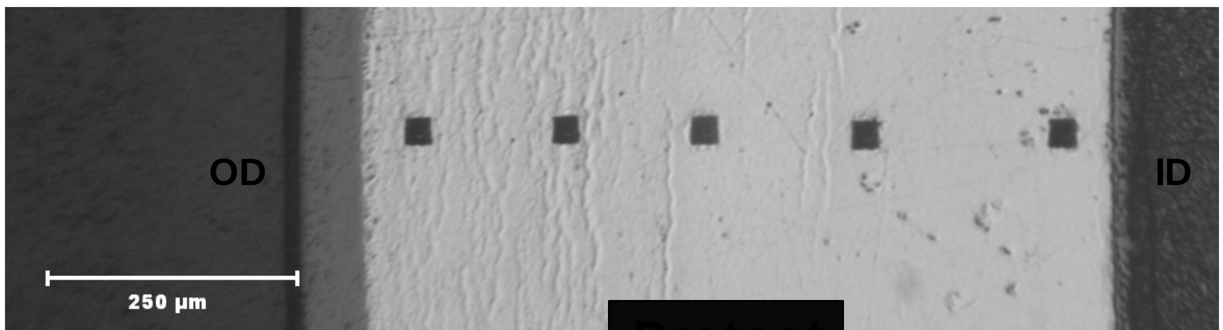
- **Annealing Test Matrix**

	2 h	10 h	20 h	48 h	72 h
420°C			C6		C7
450°C	C8	C9			
500°C	C10			C11	

Robinson Cladding Annealing Tests

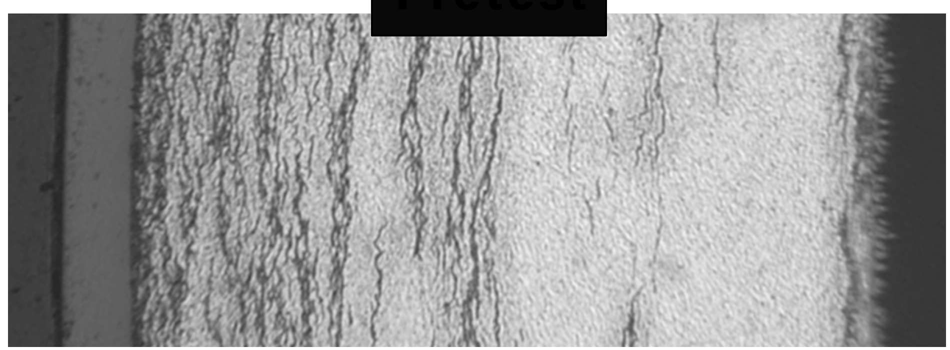
- ## Microhardness Determination
  - Apply a known load with a diamond tip, measure the size of the indentation, and convert to microhardness (DPH)

DPH uniform across thickness, Avg = 252



[redacted]

Etched, showing hydrides ~ 600 wppm H



Robinson Cladding Annealing Tests

- **Microhardness Determination**
  - **For nonirradiated sibling: Ho = 203**
  - **For as-irradiated sibling: Hi = 252**

Microhardness after annealing tests

	2 h	10 h	20 h	48 h	72 h
420°C			226		215
450°C	224	217			
500°C	218			206	

Robinson Cladding Annealing Tests

$$\text{Recovery} = \left[1 - \frac{H - Ho}{Hi - Ho}\right]$$

% Radiation Hardening Recovery

	2 h	10 h	20 h	48 h	72 h
420°C			54		75
450°C	58	71			
500°C	69			94	

Conclusion: Given time, significant recovery will occur at T >˜ 420°C.

Robinson Cladding Annealing Tests

- **Hydride Morphology Evolution**
  - **Strongly governed by hydrogen solubility in Zircaloy**

Temperature (°C)	Solubility (wppm)
25	0
200	13
400	200
420	240
450	310
500	460

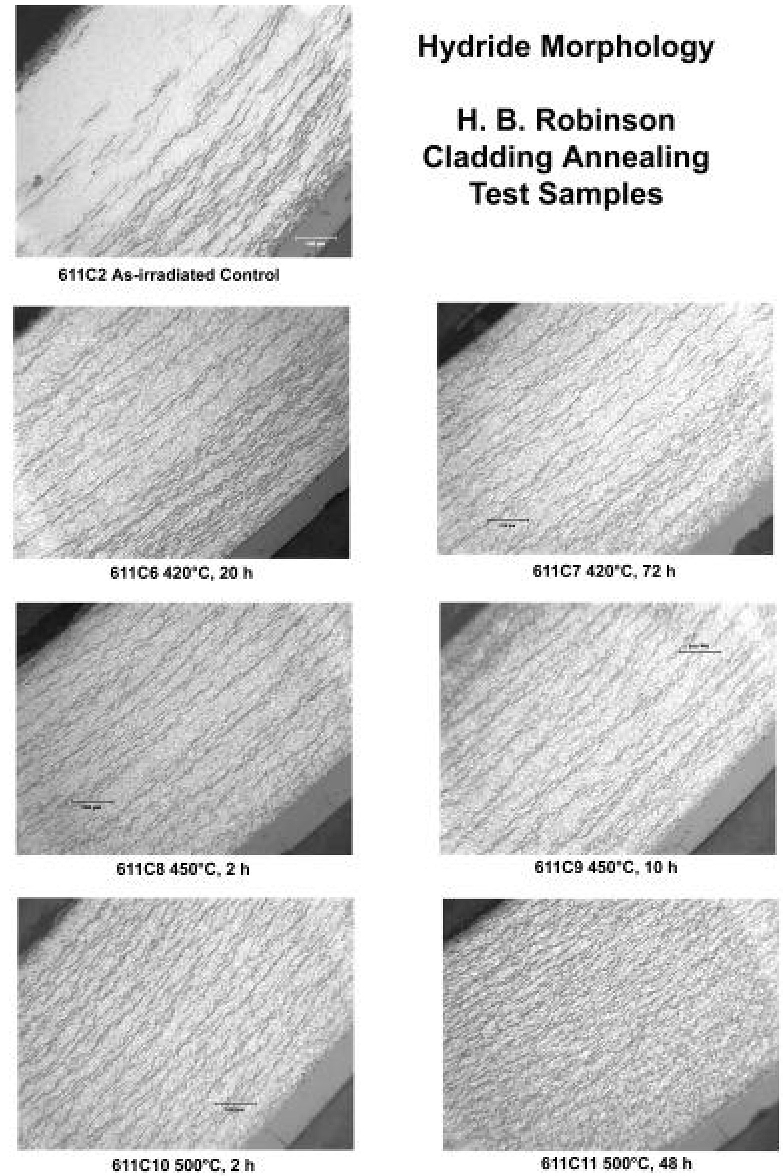
Surry: 300 wppm

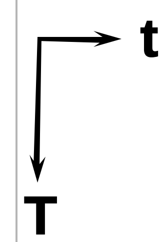
Robinson: 600 wppm

J. J. Kearns

Robinson Cladding Annealing Tests

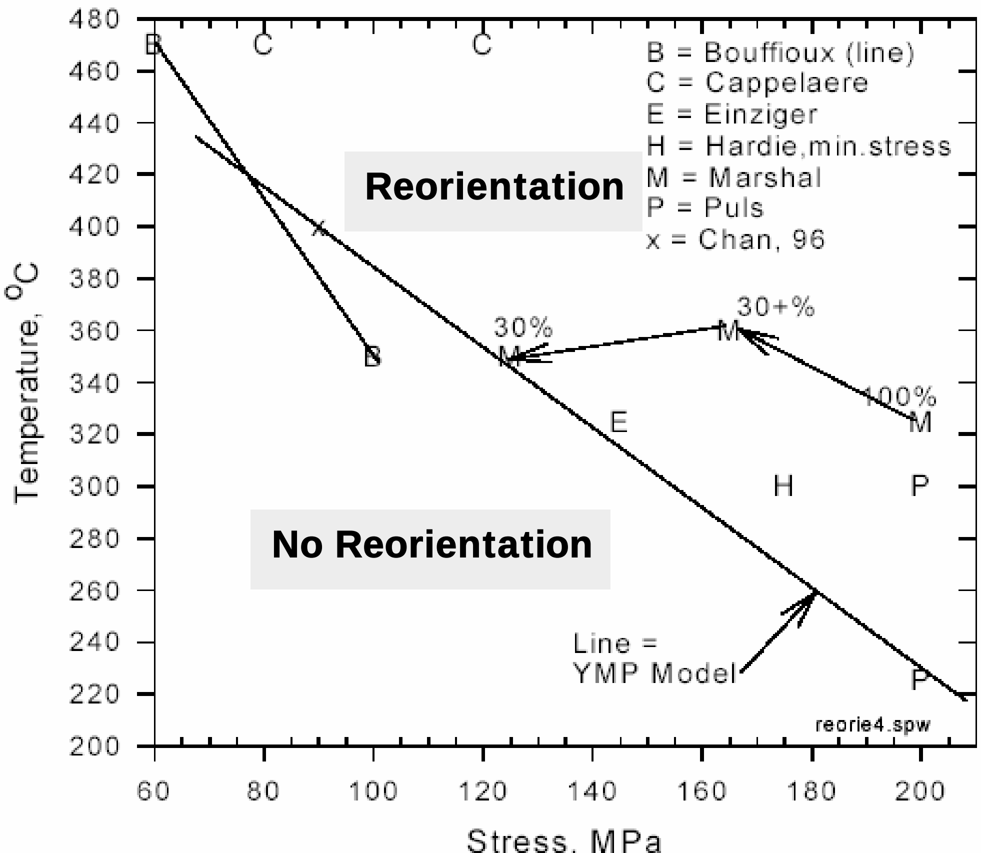
- **Hydride Morphology Evolution**
  - **Precipitates became more uniformly distributed across the thickness**
    - ***Temperature. time***
  - **No radial reorientation (being stress-free)**





Hydride Reorientation – Creep Tests

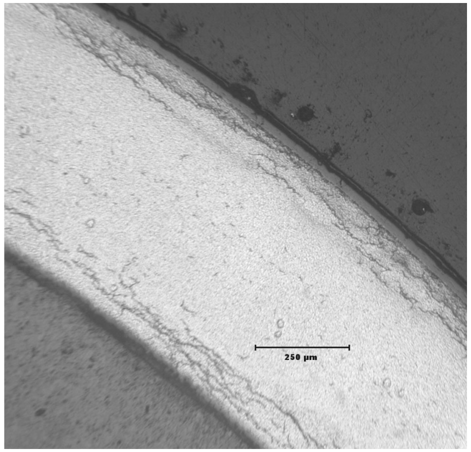
- **Radial hydrides, as little as 40 wppm, can significantly degrade cladding's mechanical properties.** **(Marshall)**
- **Stress, temperature, cool-down rate, microstructure, H content, etc., all play important roles.** **(Einziger)**
  - **Threshold hoop stress for 400°C is ˜ 100 MPa.**



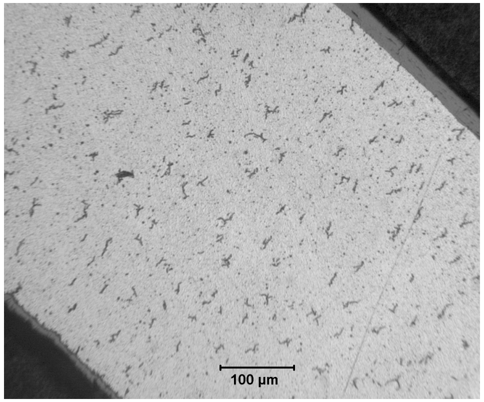
Siegmann (YMP)

Hydride Reorientation – Creep Tests

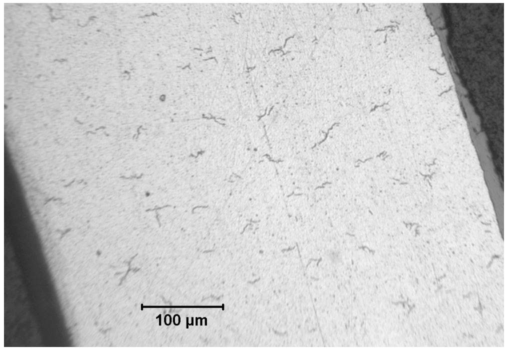
- Two Surry creep tests were intentionally shut down with samples under pressure: C3 (360°C, 220 MPa, 3760 h, 0.22% ϵ) and C6 (380°C, 190 MPa, 2400 h, 0.35% ϵ).
- Both samples survived the shutdown.
- Hydrides redistributed. Some now in radial direction, but no long-range linkage



Pretest



Posttest C3



Posttest C6

Hydride Reorientation – Creep Tests

CEA (Cappelaere et al, ICEM 2001) – 470°C

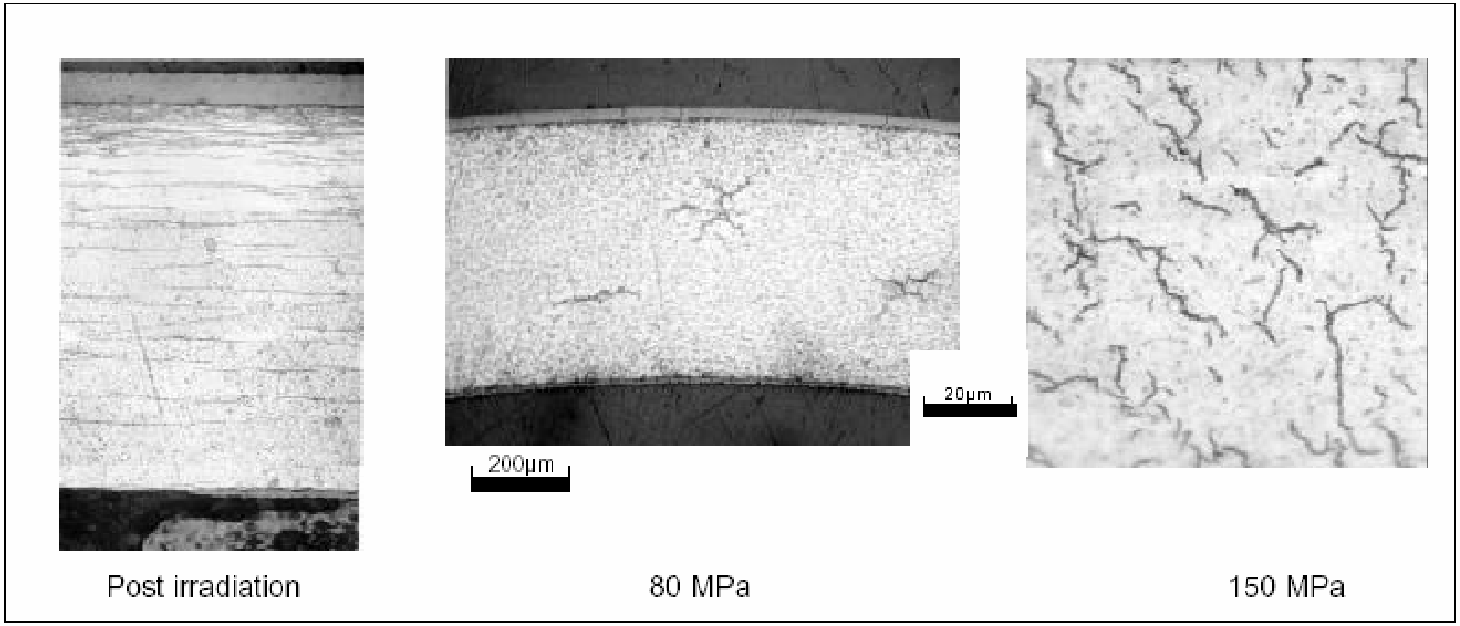
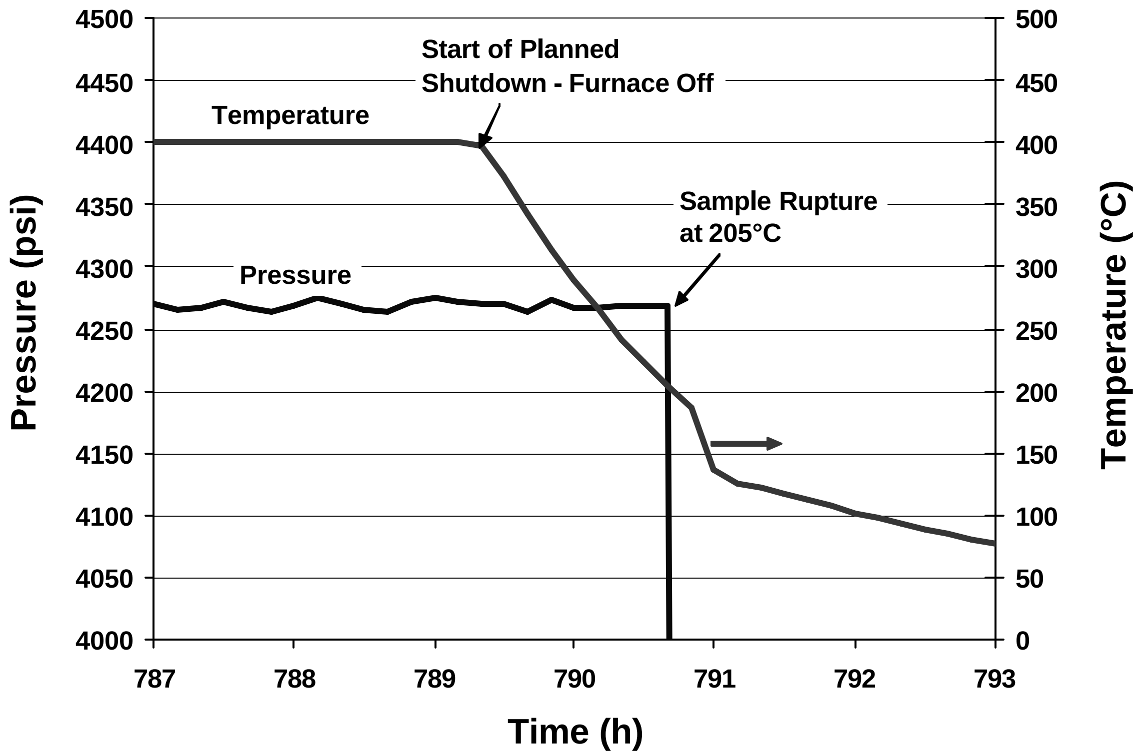


Figure 6 : Impact of creep tests on hydrides morphology, distribution and orientation

Hydride Reorientation – Creep Tests

- **Shutdown-under-pressure was repeated for one of the high-burnup H. B. Robinson creep sample: C15 (400°C, 190 MPa hoop, 2440 h, ~ 3.5% e).**

- **The sample ruptured during cool-down at 205°C.**
- **Cause being investigated**
  - **Hydride Reorientation?**



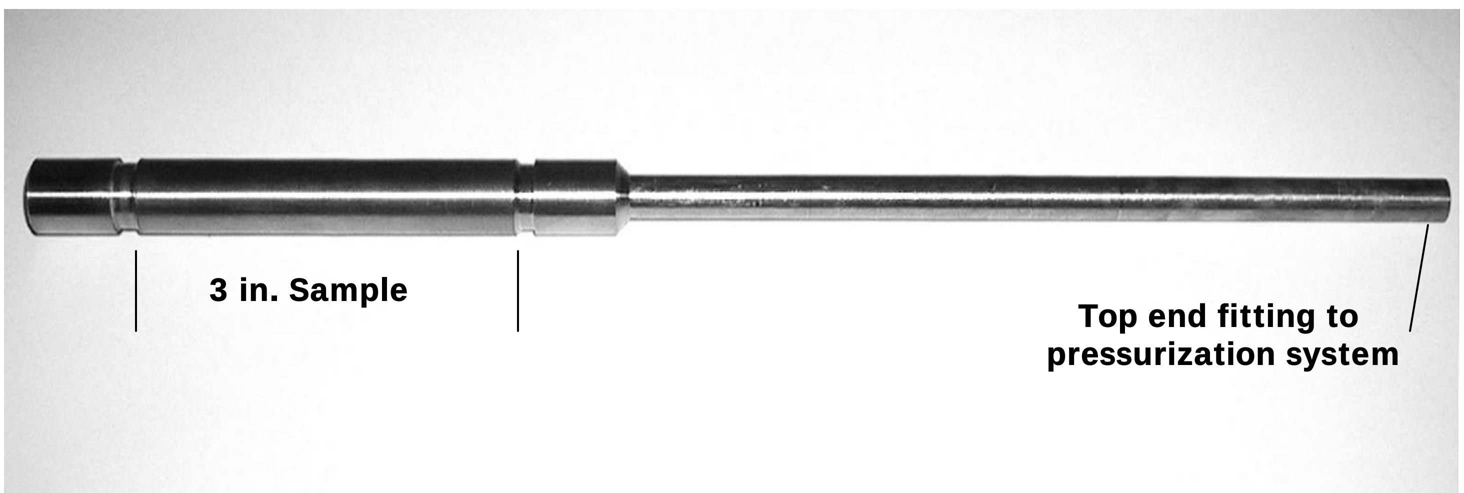
Cladding Thermal Creep

Thermal Creep Tests

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

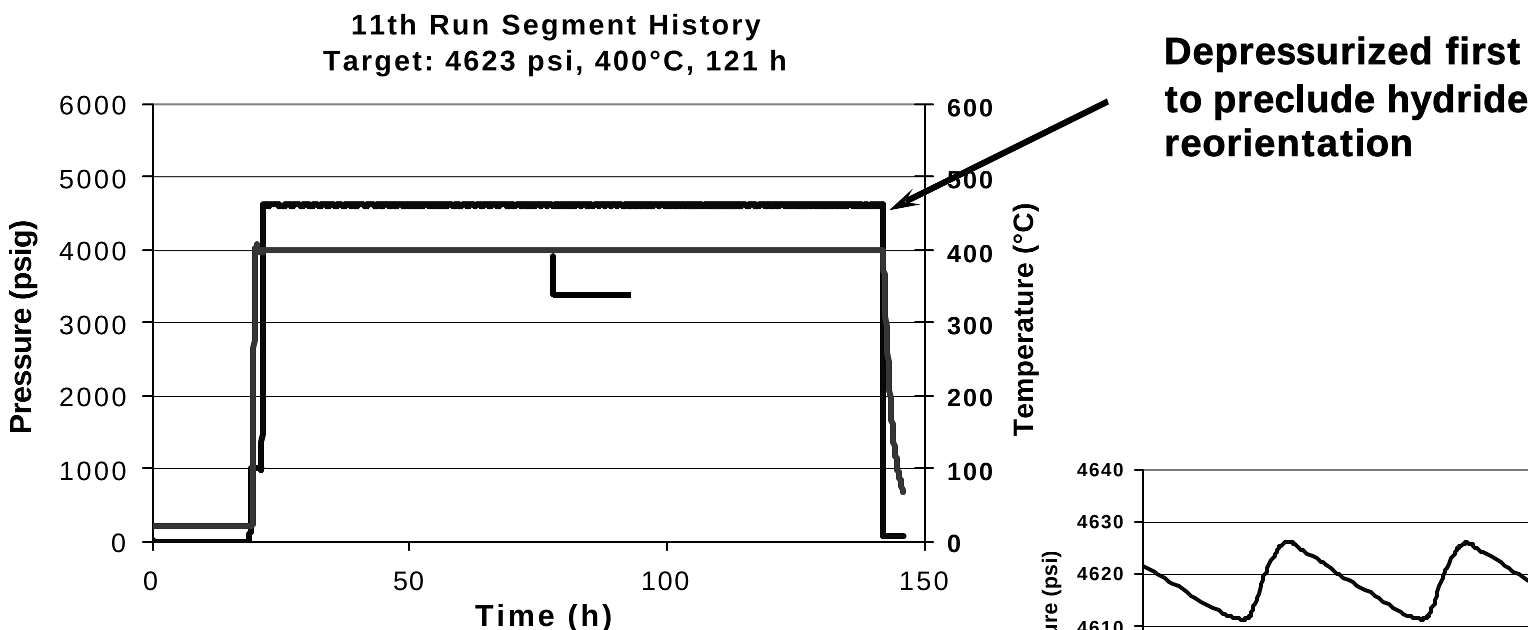
Thermal Creep Tests

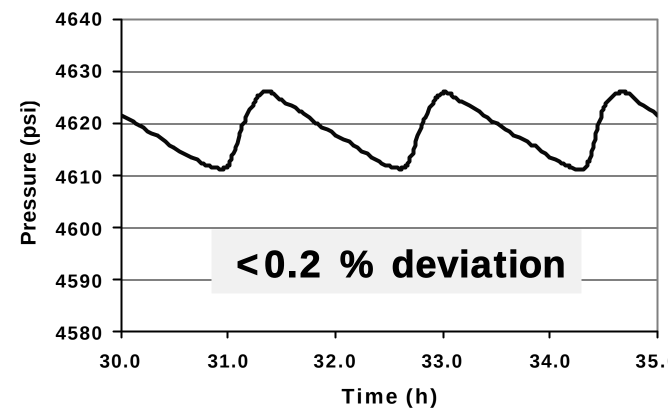
- **Creep Test Specimen**
  - **76-mm-long segments of irradiated cladding.**
  - **Welded end fittings.**
  - **Pressure actively regulated.**



Thermal Creep Tests –Typical Performance

- **Good pressure and temperature control**
- **Periodic shutdowns for laser profilometry**

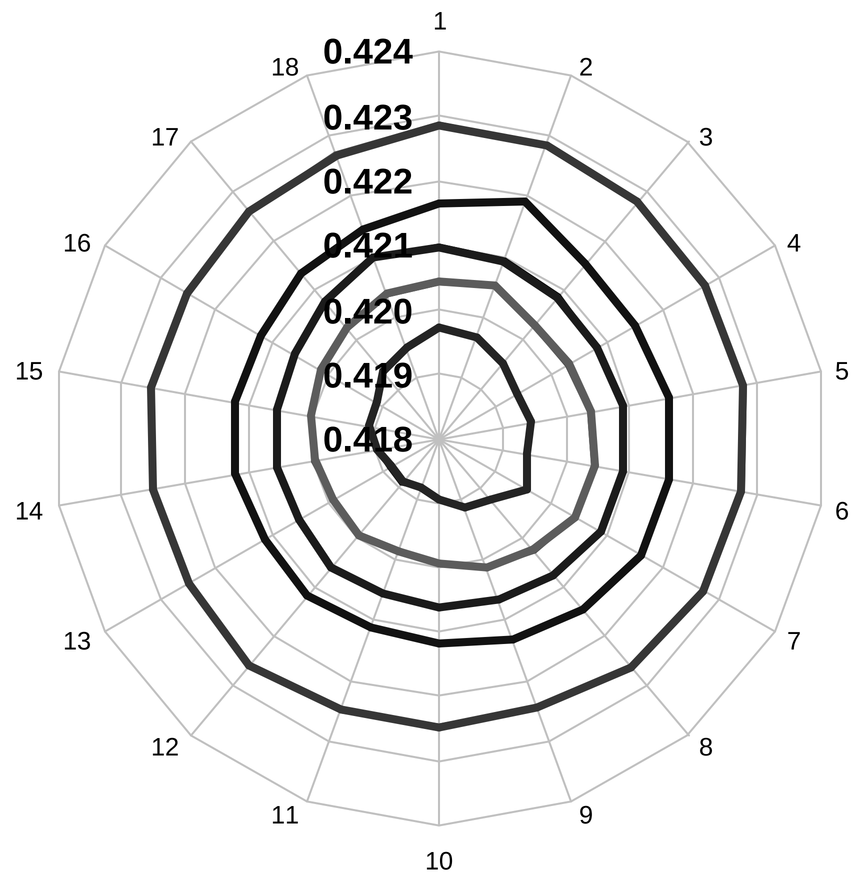




Thermal Creep Tests

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 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

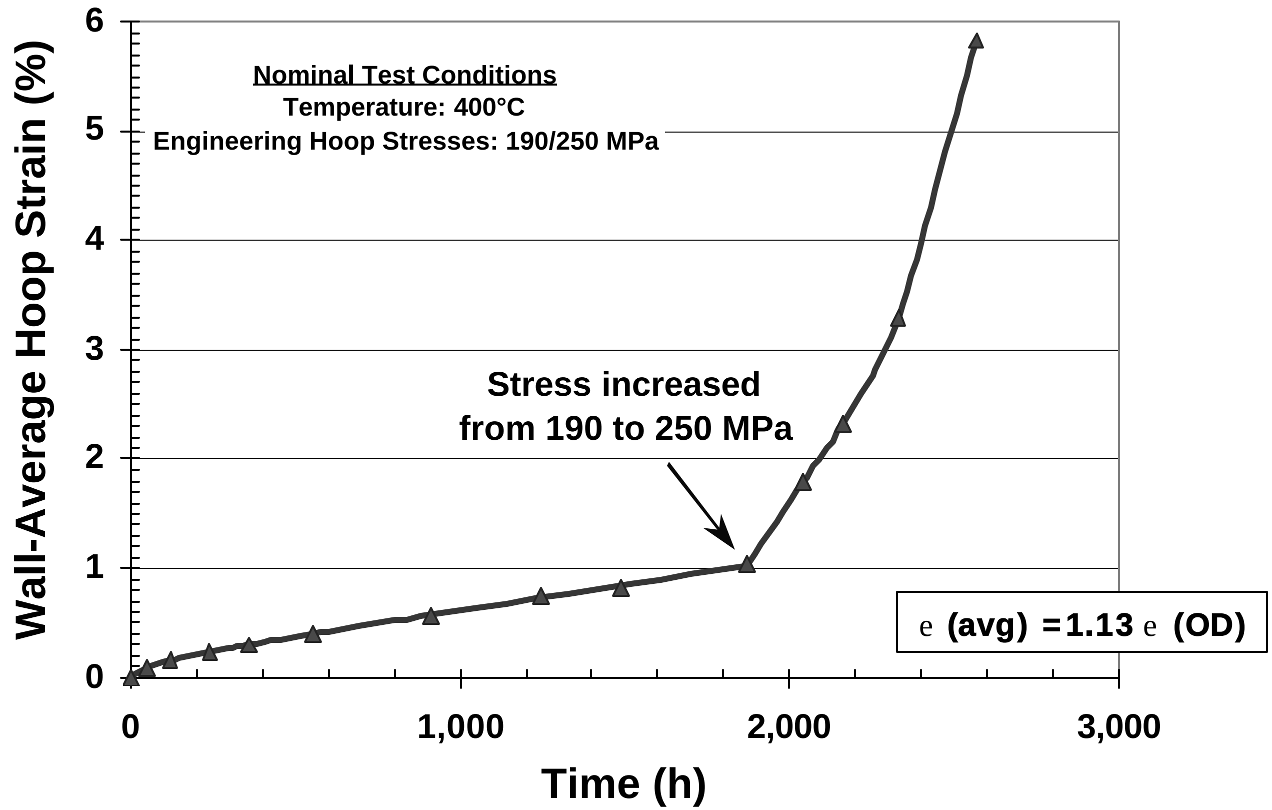
(1) DE: Destructive examination, for hydride orientation determination. For this, the final shutdown was done with sample pressurized.

(2) Incremental hours

(3) On-going

Thermal Creep Tests – Surry C9

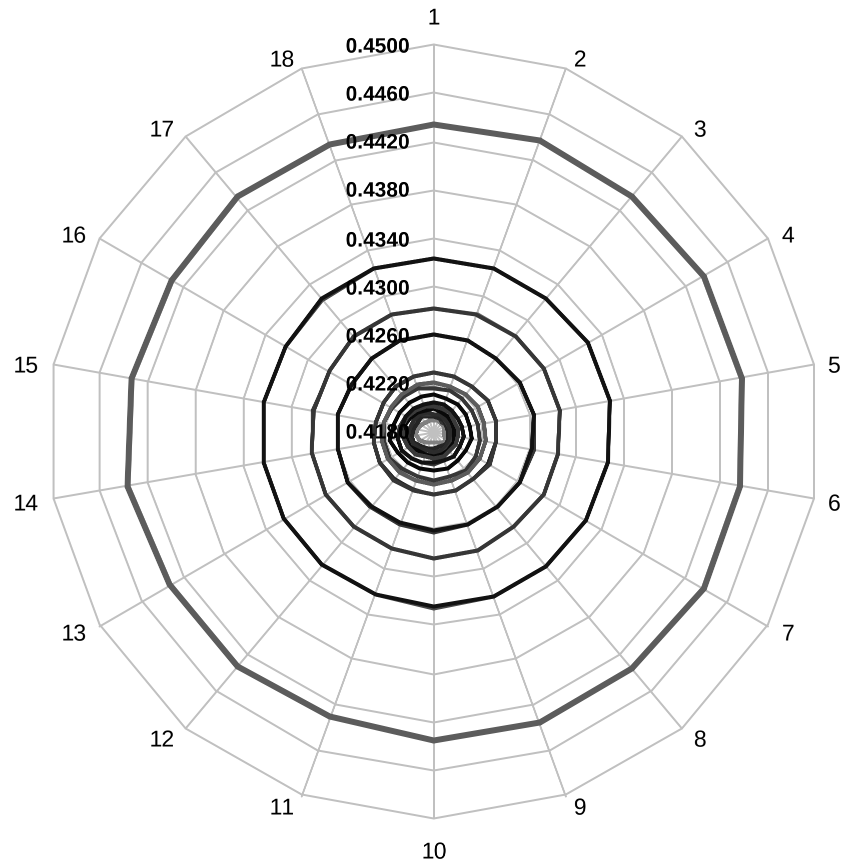
- 400°C, 190/250 MPa engineering hoop stress, 2566 h
- 5.8% average hoop strain, no rupture



Thermal Creep Tests – Surry C9

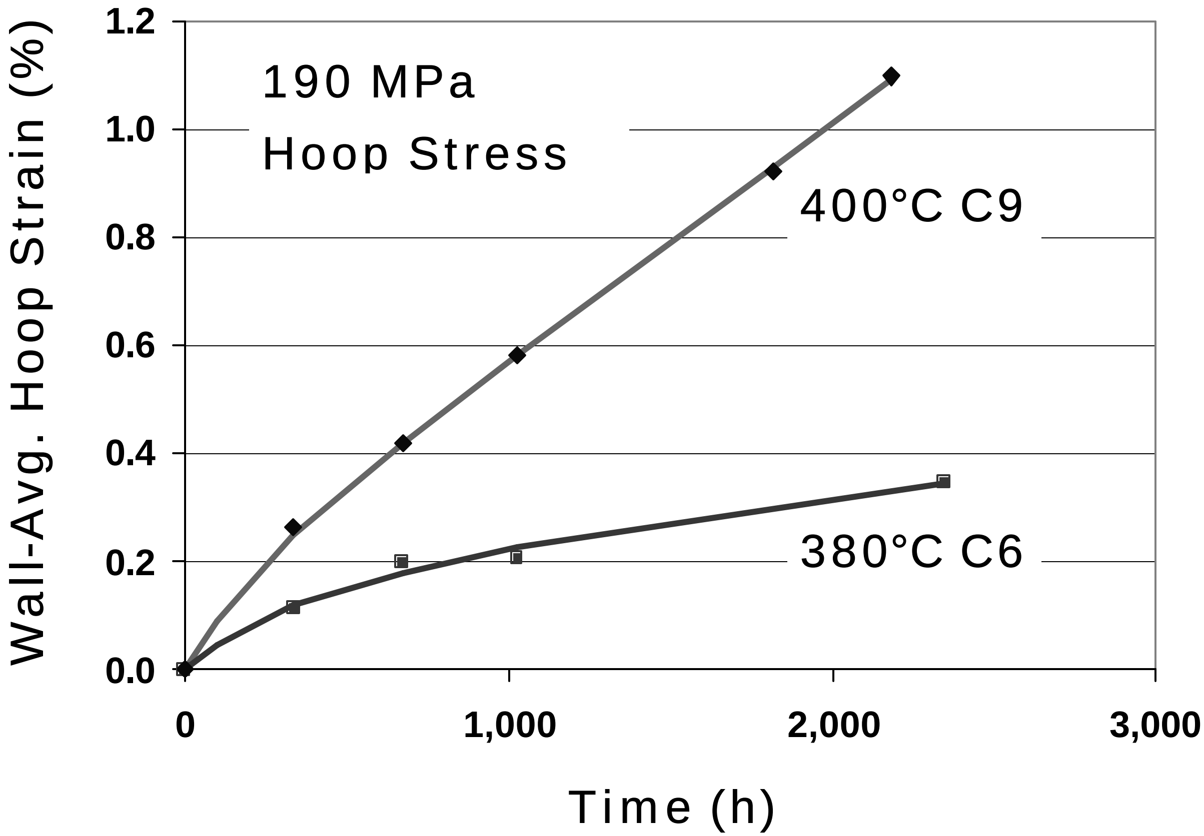
- **Deformation uniform even at high strain (5.8 %)**
- **No signs of imminent failure**
- **Additional creep ductility likely**

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



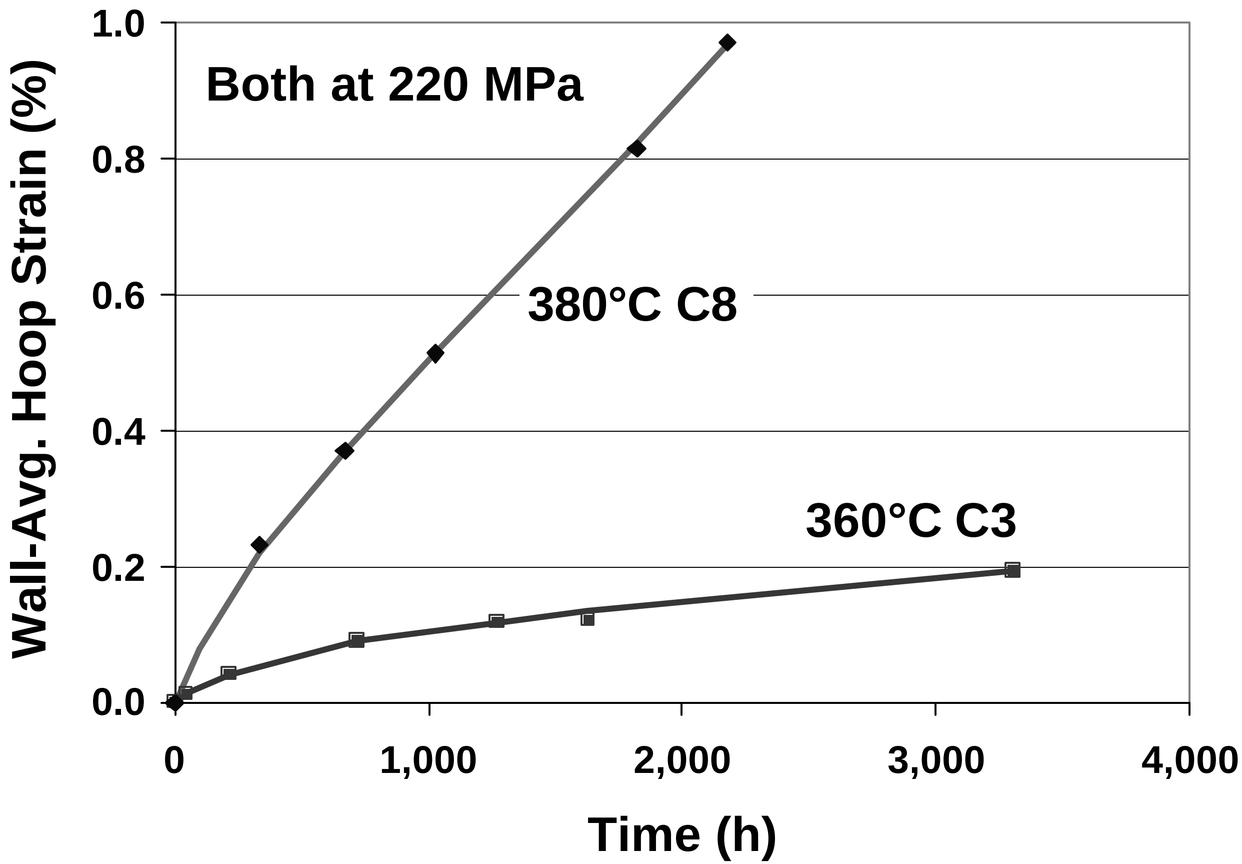
Thermal Creep of Post-Storage Surry Cladding

- **Temperature Dependency**



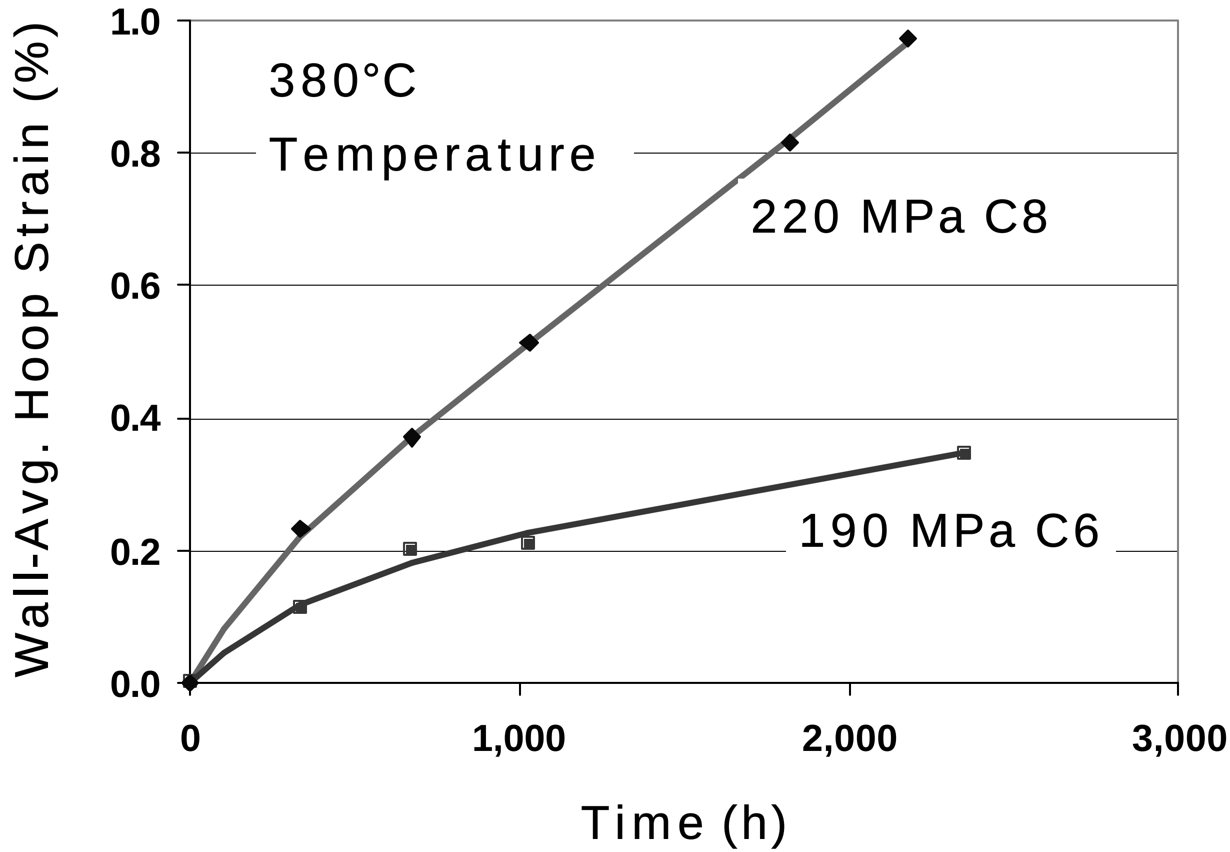
Thermal Creep of Post-Storage Surry Cladding

- **Temperature Dependency**



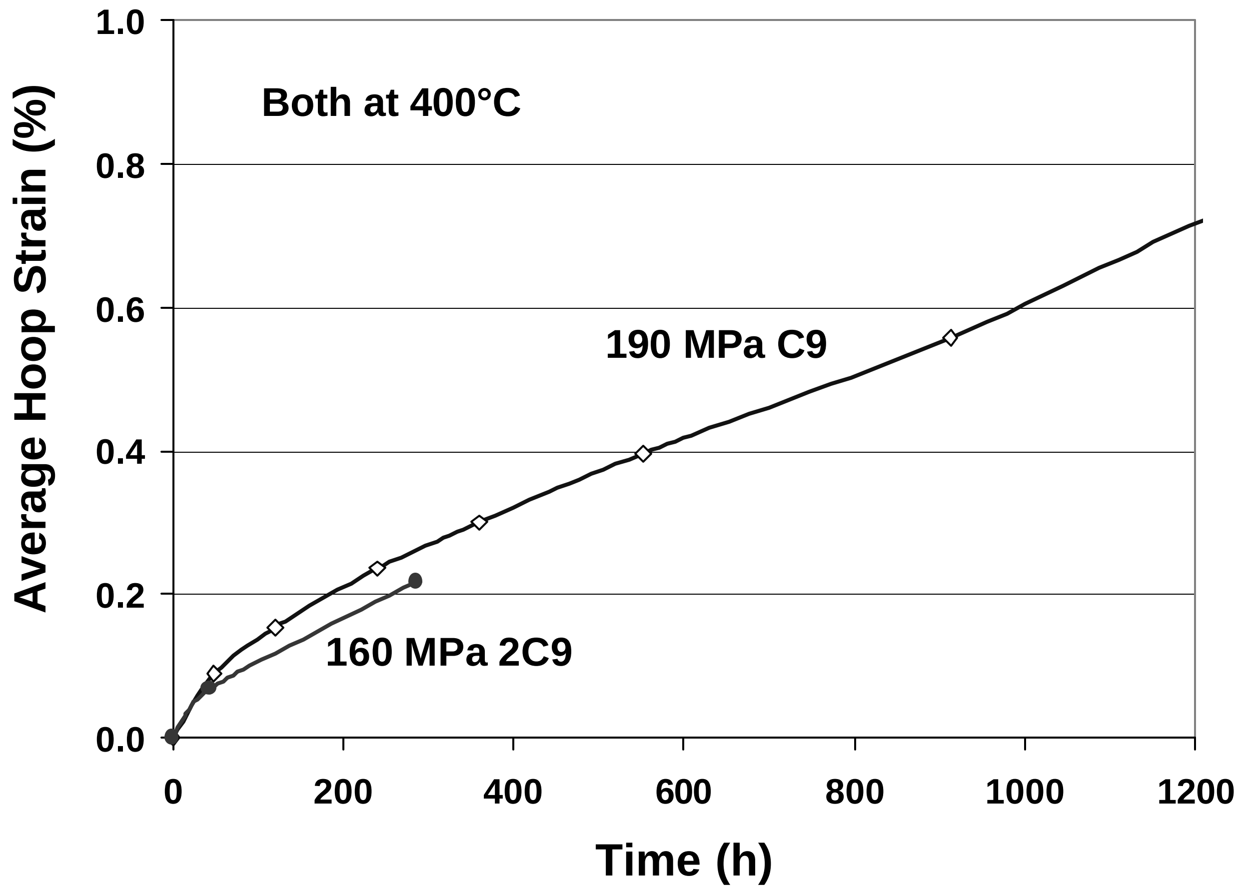
Thermal Creep of Post-Storage Surry Cladding

- **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 $\Delta\varepsilon / \Delta t$[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

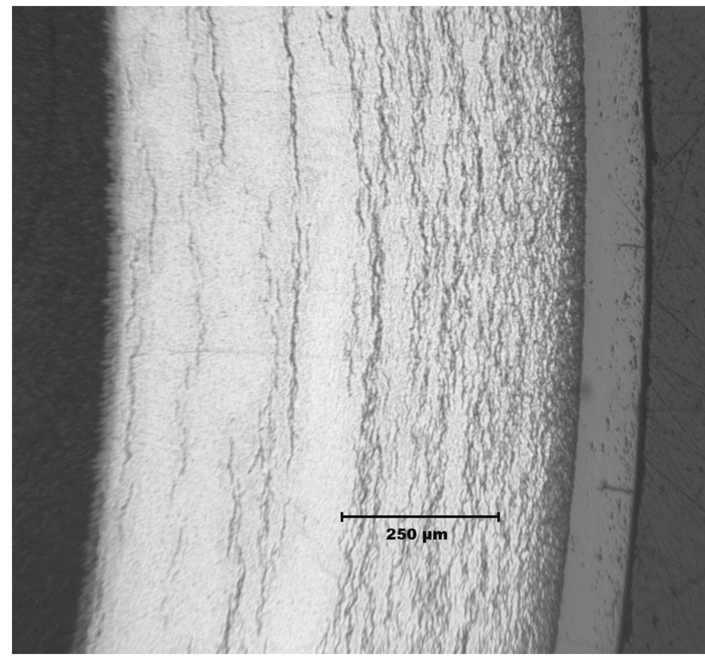
Robinson Test Matrix

		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

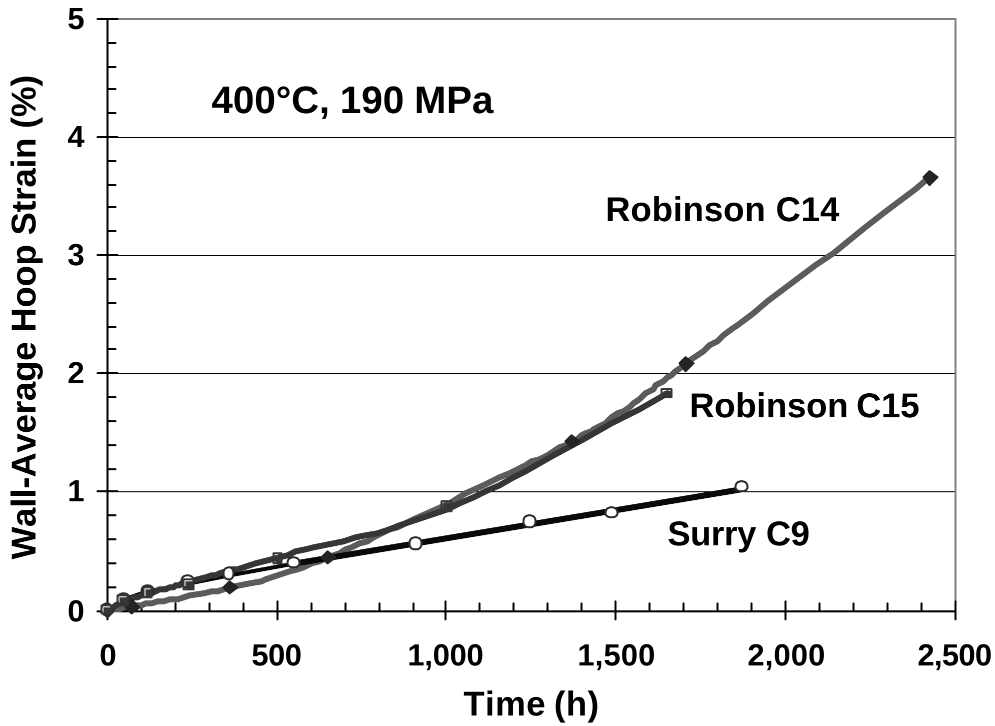
- **Significant corrosion and H uptake from extended operation to high burnup**
  - *~100 μm max. oxide*
  - *~800 wppm max. hydrogen*
  - *Circumferentially-oriented hydrides*

- **What are the effects of increased hydrogen and radiation damage on creep?**



Thermal Creep Tests – H. B. Robinson

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

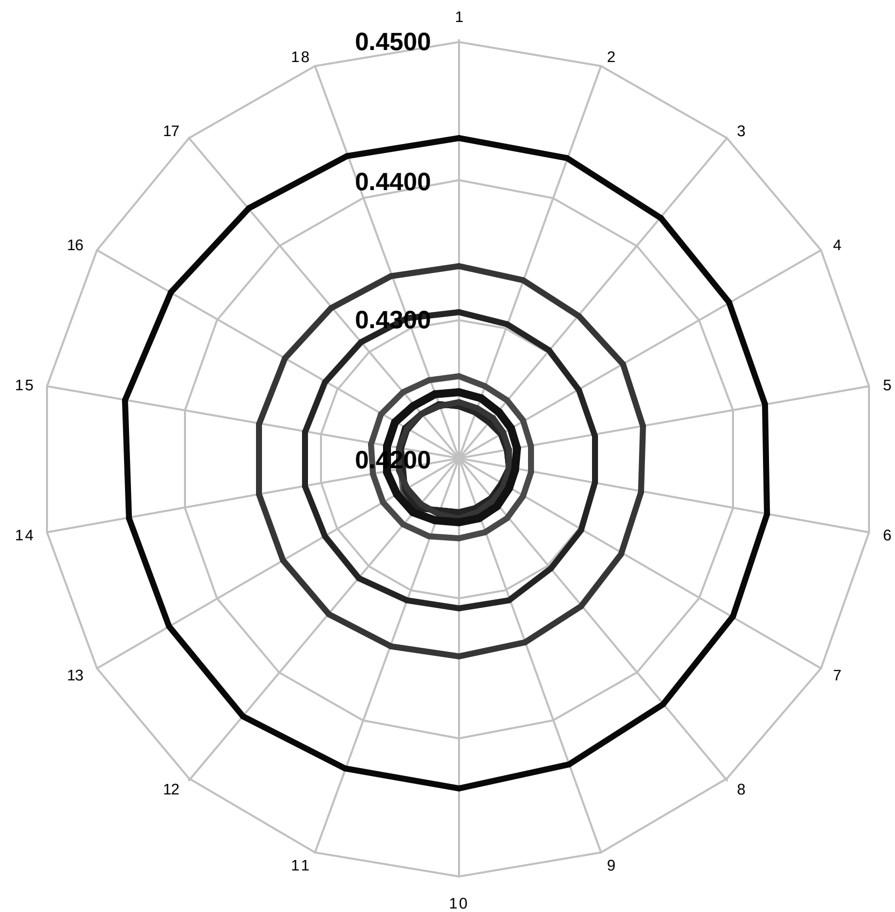


Thermal Creep Tests – H. B. Robinson

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

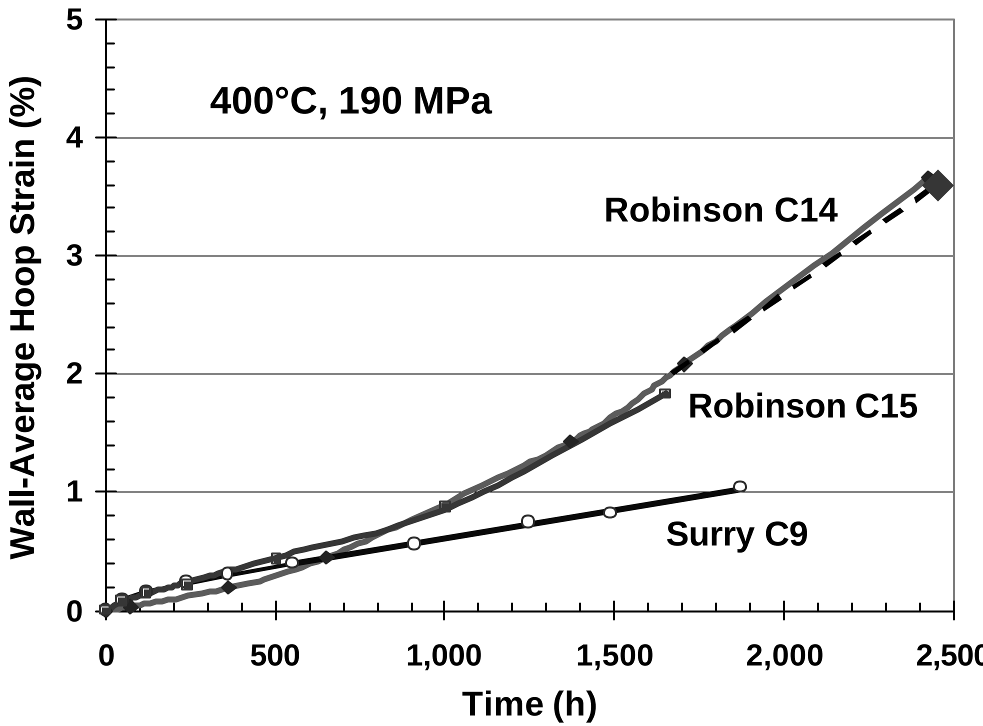
- **Deformation still azimuthally uniform at end of test**
- **Additional creep life likely**

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



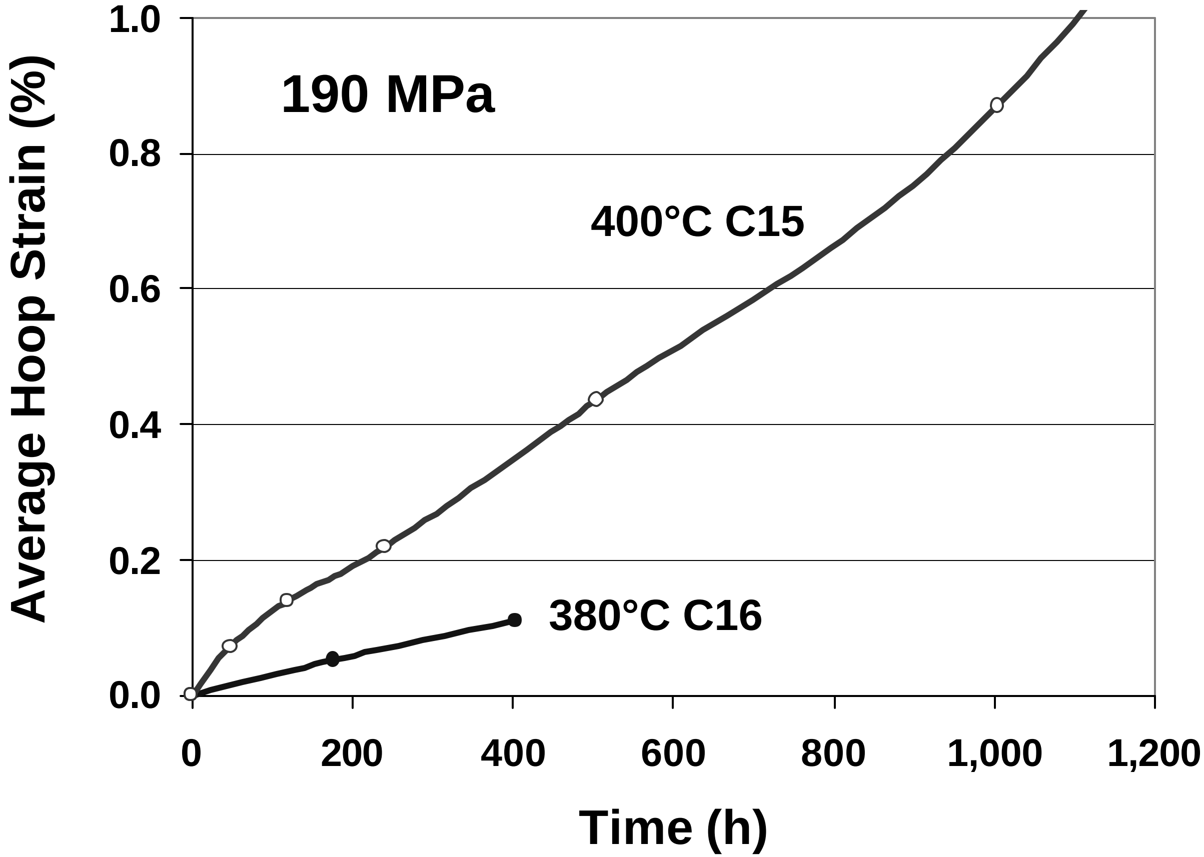
Thermal Creep Tests – H. B. Robinson

- **C15 developed a rupture during the final shutdown, which involved cooling from 400°C under full pressure to yield hydride reorientation data.**
- **Note, 190 MPa is a significant overtest for PWR rods.**



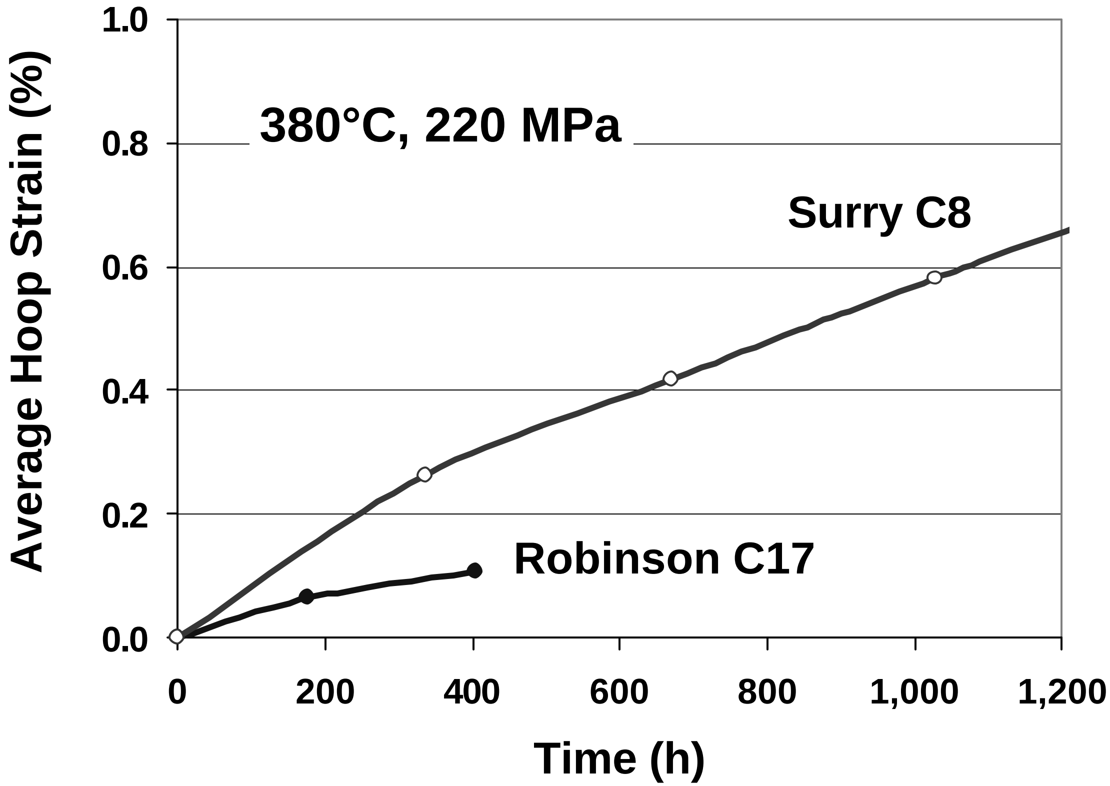
Thermal Creep Tests – H. B. Robinson

- **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.**
  - **Less recovery at the lower temperature?**



Summary and Conclusions

- **15-y storage (with extensive thermal benchmark tests) caused no discernible degradation of the Surry rods.**
  - **Data useful for dry-cask license extension.**
- **Significant residual creep ductility has been demonstrated for the post-storage Surry cladding.**
  - **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.**

Summary and Conclusions (cont'd)

- **Robinson cladding annealing tests showed substantial fraction of radiation hardening can be annealed out at 420-500°C from hours to days.**
- **Early data show high-burnup Robinson cladding possesses good creep ductility and has a creep rate comparable to that of lower-burnup Surry at 400°C.**
  - **Because radiation damage has saturated? Annealing/recovering during tests? Insignificant H effect as long as there is no reorientation?**
  - **More tests are underway.**

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 happen in real PWR fuel rods? (C15 with full pressure was a significant over-test.)**
- **Hydride reorientation may be a crucial issue for dry-cask storage and transportation, as it can affect cladding integrity. Efforts underway include**
  - **Annealing tests with sealed pressurized samples and with controlled cooling rates.**
  - **Post-creep characterization and mechanical tests.**