An Integrated Approach for Closing the Gaps Associated with Spent Nuclear Fuel Cladding Hydrides

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- Spent Fuel and Waste Science and Technology (FSWST; formerly known as the Used Fuel Disposition program) storage and transportation R&D program priorities
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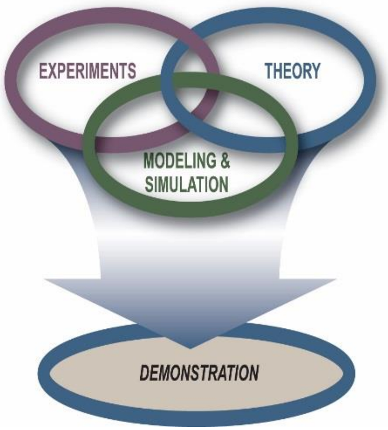
SFWST ST R&D Program Objectives

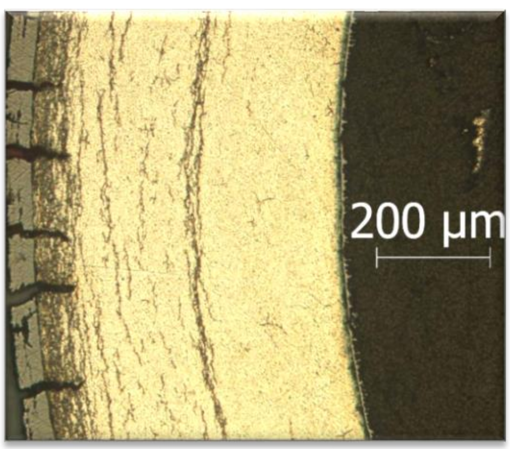
Storage and Transportation Program Objectives

Support the development of the technical bases:

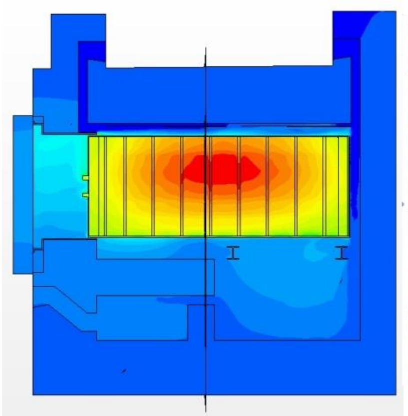
- to demonstrate used fuel integrity for extended storage periods
- for fuel retrievability and transportation after long term storage
- for transportation of high burnup fuel



This talk will focus on the development of the technical basis associated with fuel cladding/hydride issues that have been identified as a high priority technical gap (2011, 2012, 2014 DOE gap analysis reports)



UFD Telecon, April 12, 2012
Billone, Liu; Argonne



UFD Telecon, April 12, 2012
Wagner, Adkins; ORNL

'Jones 2010.ppt',
Calvert Cliffs Dry Fuel Storage and Industry Lessons Learned

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U.S. High Burnup Fuel Inventory: What level of burnups are we discharging to dry storage?

	Number of Assemblies		Average burnup (GWd/MTU)	
Year	BWR	PWR	BWR	PWR
2000	4603	3122	**38.3**	**44.9**
2001	3617	2896	**40.1**	**45.5**
2002	4148	3765	**40.2**	**46.0**
2003	4584	3585	**39.5**	**46.4**
2004	4431	2669	**42.8**	**46.9**
2005	4075	3704	**42.8**	**46.6**
2006	3995	3516	**43.1**	**46.9**
2007	4574	2782	**43.3**	**46.9**
2008	4480	3550	**43.1**	**47.2**
2009	4395	3677	**45.1**	**46.5**
2010	4617	2856	**44.3**	**46.8**
2011	4105	3663	**45.1**	**46.6**
2012	4476	3759	**45.0**	**44.5**
2013	3246	1534	**44.1**	**45.4**

GC-859 Reported Average Assembly-Average Discharge Burnup

- **High burnup defined as > 45 GWd/MTU**
- **Over the past 15 yrs:**
  - >70% of discharged PWR SNF is < 50 GWd/MTU
  - Max discharge burnups do not appear to be increasing

  [EPRI Fuel Reliability Database (FRED)]
- **Limits to much higher burnup:**
  - 5 w/o ^{235}U enrichment
  - Cycle length (18, 24 months in US)
- **Moving from low burnup to high burnup is a continuum that needs to be put in proper context relative to:**
  - Total hydrogen content in clad
  - Maximum fuel temperatures
  - Internal rod plenum pressures

Integrated Approach to Closing Cladding Gaps

- **Thermal Analysis**
  - What are the ***realistic*** temperatures that cladding experiences during drying and extended storage?
- **Hoop Stress**
  - What is the range and distribution of end of life rod internal pressures, accounting for He and pellet swelling/bonding, and clad thicknesses and diameters?
- **Ring Compression Tests**
  - Identify the ductile to brittle transition temperatures for cladding under ***realistic*** temperatures and hoop stress
- **Cyclic Integrated Reversible Bending Fatigue Test**
  - Identify the role of fuel/clad and pellet/pellet bonding, the number of cycles as a function of applied stress to failure
- **External Stresses**
  - Identify ***realistic*** stresses to cladding during extended storage and normal conditions of transport
- **Confirm post-drying materials properties**

Thermal Analysis:

Cladding temperatures are limited to < 400° C during drying and in dry storage; NRC ISG-11.3

- **Develop realistic thermal profiles**
  - Remove conservative assumptions in thermal models
  - Use actual and realistic times for drying and transfer times
  - Actual, not design basis, decay heat loadings
  - Remove conservatisms in assembly decay heat calculations
  - Actual, not conservative, ambient conditions (assumed 100°F average)

- **Realistic temperatures expected to be well below the 400°C regulatory guidance**
  - Used in numerous calculations for creep, He release, pressure calculations, etc.

Thermal analyses of DOE/EPRI dry storage demo cask TN-32B with HBU PWR fuel

	270	284	279	267	
267	297	312	312	295	268
275	311	300	315	312	283
283	311	307	301	313	284
271	291	312	312	296	272
	273	284	281	268	

Peak Cladding Temperature (°C) with 36.8 kW heat load

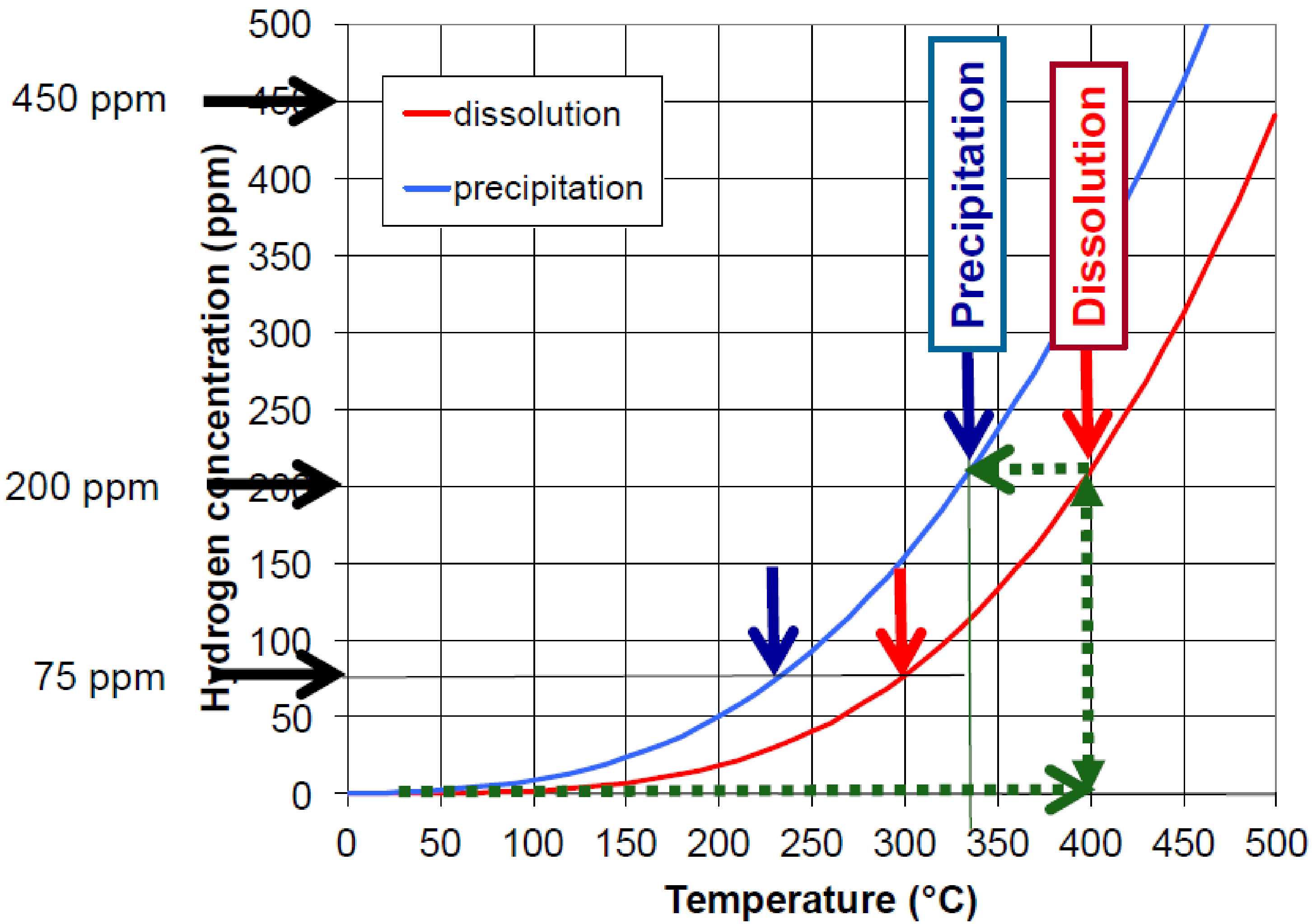
	238	247	244	234	
234	257	269	268	256	235
241	268	255	271	269	246
247	268	268	260	269	247
238	255	269	269	257	238
	239	248	246	235	

Peak Cladding Temperature (°C) with 30.6 kW heat load (same fuel)

Thermal Analysis:

Temperature Effect on Hydride Dissolution:

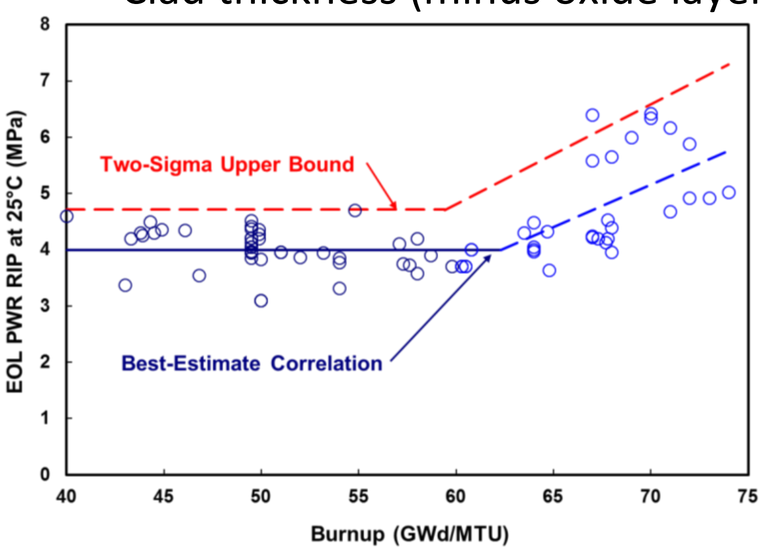
During the drying phase, less hydrogen will dissolve and then potentially reprecipitate back as a radial hydride

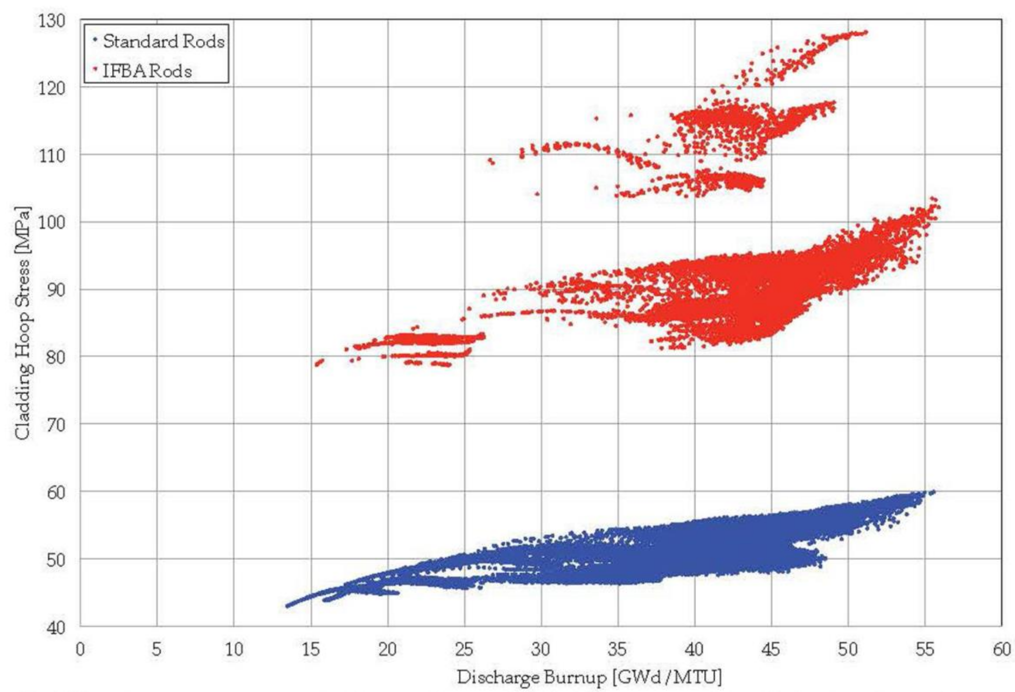


Hoop Stress:

FRAPCON analyses:
Lower maximum cladding temperatures result in lower hoop stresses that, in turn, reduces precipitation of radial hydrides

- **Hoop stress is a function of**
  - End of Life Rod Internal Pressure
    - Initial He fill pressure
    - Fission gas release
    - Temperature
    - Void volume
      - Creep down/swelling
  - Clad inner diameter
  - Clad thickness (minus oxide layer)





FRAPCON predictions for Watts Bar Unit 1 rods discharged during Cycles 1-12 assuming 400°C peak clad temperature

Ring Compression Tests (RCT):

RCT Results on HBU ZIRLO® provide indication of ductility as a function of temperature and H content

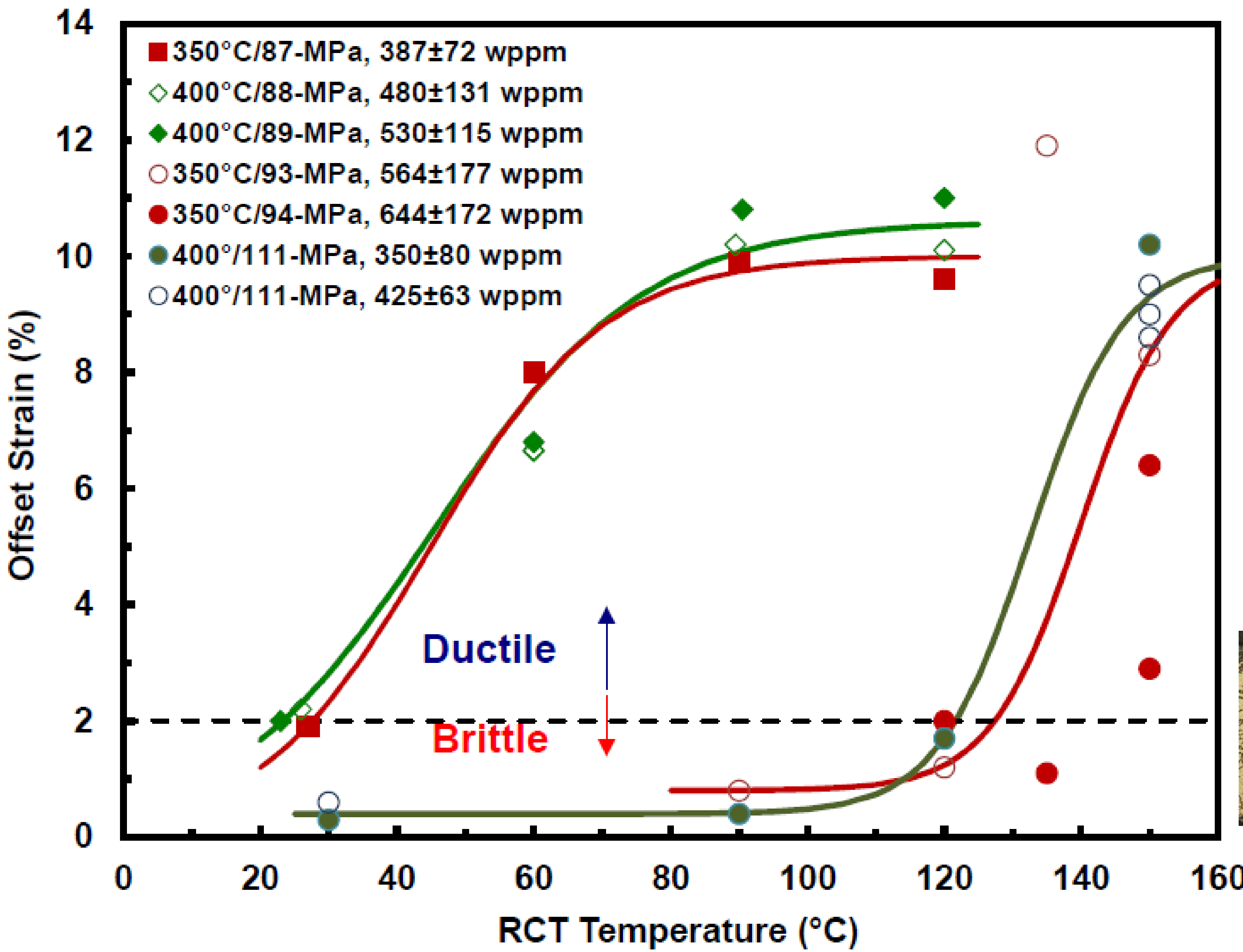
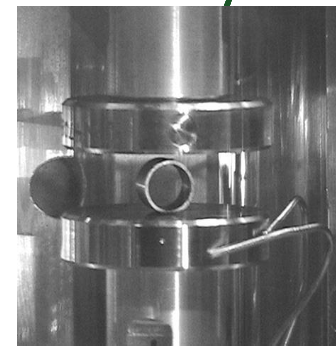
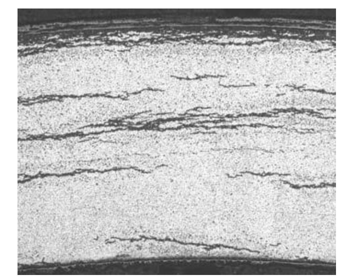


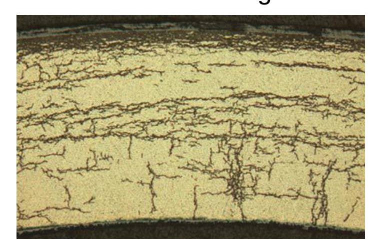
Figure 25: Summary of ductility data for HBU ZIRLO™ following RHT at 400°C and 350°C PCTs.



Picture from Billone, FCRD-USED-2012-000039



As-irradiated HBU cladding



HBU cladding After cooling from 400°C

Pictures from Billone, NWTRB meeting, Feb 17, 2016

Ring Compression Tests:

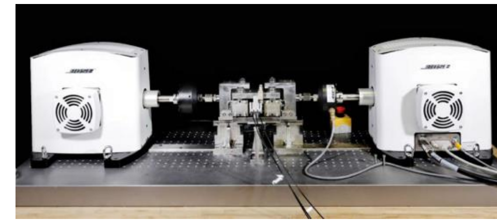
Factors to consider

- **Need to be very careful when drawing conclusions based on limited data**
- **Especially when many samples came from lead test assemblies or other "anomalous" sources that do not have typical total hydrogen content**
  - Could be very applicable to European reactors with higher duty and higher burnup
- **Threshold of reorientation vs threshold of change in DBTT or material properties/performance**
  - Caution when using literature values especially on unirradiated samples
- **Hydride reorientation a function of cladding type (chemistry?, grain orientation), total hydrogen content, hydride distribution (rim), RHT temperature, RHT/precipitation hoop stress**
- **Given these cautions, trends look very positive that DBTT will not be an issue for HBU spent fuel under representative storage and normal conditions of transport environments**

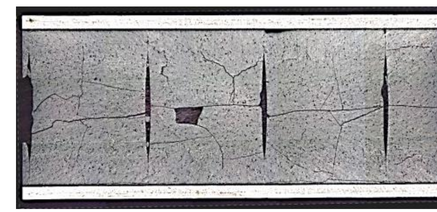
Cyclic Integrated Reversible-Bending Fatigue Tests (CIRFT):

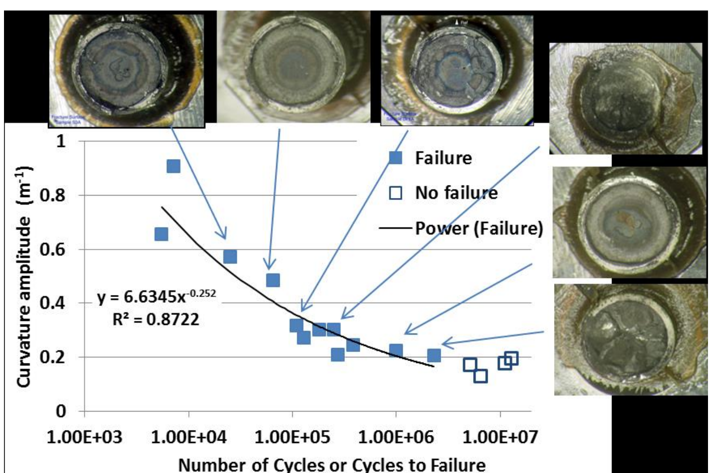
Provides stiffness/strength/fatigue data on HBU fuel

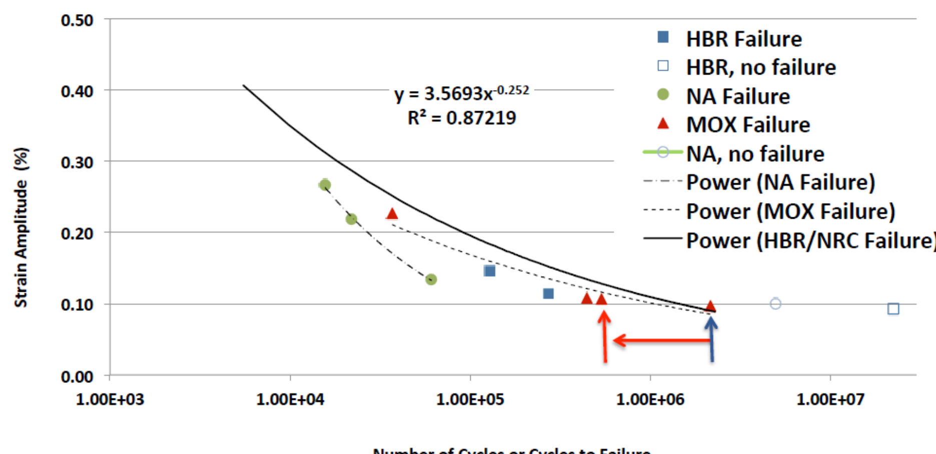
Mechanical testing on high burnup spent fuel:



- Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) at Oak Ridge National Laboratory
  - Determines the flexural stiffness of the cladding/fuel "system"
    - Stiffness provides a measure of fuel/cladding strength under mechanical loads
    - CIRFT testing provides valuable insights regarding
      - Pellet-Clad interactions
      - Pellet-Pellet interactions
    - CIRFT testing provides a good measure of fatigue strength



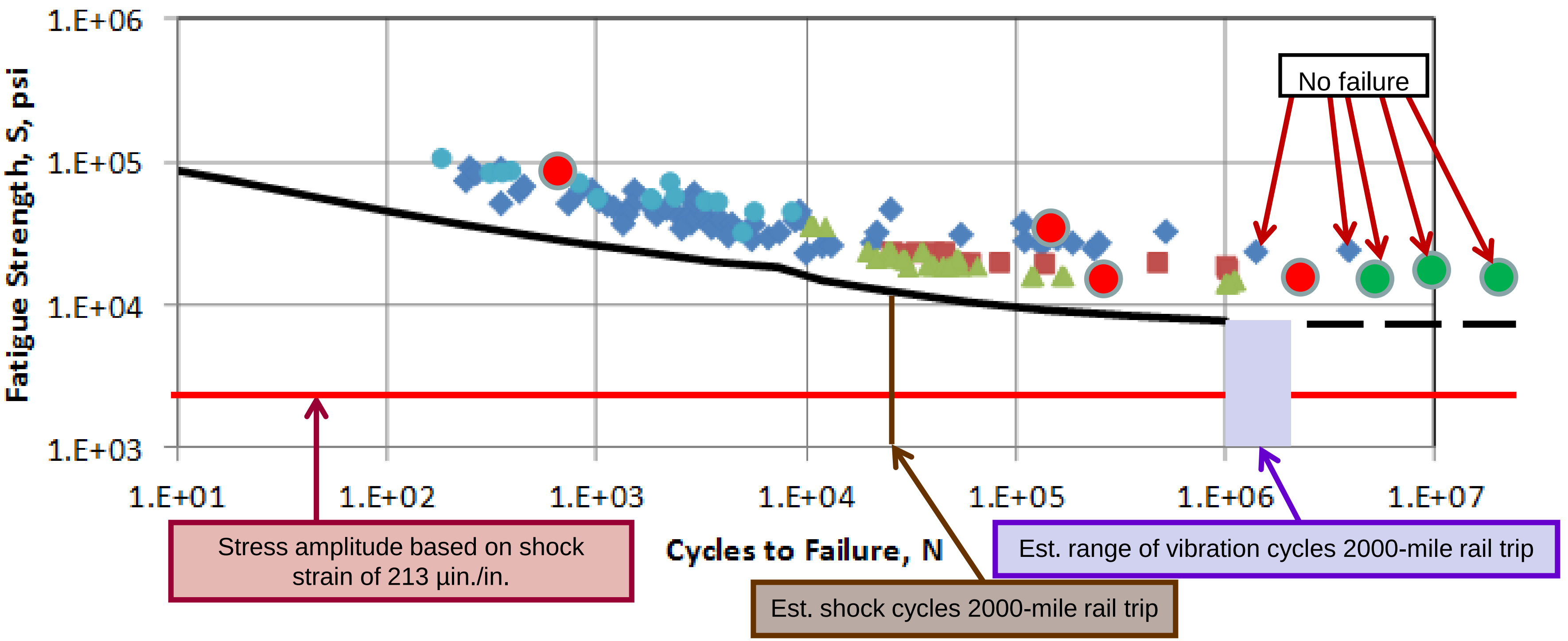




All figures and picture:
Wang, et al., "CIRFT Testing of High-Burnup Used Nuclear Fuel from PWRs and BWRs", U.S. NWTRB Meeting, Presentation, Feb 17, 2016, Oak Ridge National Laboratory

Cyclic Integrated Reversible-Bending Fatigue Tests (CIRFT):

Normal Conditions of Transport (NCT) vibrations unlikely to result in fatigue failure



Fatigue design curve▬▬ : O'Donnel and Langer, "Fatigue Design Basis for Zircaloy Components," Nucl. Sci. Eng. 20, 1, 1964. cited in NUREG-0800, Chapter 4)

Data plot courtesy of Ken Geelhood, PNNL. The large circles are ORNL HBR data.

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External Stresses:

Tests simulated normal conditions of transport loadings on the fuel rods to measure strains on fuel rods in a surrogate assembly

SNL Shaker 2013	Over-the-Road Truck 2014	DCL Multi-Axis Shaker 2015
 **Normal Conditions of Transport Truck**	 **Normal Conditions of Transport Truck**	 **Normal Conditions of Transport Truck and Rail**

All tests used a surrogate PWR assembly which was placed within a surrogate truck-cask basket.

The assembly and rods were instrumented with strain gauges and accelerometers.

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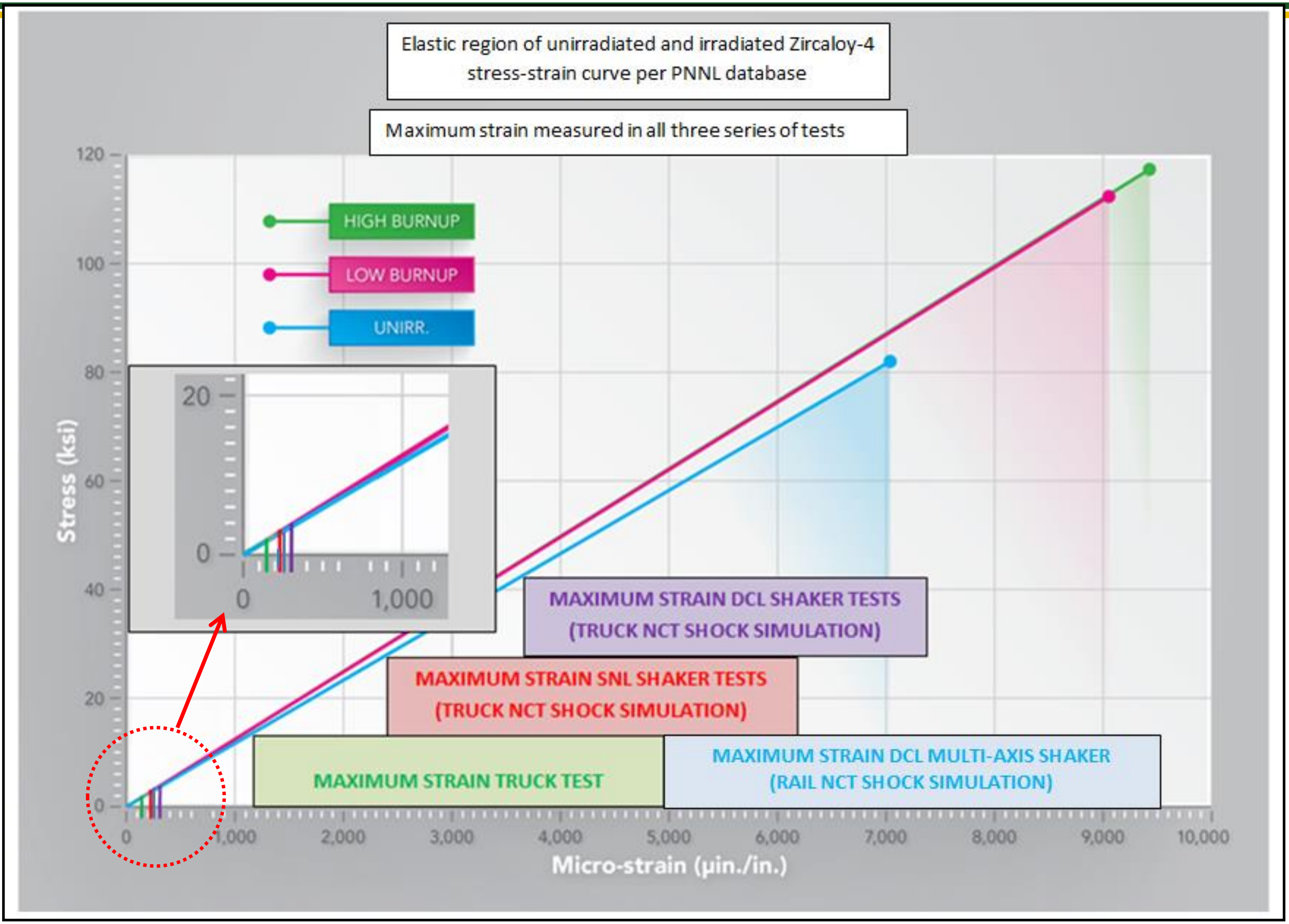
External Stresses:

Maximum measured NCT strains relative to elastic limits of Zircaloy



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Conclusions

- Hydride effects on spent fuel ductility appear to be minimal in the context of extended dry storage followed by normal conditions of transport
- This high priority technical gap, as identified by numerous gap reports, has been effectively addressed
- An up-dated gap report will be issued by the DOE in the spring of 2017, detailing this conclusion