SAND2016-3882C

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Closing the Technical Data Gap on High Burnup Spent Nuclear Fuel

ESCP Committee Meeting
May 2, 2016
Orlando, Florida

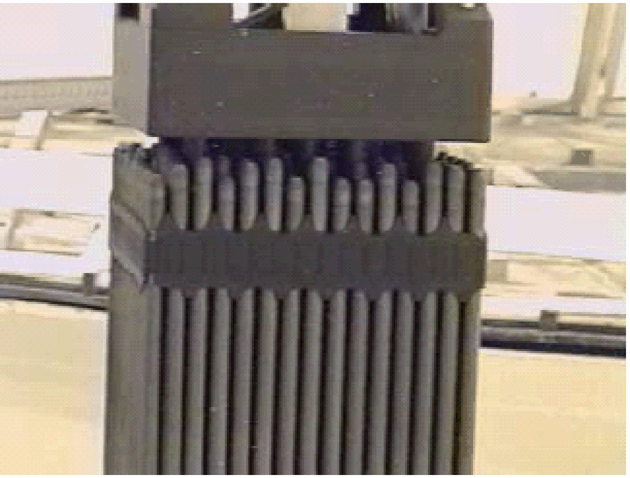
Ken Sorenson[1], Brady Hanson[2], Sylvia Saltzstein[1]
[1] Sandia National Laboratories
[2] Pacific Northwest National Laboratory

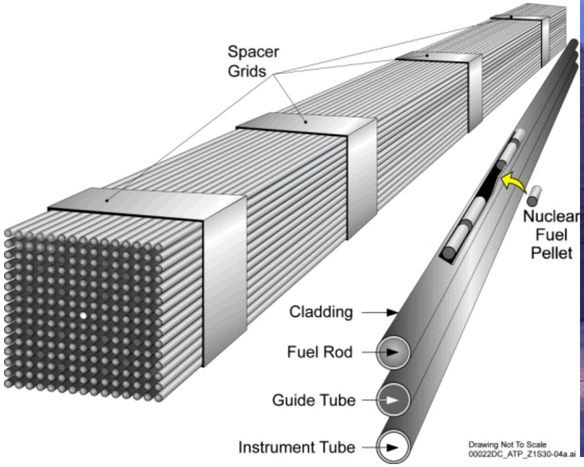
Ned Larson
U.S. Department of Energy – Office of Nuclear Energy

SAND2016-XXXX

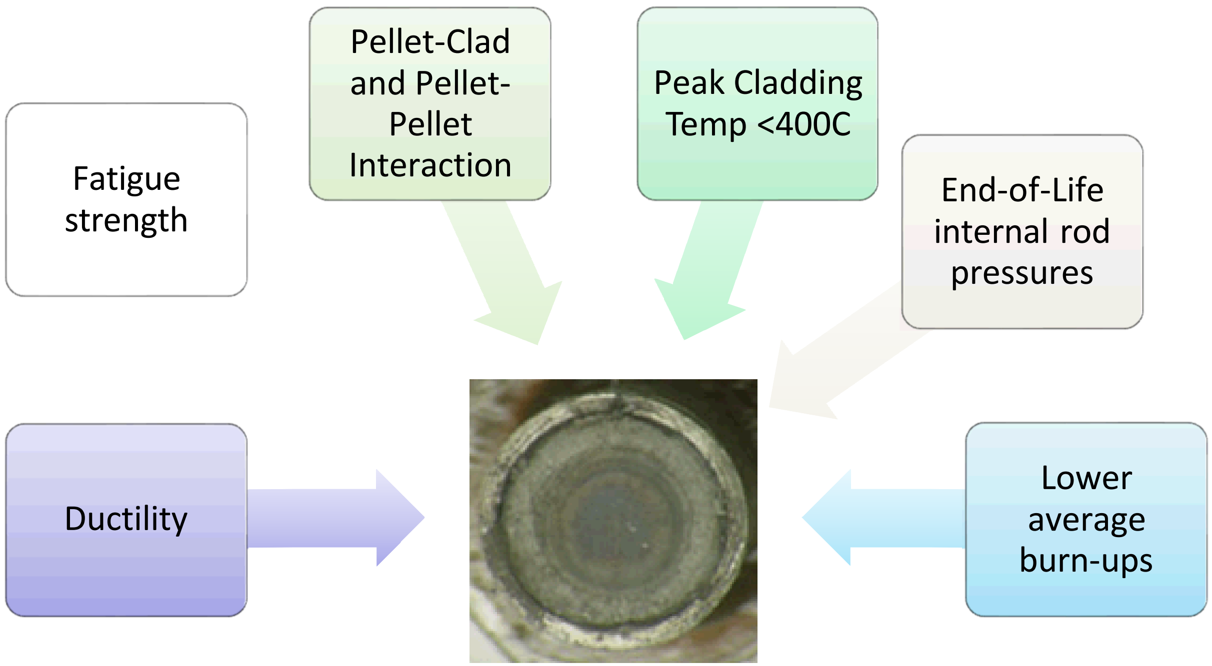
UFD Storage and Transportation R&D Objectives

- **Verify and enhance the technical bases for maintaining used fuel integrity and ensuring fuel retrievability during continued storage**
- **Develop the technical basis for transportation of high burnup fuel**





What we are learning indicates that spent fuel is more robust than was previously thought:



U.S. DEPARTMENT OF ENERGY

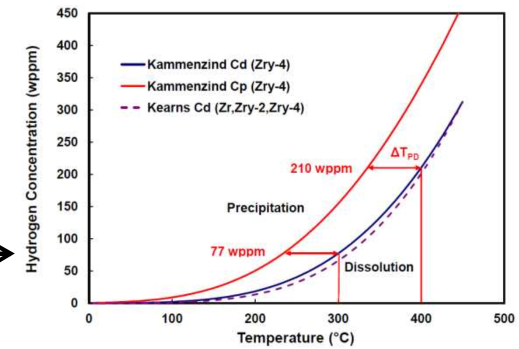
Nuclear Energy

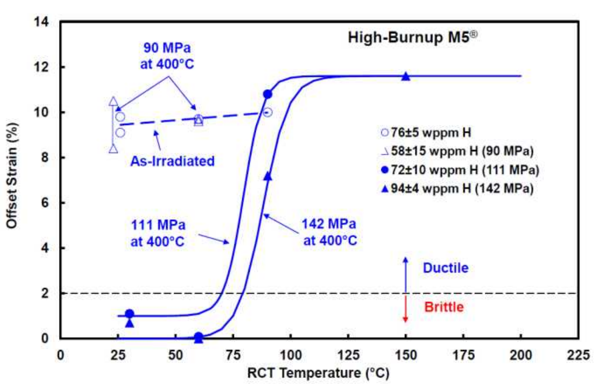
Closing the high burnup used fuel technical gap associated with the fuel cladding: Ductility

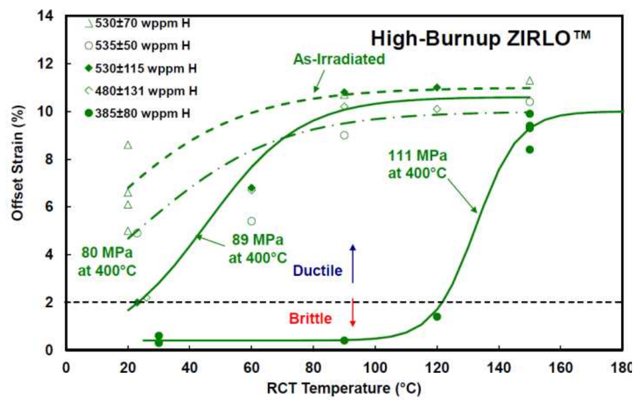
Mechanical testing on high burnup cladding:

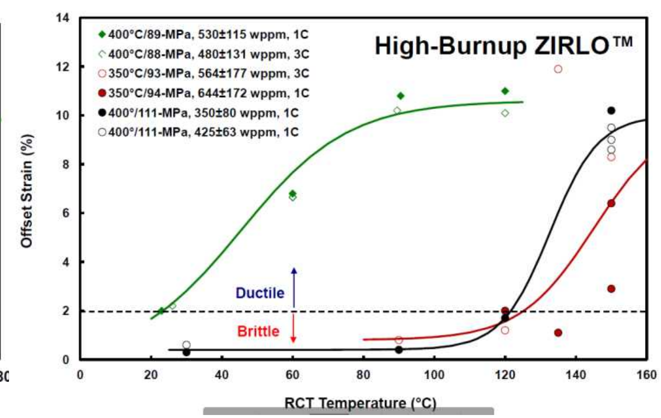
- Ring compression testing at Argonne National Laboratory
  - Determines Ductile-to-Brittle Transition Temperature (DBTT) of cladding, an indicator of material brittleness
    - Highly dependent on internal rod pressure
    - dependent on maximum temperatures seen during drying

→







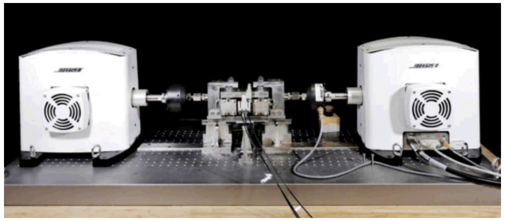


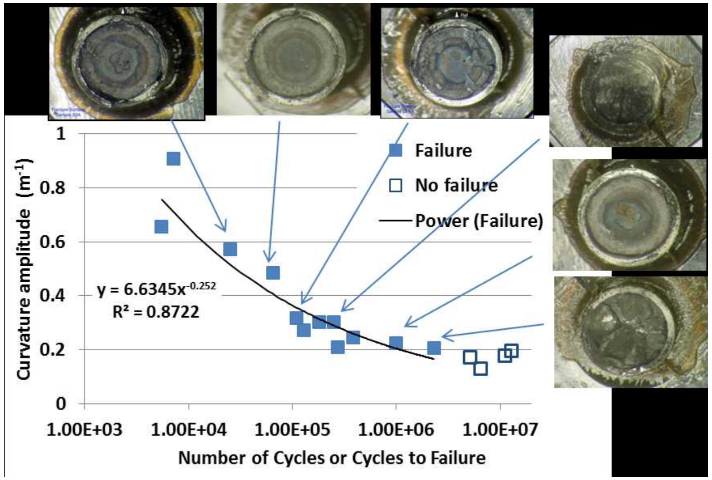
All figures:
Billone, "Update on Testing to Evaluate Radial Hydrides", U.S. NWTRB Meeting, Presentation, Feb 17, 2016, ANL

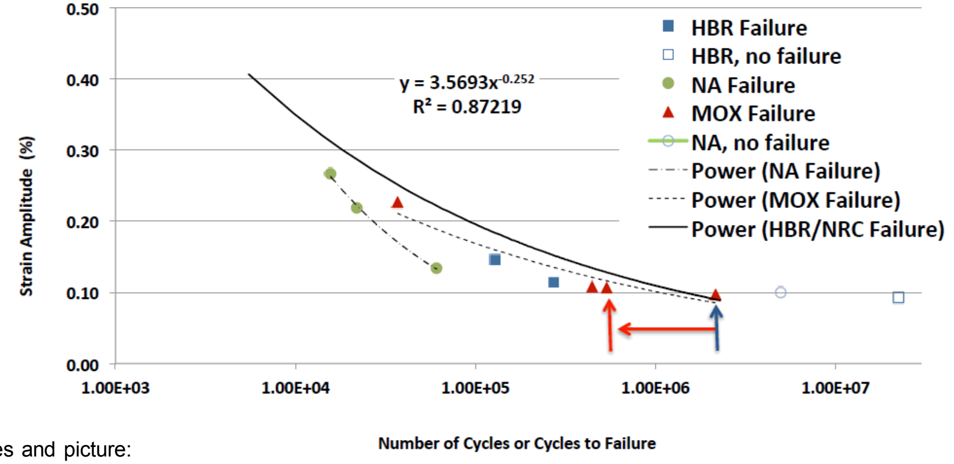
Closing the high burnup used fuel technical gap associated with the fuel cladding: Fatigue

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

Closing the high burnup used fuel technical gap associated with the fuel cladding: Thermal Effects

Thermal analyses on high burnup spent fuel in storage:

- DOE/EPRI Confirmatory Data Project cask loading with high burnup fuel:
  - Best estimate given fuel vendor data and current drying processes
  - Regulatory thermal analyses penalty factors removed
  - Best estimate maximum cladding surface temperatures are << 400º C
  - **Indicating**:
    - Less Hydrogen going into solution that can re-precipitate in a radial orientation
    - Lower internal rod pressures that effect H radial hydride reorientation (PV=NRT)

	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	

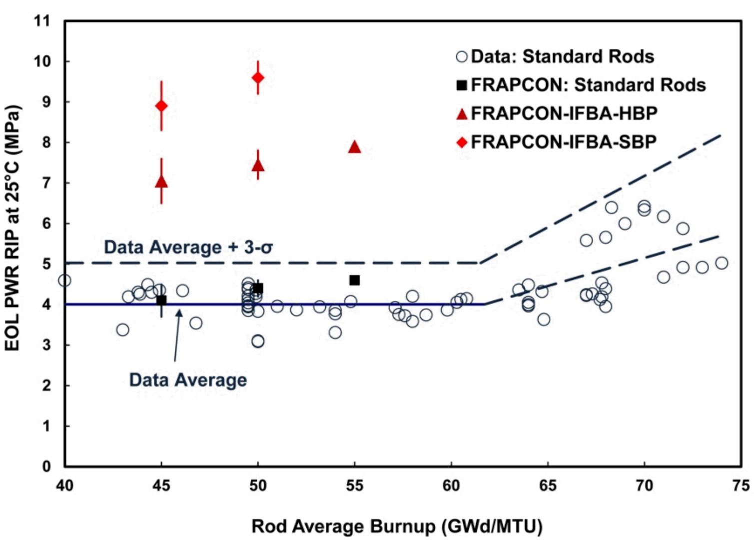
Maximum cladding surface temperature for each assembly in the demo cask

Hanson, "DOE R&D in Support of High Burnup Spent Fuel Dry Storage and Transportation", EPRI ESCP International Subcommittee Meeting, Apr 14, 2016, PNNL.

Closing the high burnup used fuel technical gap associated with the fuel cladding: Internal Rod Pressures

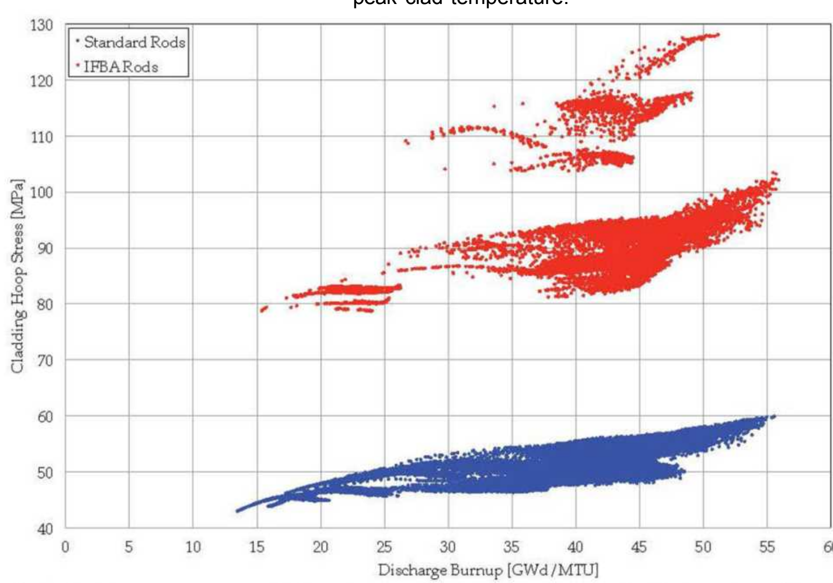
End of Life internal rod pressure analyses:

- FRAPCOM predicts EOL internal rod pressures from burnup histories:
  - End of Life Rod Internal Pressure is a function of:
    - Initial He fill pressure, fission gas release, temperature, void volume, creep down/swelling, clad inner diameter, clad thickness (minus oxide layer)
  - Indicates:
    - Hoop stresses may be lower than expected and lower than RCT test conditions



Hanson, "DOE R&D in Support of High Burnup Spent Fuel Dry Storage and Transportation", EPRI ESCP International Subcommittee Meeting, Apr 14, 2016, PNNL.

Watts Bar Unit 1 spent fuel **assuming 400º C** peak clad temperature.



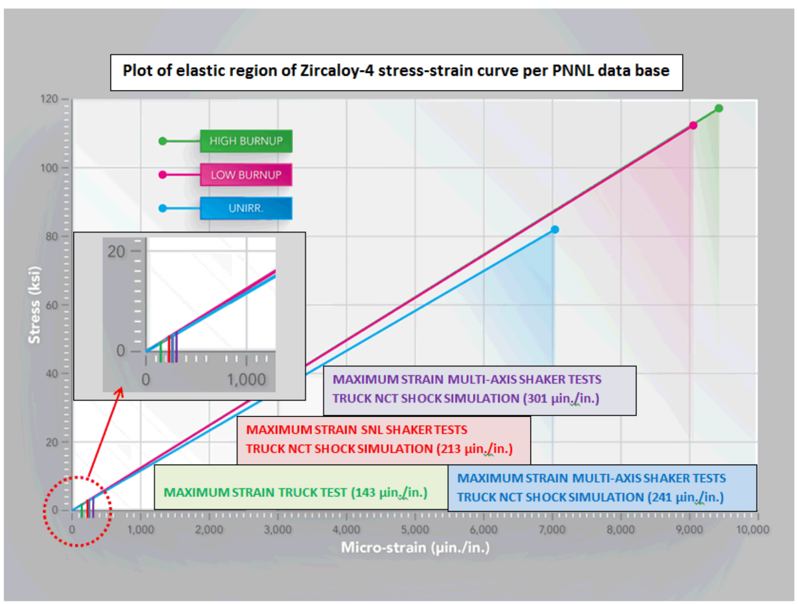
@ 350° C
Max ~ 90 Mpa

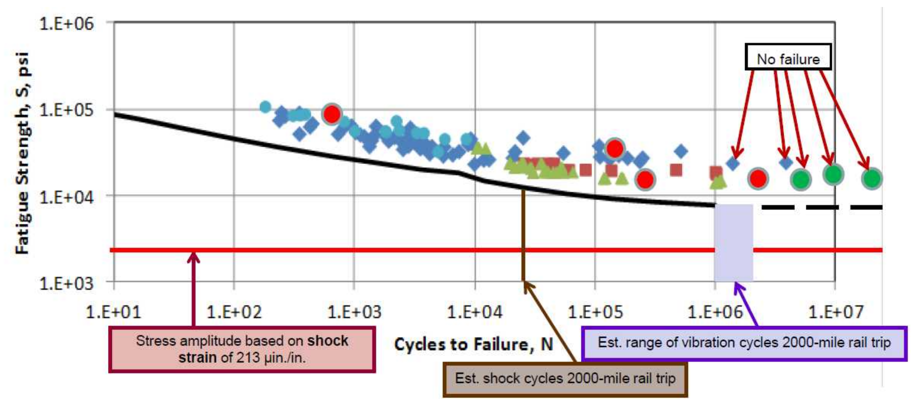
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Closing the high burnup used fuel technical gap associated with the fuel cladding: Loadings

Normal Conditions of Transport (NCT) Loadings:

- Shaker table and Over-the-Road Truck and Rail (shaker table only) tests were conducted on a surrogate PWR assembly to estimate realistic loadings that a spent fuel assembly may see during transport.
  - Accelerations and strains were obtained on both the surrogate assembly and the conveyance
  - Placement of instrumentation was informed by analyses





The large circles are ORNL HBR data

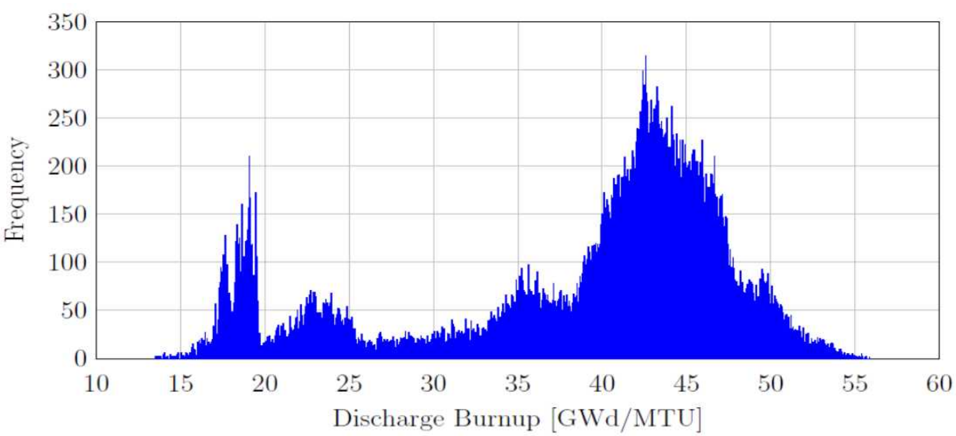
Both figures:
McConnell, “Sandia Shaker Table and Over-the-Road Vibrations Studies”, US NWTRB Meeting, Feb 17, 2016, SNL.

- Indicating:
  - Large margin of safety relative to either elastic or fatigue failure criteria

Closing the high burnup used fuel technical gap associated with the fuel cladding: Fleet Burnup

	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**

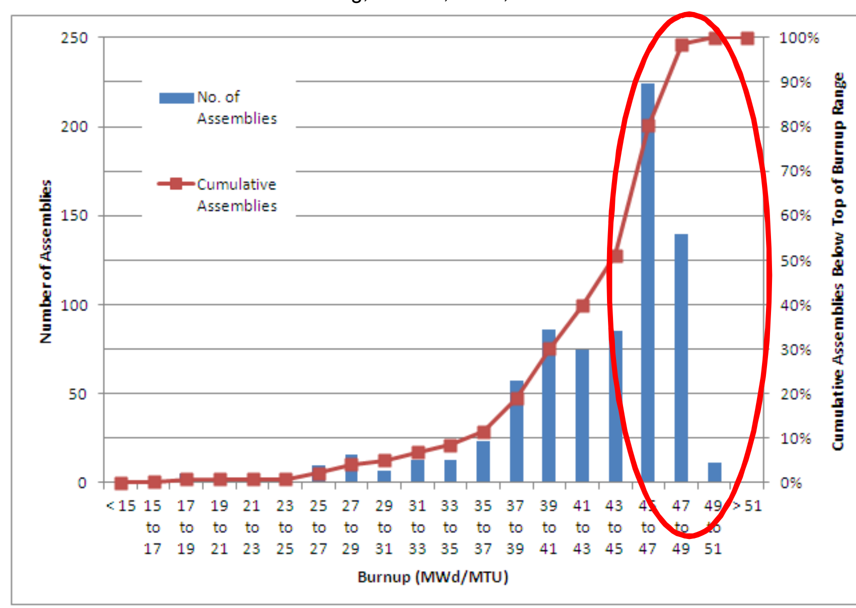
GC-859 Reported Average Assembly-Average Discharge Burnup



Watts Barr Unit 1 Cycles 1-10 Discharge Burnup

- **NRC limit of 62 GWd/MTU peak rod-average burnup**
- **Limits to much higher burnup:**
  - 5 w/o ^{235}U enrichment
  - Cycle length (18, 24 months in US)

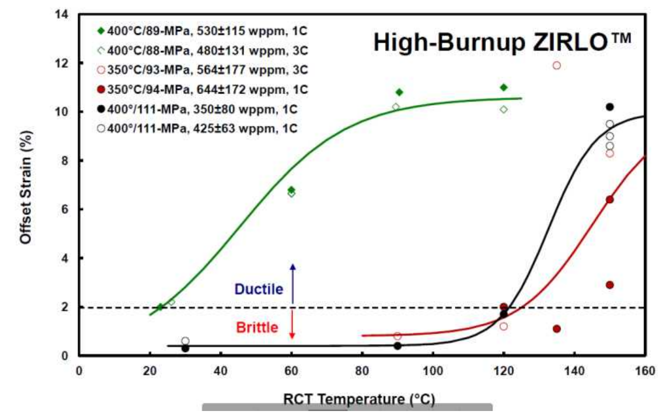
Both figures and table:
Hanson, "High Burnup Fuel, Associated Gaps, and Integrated Approach for Addressing the Gaps", US NWTRB Meeting, Feb 17, 2016, PNNL.



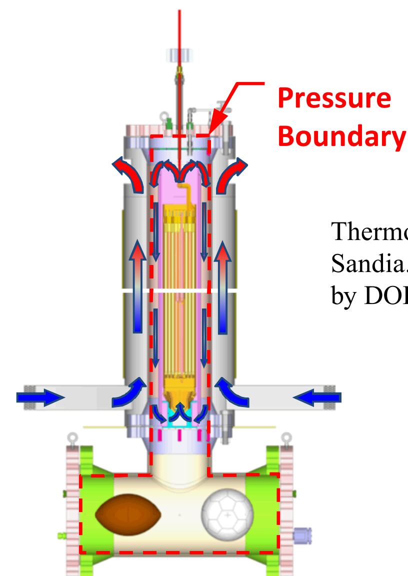
Calvert Cliffs 24 Loaded 32P DSCs as of April 2013

Closing the high burnup used fuel technical gap associated with the fuel cladding

FY16 Activities:



- RCTs: Conduct additional RCTs to better understand DBTT Zirlo results at 350º C:
  - Higher H content?
  - Lack of radiation-hardening annealing at 350º C?
- CIRFT Tests:
  - Tests on TMI (low Sn Zirc) and Surry (Zirc) samples
  - Tests on lower sections of fuel rod
- Thermal Analyses:
  - Conduct best estimate analyses of other licensed storage designs
- Thermal Tests:
  - Conduct thermal benchmark test to obtain maximum cladding surface temperature data using higher design temperatures/pressures
- Transportation NCT:
  - Plans are underway to conduct a full-scale ENSA ENUP-32P rail cask with surrogate assemblies to obtain over-the-rail loading data.



Thermohydraulic test at Sandia. Jointly funded by DOE and NRC.

Closing the high burnup used fuel technical gap associated with the fuel cladding

SUMMARY

- **UFD has identified gaps associated with cladding and is pursuing closing them using an integrated approach**
- **Average discharge burnups are not as high as originally predicted they would be**
- **Further testing will focus on cladding response and performance under realistic temperatures, hoop stresses, and external stresses**
- **Indications are that cladding, including for high burnup fuel, will continue to perform its safety functions during extended storage and normal conditions of transport**