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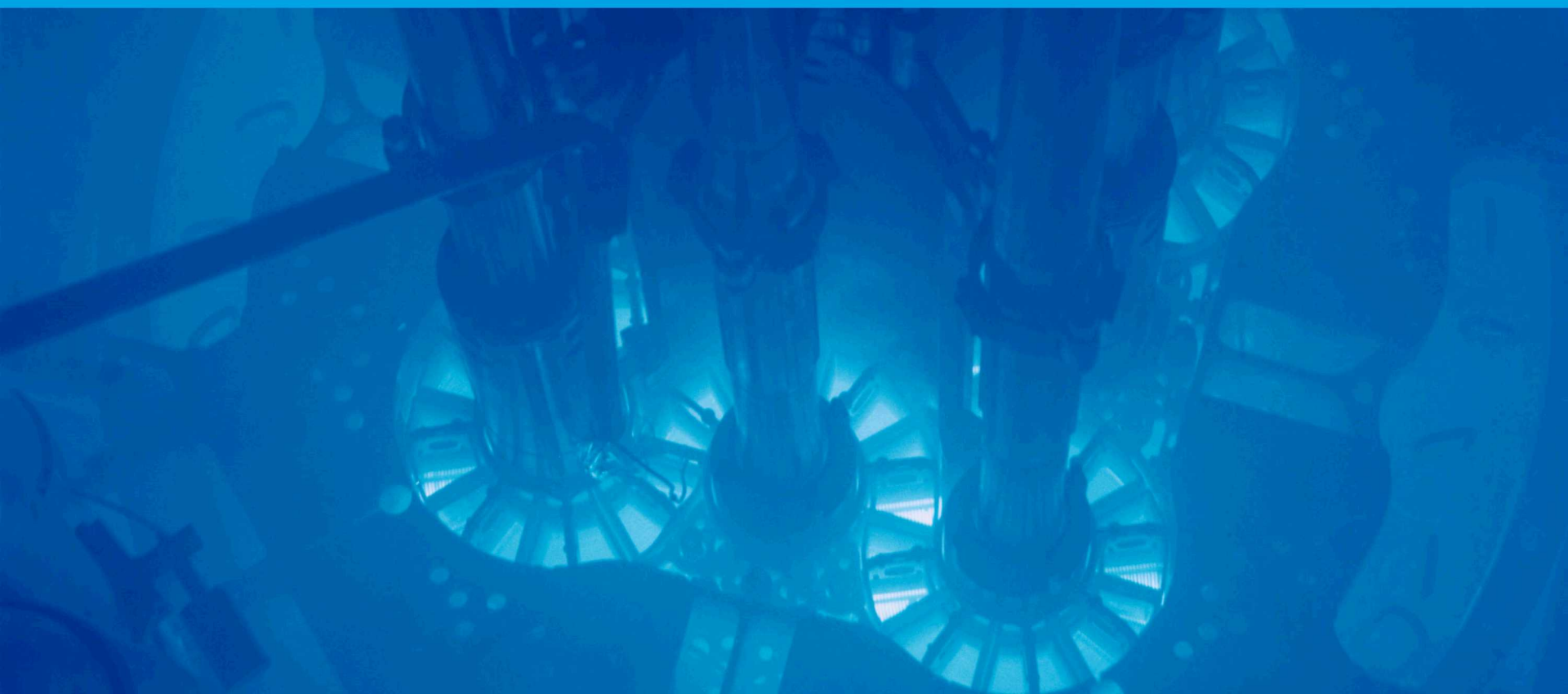
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Spent Fuel and Waste Science and Technology (SFWST)



Making the Case: Demonstrating the Integrity of Spent Nuclear Fuel During Long-term Storage and Subsequent Transportation

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Outline

- Cladding data gaps
- Integrated approach to closing cladding data gaps
- Thermal profiles
- Stress profiles
- Mechanical properties
- Mechanical loading
- Conclusions

Technical Data Gaps Associated with Cladding - 2012

- Thermal profiles
- Stress profiles
- H₂ effects: hydride reorientation and embrittlement
- H₂ effects: delayed hydride cracking
- Annealing of radiation damage
- Oxidation
- Creep

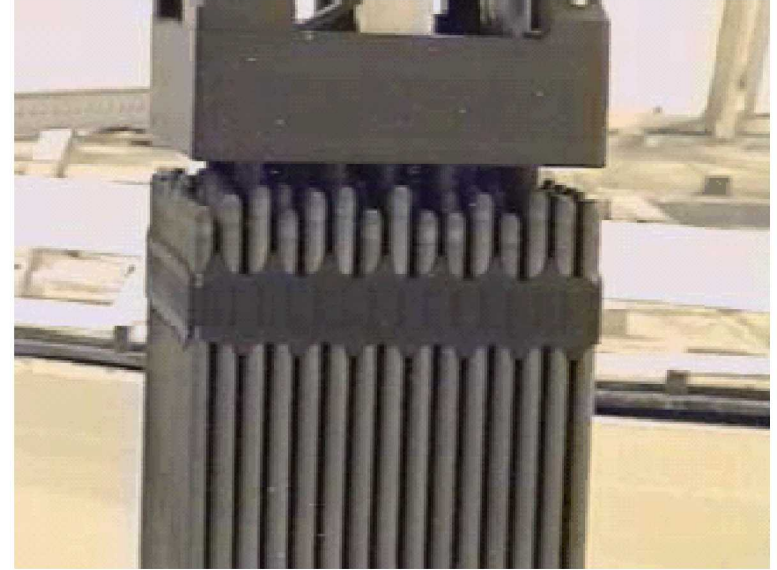


Photo courtesy of Idaho National Laboratory

Substantial progress has been made on the first three gaps. The last four gaps are less important factors to safety than the first three gaps.

Integrated Approach to Closing Cladding Data Gaps

- Thermal Profiles
 - What are the **realistic** temperatures that cladding experiences during drying and extended storage?
 - Use demonstration TN-32B storage cask to obtain actual high burnup SNF cladding temperatures during transfer from wet to dry storage.
 - Benchmark modeling codes to data to expand analytic capabilities to other vertical dry storage systems.
- Stress Profiles (Hoop Stress)
 - What is the range and distribution of end of life rod internal pressures (EOL RIP), accounting for He and pellet swelling/bonding, and clad thicknesses and diameters? How does this effect cladding hoop stress?
 - Obtain industry data on high burnup SNF EOL RIP
 - Measure RIP in high burnup SNF through sister rod testing at PNNL and ORNL.
- Mechanical Properties
 - Establish the ductile-brittle behavior of cladding as a function of temperature, RIP, and hoop stress
- Mechanical Loading (External Stresses)
 - Identify **realistic** stresses to cladding during extended storage and normal conditions of transport. How do these stresses compare with measured mechanical properties of high burnup SNF cladding?
 - Conduct shaker table tests and measure actual fuel rod strains and accelerations
 - Conduct multi-model tests and measure actual fuel rod strains and accelerations

Thermal Profiles:

Licensing Changes for TN-32B Research Project Cask

	TN-32 Safety Evaluation Report	TN-32B Research Project Cask
Maximum burnup (GWd/MTU)	≤ 45	≤ 60
Maximum decay heat per assembly	1.02 kW	1.5 kW
Total decay heat	32.7 kW	36.96 kW
Minimum decay time	7-10 years	4.81 years
Est. Peak cladding temperature	328°C	348°C



Photo courtesy of Dominion Energy

Thermal Profiles: Round Robin Analysis Comparison with Measured Data

- Steady state PCTs from all models and measurements significantly lower than the design licensing basis:

Parameter	FSAR	LAR	Best-Estimate	HBU Cask Measurements
PCT (model vs data)	348°C	318°C	254-288°C	229°C
Heat Loadouts	36.96kW	32.934kW	30.456kW	30.456kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?



Slide courtesy of Al Csontos, Co-chair of EPRI ESCP Thermal Subcommittee

Thermal Profiles: Temperature Sensitivities and Summary

- Conservative decay heat calculations → 20°C - 50°C+ margin
- Actual loading (50%-90%) vs. design basis heat load → 20°C - 50°C+
- Actual drying times vs. vacuum steady state asymptote → 0°C - 50°C+
- Ambient temperature assumption → 0°C - 20°C+
- “Best Estimate” thermal models removing known conservatisms → 10°C - 20°C+

- Modeling of high burnup dry cask storage systems loaded to date:
 - Peak Cladding Temperatures \ll 400°C
 - All cladding temperatures $<$ 325°C
 - Most $<$ 300°C
 - Many 250°C - 275°C
 - Fraction of cladding near PCT is very small

Stress Profiles:

Modeled Hoop Stress from Rod Internal Pressure

Table 1. Maximum Hoop Stress (MPa) 400°C Peak Temperature

Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	40.0	43.8	41.7
17x17	49.9	53.4	50.5
17x17 IFBA	84.4	88.1	86.3

Table 2. End of Life Rod Internal Pressure (MPa) 400°C Peak Temperature

Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	5.4	6.1	6.4
17x17	6.2	6.8	7.0
17x17 IFBA	10.6	11.1	11.5

Table 3. Maximum Plenum Temperature (all fuel types)

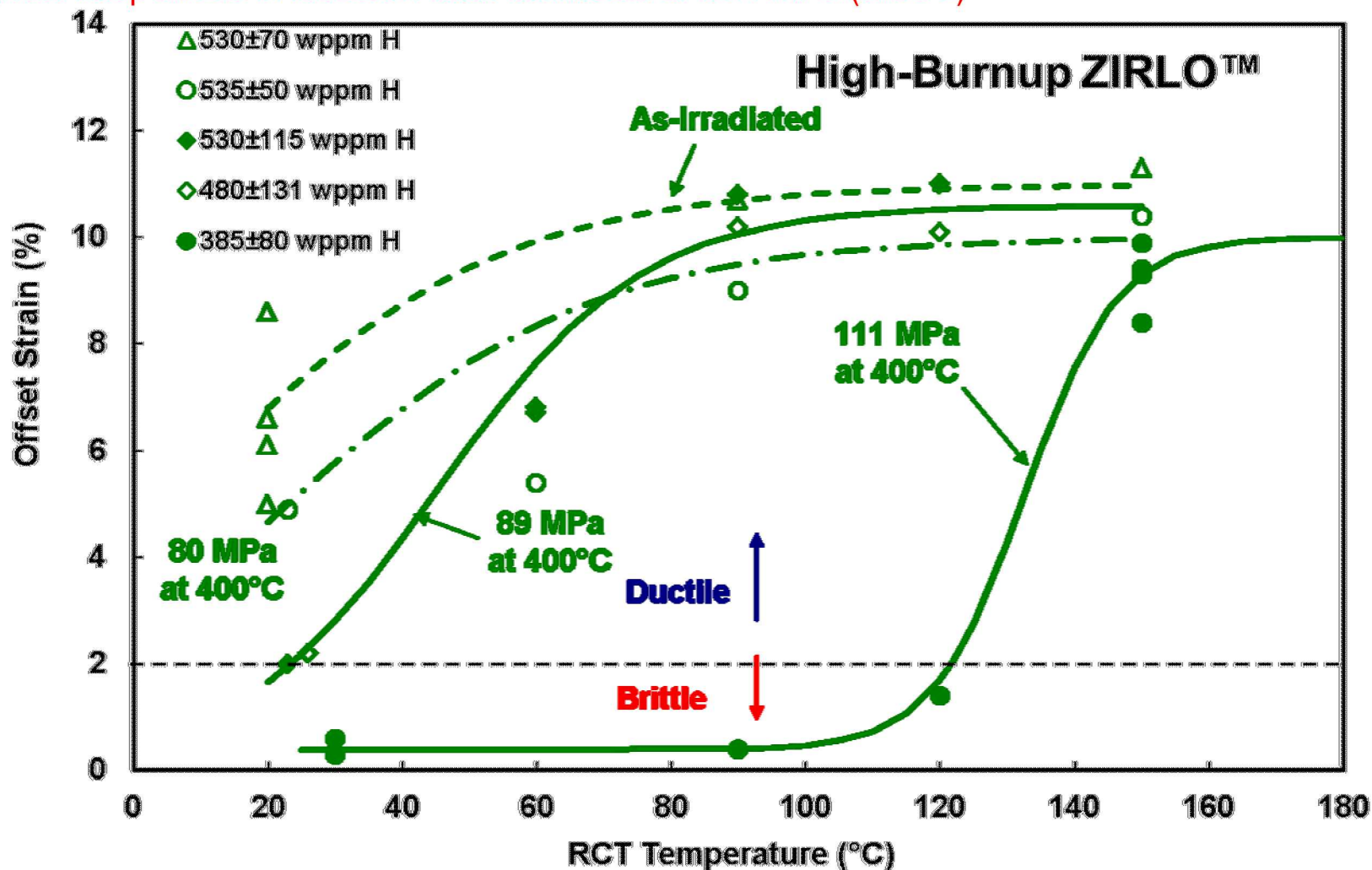
Profile	Temperature (°C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

Mechanical Properties:

Ductile-Brittle Transition Temperature using Ring Compression Tests

Apparent threshold for reduced ductility with radial hydride treatment at >90MPa hoop stress.

Highest hoop stress in research cask estimated at 53.4 MPa (slide 8)



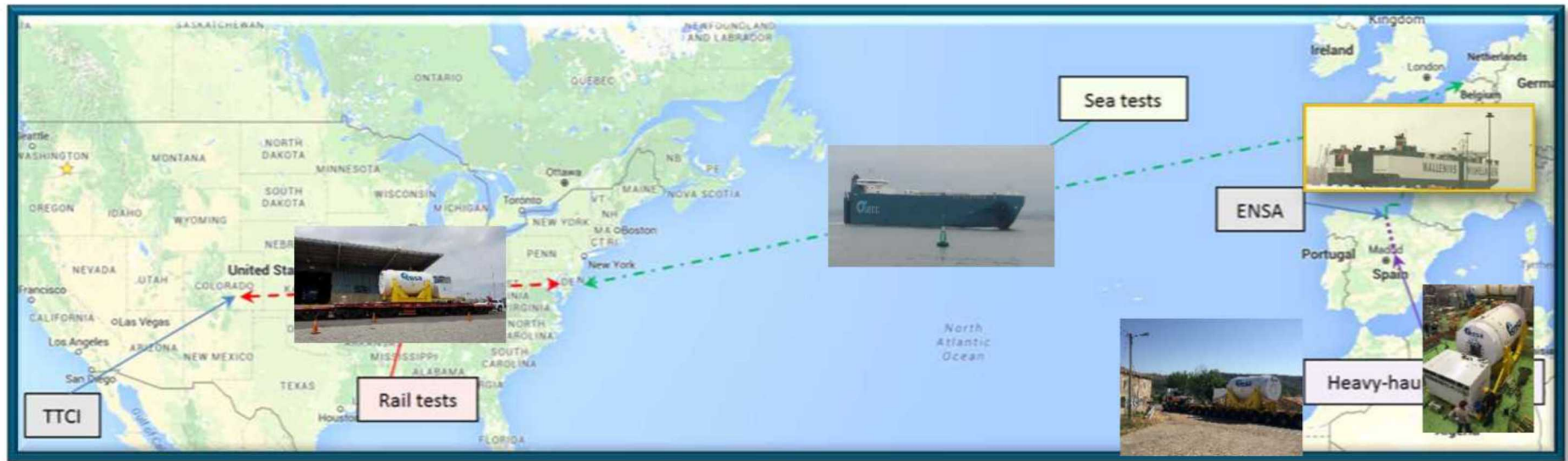
Billone, M.C., T.A. Burtseva, Z. Han, and Y.Y. Liu, *Embrittlement and DBTT of High-Burnup PWR Fuel Cladding Alloys*, Argonne National Laboratory Report ANL-13/16, FCRD-UFD-2013-000401, Sept. 30, 2013.

Mechanical Properties: Summary

- At peak hoop stress <90 MPa, hydride reorientation may occur, but it is not expected to result in loss of ductility
 - Expect no failure from pinch loading
- Argonne National Laboratory will continue to perform RCT on defueled cladding samples that have undergone radial hydride treatment at 400°C
- Oak Ridge National Laboratory will perform Ring Compression Tests (RCT) on fueled cladding segments both on as-received (no heat treatment) and from rods subjected to whole rod heating at 400°C
 - Determine how the presence of fuel affects pinch load response, limits displacement, load bearing?

The upper bound testing parameters of 400°C and 90 MPa hoop stress provide significant margin for cladding performance based on measured data.

Mechanical Loading: Multimodal Transportation and Handling Tests



Photos provided by Steve Ross, PNNL

- 1) Heavy-haul truck from within Spain ~ June 14, 2017
- 2) Coastal sea shipment from Santander to large northern European port ~ June 27, 2017
- 3) Ocean transport from Europe to Baltimore
- 4) Commercial rail shipment from Baltimore to Pueblo, Colorado ~ Aug 3, 2017
- 5) Testing completed at the Transportation Technology Center, Inc.
- 6) Return trip to ENSA, September 5, 2017

Data was collected throughout all legs of the transport as well as the transfers between legs.

Mechanical Loading:

Maximum Strains and Accelerations from all Tests

	Highway	Ship	West Rail	TTCI	East Rail
Peak Strain (μE)	17	7.2	46	96	74
Peak Fuel Assembly Acc.	0.6	1.5	1.4	15.1	2.3
Peak Basket Acc	0.2	1.3	0.3	0.8	1.2
Peak Cask Acc	0.2	0.17	0.3	1.2	0.7
Peak Cradle Acc	0.2	0.17	0.6	6	2.8
Peak Deck Acc (ends/mid)	15/5	1.6	8/0.9	27/7	24/5

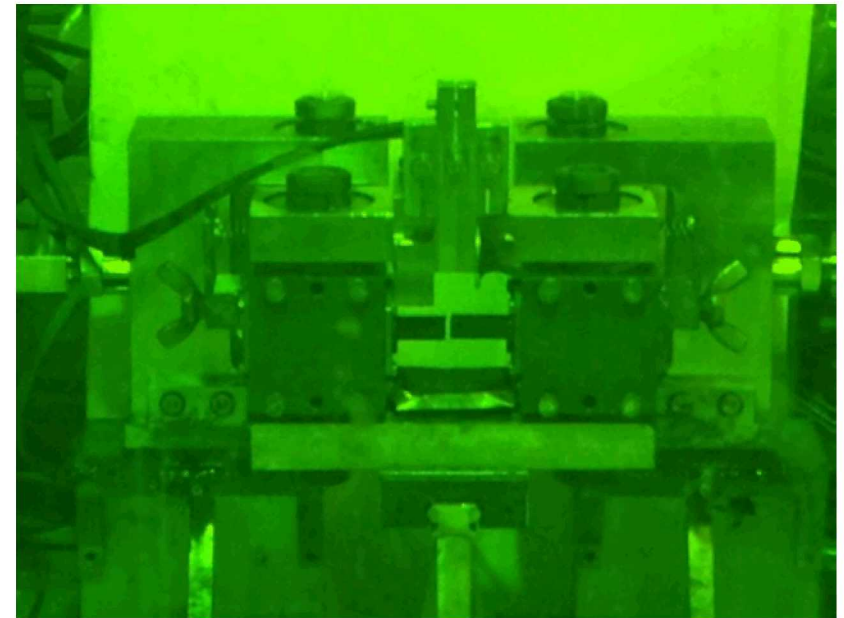
Measured yield stress levels for irradiated SNF cladding is $\sim 7000 - 9000 \mu\epsilon$

Mechanical Loading: Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT)

- Developed at ORNL under an NRC program
- Both static bending and cyclic fatigue
- Determine the load, curvature, # of cycles for failure
- Pellet-clad and pellet-pellet bonding provides additional stiffness → increase the load and # of cycles for failure
- Fatigue life depends on the level of loading

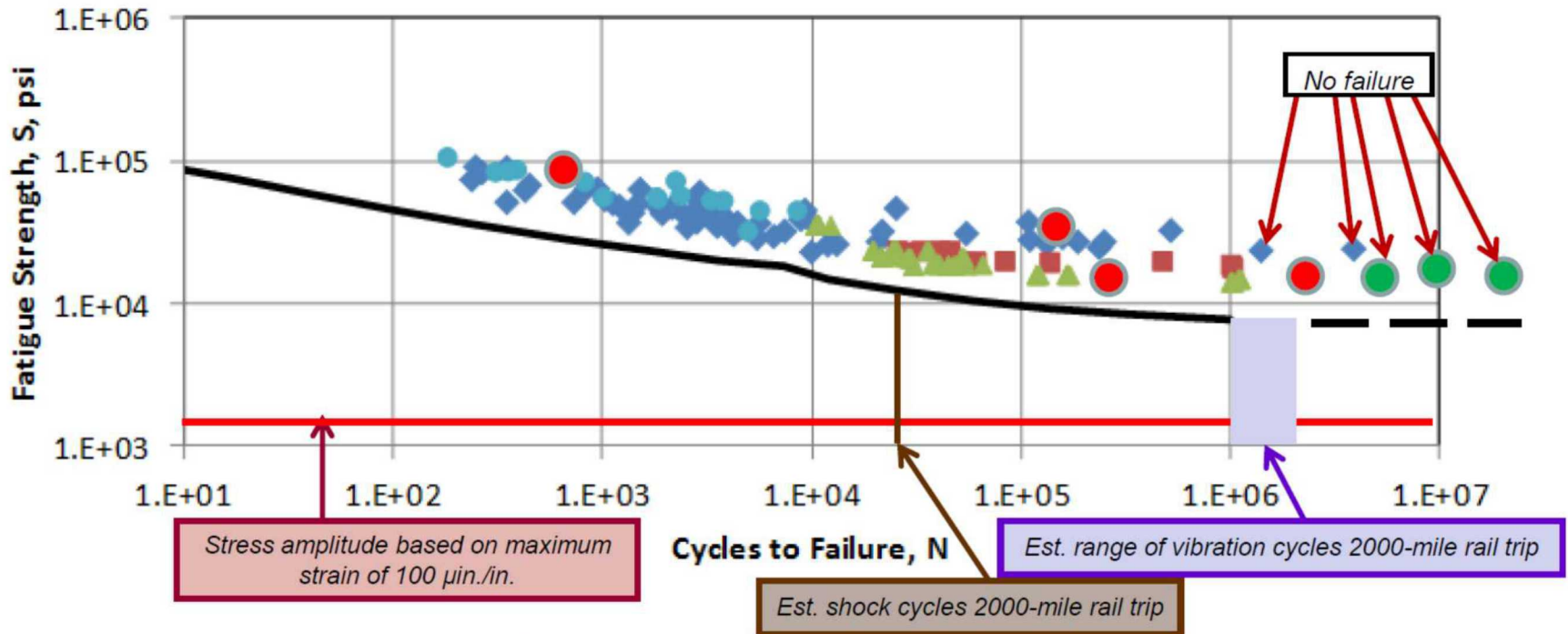
J-A Wang et. al. Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications, NUREG/CR-7198/R1 ORNL/TM-2016/689, Oak Ridge National Laboratory, January 2017.

Similar to the ductile-brittle RCT testing, upper bound limits were chosen to induce failure.



Mechanical Loading:

Will Fatigue Failure Occur During Normal Conditions of Transport?



Fatigue design curve (—): O'Donnell 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

J-A Wang et. al. Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications, NUREG/CR-7198/R1 ORNL/TM-2016/689, Oak Ridge National Laboratory, January 2017.

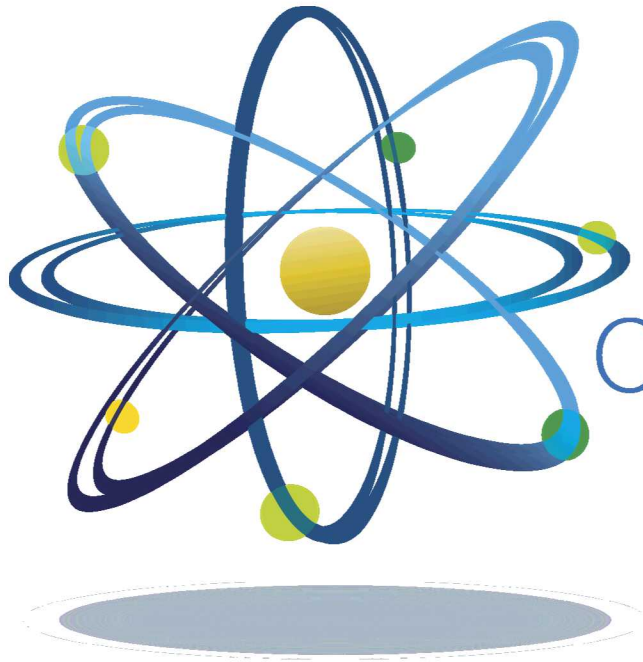
- Large red and green circles represent CIRFT data.
- Horizontal red line represents highest recorded stress value from the multimodal tests.
- Bold black line represents failure criteria above which failure may occur. Stress levels and the number of fatigue cycles from the multimodal tests are well below the failure limits.

Conclusions

- Models can accurately predict cask and component temperatures when accurate inputs are provided. Work needs to be done to benchmark models to horizontal dry storage systems data.
- Measured PCT (229° C) from the demonstration cask were far below the regulatory threshold of 400° C. This limits amount of hydrogen that is available to reorient in the radial position during drying.
- Ring Compression Tests show that cladding operating in representative storage environments will behave in a ductile fashion. Upper bound tests at 90 MPa and 400° C were well above the demonstration cask values of 50 MPa and 400° C .
- Additional mechanical testing on irradiated fuel is currently being conducted to validate and substantiate cladding integrity behavior.
- Estimated stresses from measured mechanical loads are far below yield stress levels and fatigue limits.

With the data that is currently available and using the integrated approach, cladding integrity will not be challenged during extended storage and normal conditions of transport

Questions?



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