



Engineering Application of Test Data for Determining Behavior of Actual Fuel during Normal Transportation

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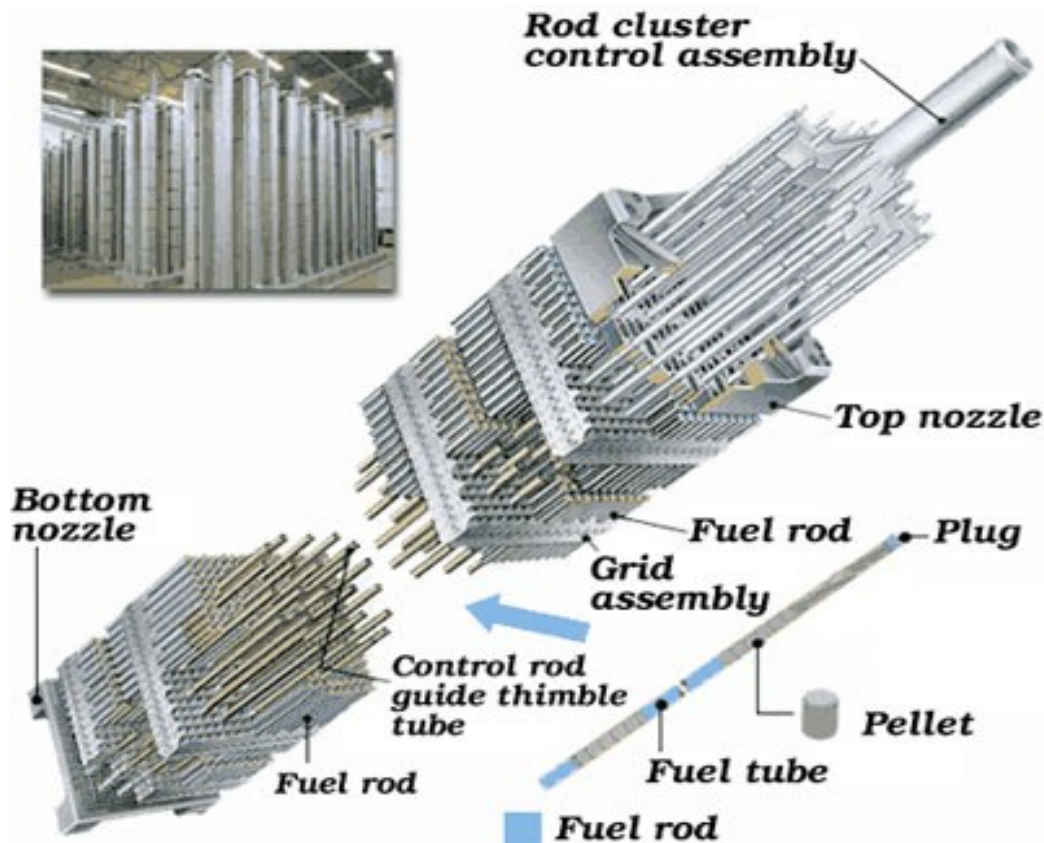


Overview

- Normal Conditions of Transport (NCT)
 - Structural analysis perspective
 - Regulatory perspective
- Fuel Assembly Loading Environment
 - Fuel assembly shaker test
 - Over-the-road vibration studies
- High Burnup Fuel (HBF) Bending and Fatigue Tests
 - Fuel rod performance with circumferential hydride
 - Effect of hydride re-orientation
- Licensing Review Implications

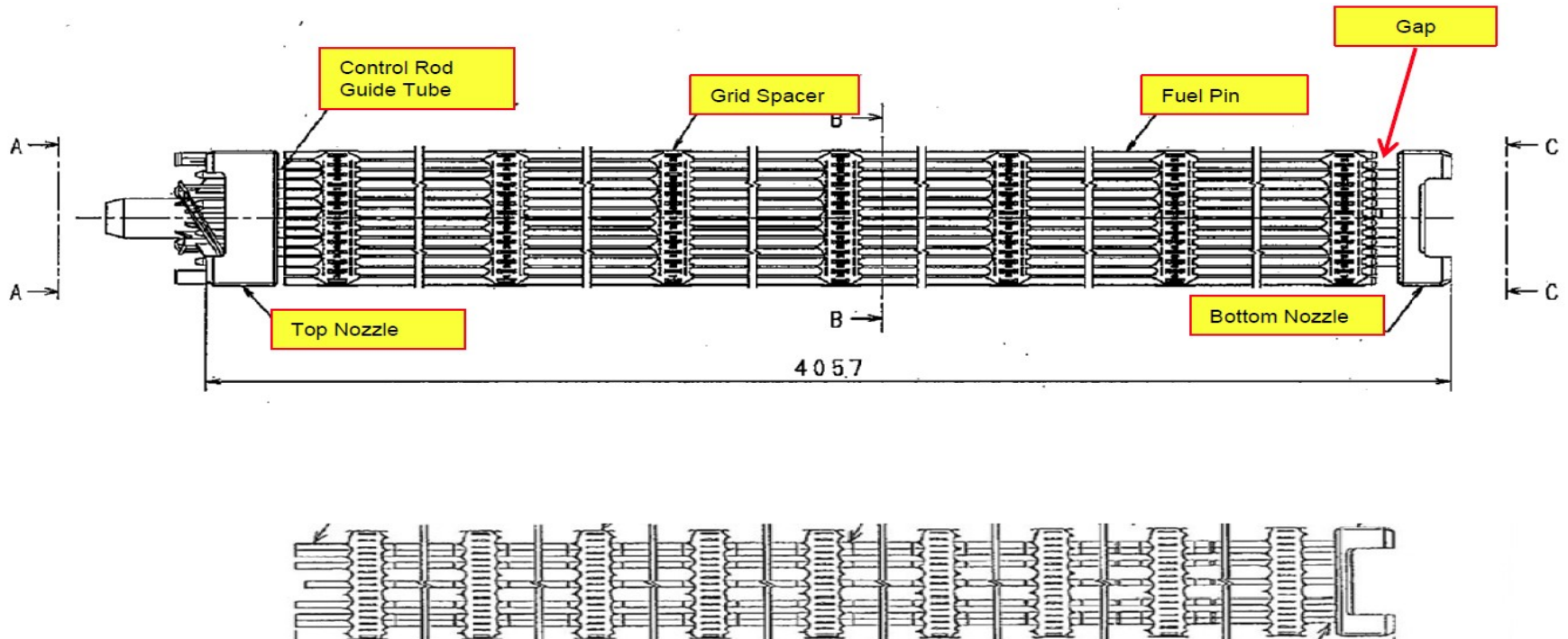
Structural Analysis Perspective

Fuel Assembly Schematic



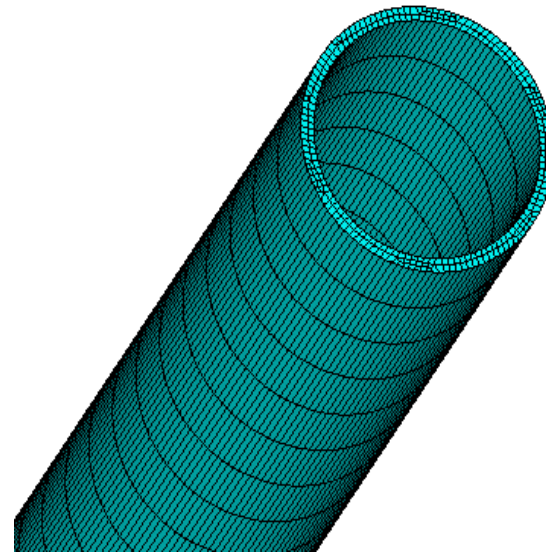
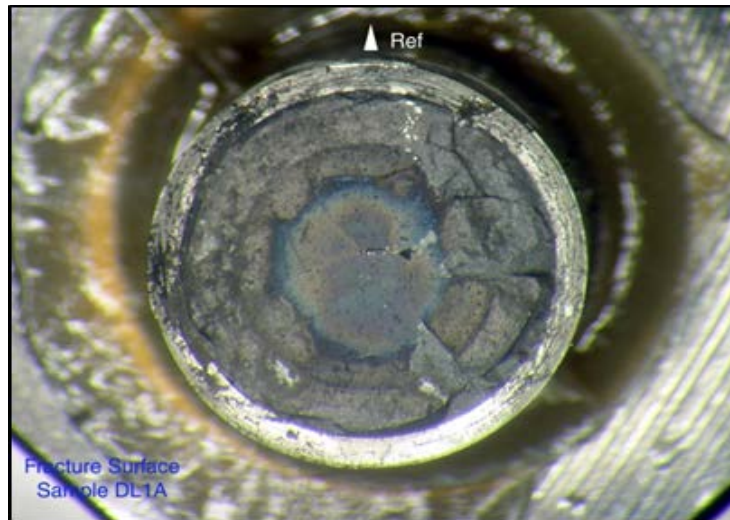
Structural Analysis Perspective

Modeling Attributes Consideration



Structural Analysis Perspective

hollow tube assumption as bounding



Regulatory Perspective

- Normal conditions of transport
 - 71.71 Normal conditions of transport (NCT)
 - 71.71(c)(5) - Vibration
 - 71.71(c)(7) - 1-ft free drop
 - 71.55 General requirements for fissile material package
 - 71.55(d)(2) - the geometric form of the package contents would not be substantially altered, under the tests specified in 71.71
- Regulatory gap – fuel condition at the next storage sites
 - 71.33(b)(3) – the application must include a description with respect to the contents of the package (prior to SNF transport)
 - 72.236(a) – specify details of SNF to be stored (after transport)

Regulatory Perspective

- Regulatory Guide (RG) 7.9*, Section 2.6.5
 - “The combined stresses attributable to vibration, temperature, and pressure loads should be considered, and a fatigue analysis should be included, if applicable
 - Packaging components, including internals, should be evaluated for resonant vibration conditions that can cause rapid fatigue damage
- NUREG-1617**, Section 2.5.5.5
 - Similar guidance language to that of RG 7.9, Section 2.5.6
 - Reference to NUREG/CR-0218 and NUREG/CR-2146

* “Standard Format and Content of Part 71 Application for Approval of Packages for Radioactive Material”

** “Standard Review Plan for Transportation Packages for Spent Nuclear Fuel”

Regulatory Perspective

- 10 CFR 71.71(c)
 - (5) *Vibration*. Vibration normally incident to transport.
 - Language on *Vibration* condition and test is non-prescriptive for the performance based 10 CFR Part 71.71 regulations.
 - “Shock loading” not called out as part of NCT vibration condition
 - NUREG/CRs, DOE National Laboratories reports*

- *
1. NUREG/CR-0128, “Shock and Vibration Environments for a Large Shipping Container during Truck Transport (part II).”
2. NUREG/CR-2146, “Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Volume 3: Final Summary Report.”

Regulatory Perspective

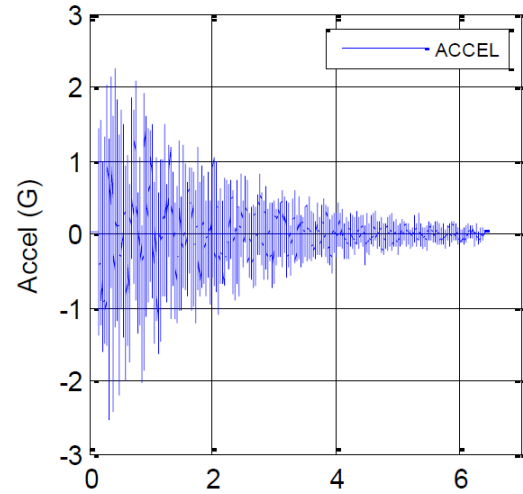
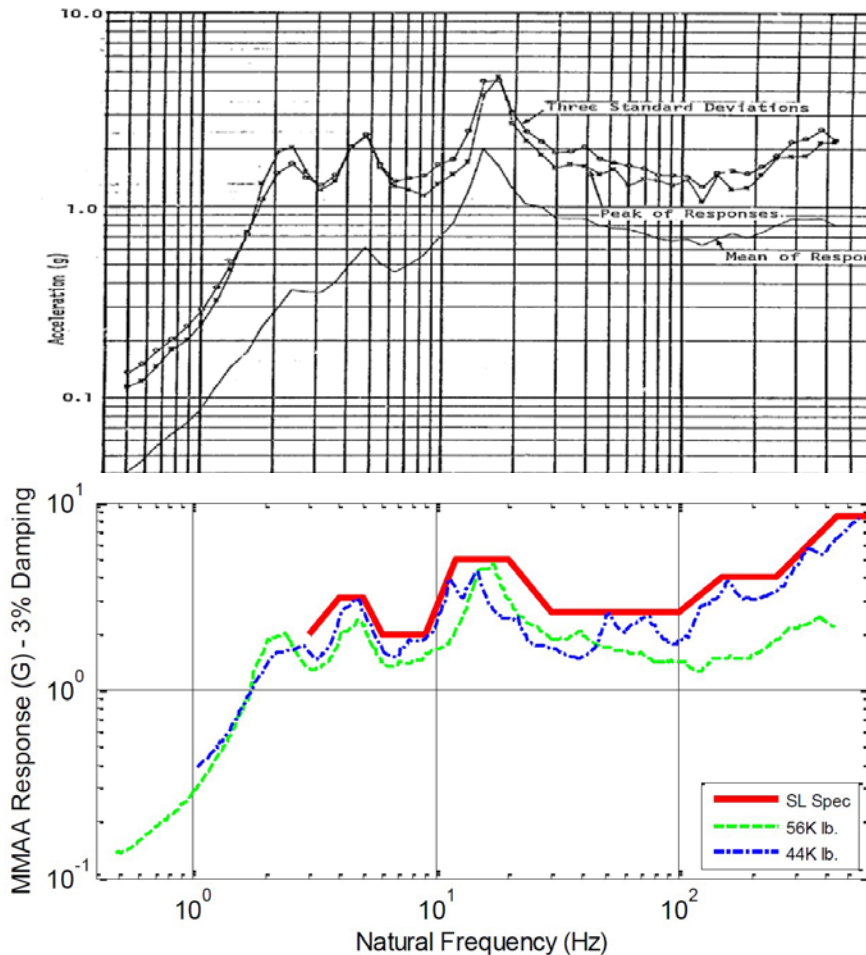
- Safety review also based on engineering judgment/operating experience
 - Large latitude for selecting vibration g-load for design analysis.
 - Small vibration g-load unlikely to result in fatigue damage to properly designed cask systems, including spent fuel assembly
- Issues may arise for a more rigorous definition of loading conditions and spent fuel performance demand
 - Condition of spent fuel as content during and after transportation
 - Effect of hydride presence and hydride re-orientation

Fuel Assembly Shaker Test*

- Strain of surrogate rods in a 17x17 PWR assembly
- Shaker vertical vibrations simulating previous 700-mile over-the-road truck tests – NUREG/CR-0128
- Test to a shock response spectrum at 3% damping
- Time series peak acceleration: approximately $\pm 2.5g$
 - Realization by a waveform comprising 50+ decayed sines
 - 3.3 Hz to 600 Hz, each with amplitude at about 0.02 up to 0.38 g

* FCRD-UFD-2013-000190, “Fuel Assembly Shaker Test for Determining Loads on a PWR Assembly under Surrogate Normal Conditions of Truck Transport.”

Fuel Assembly Shaker Test



T:

Frequency (HZ)	MMAA 3% (G)
3	2
4	3.1
5	3.1
6	2
9	2
12	5
20	5
30	2.6
100	2.6
150	4
250	4
450	8.5
600	8.5

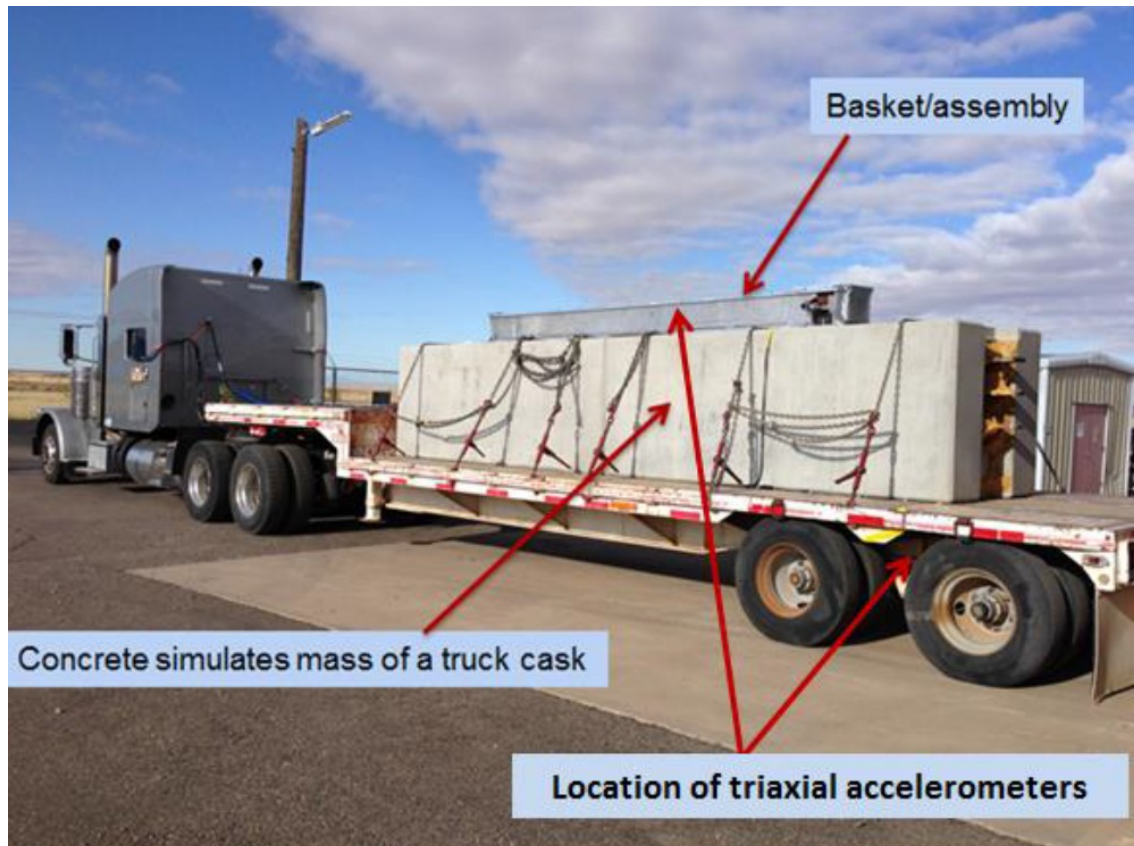
Figure 27. Recommended Test Specification and Underlying Shock Spectra.

Over-the-Road Vibration Studies*

- Test configuration
 - Same fuel assembly/basket used in the SNL shaker test
 - Basket bolted to two concrete blocks simulating a loaded NAC-LWT cask
 - Concrete blocks strapped to a trailer driven over a 40.2-mile route of a variety of road surfaces, including crossing railroad tracks and applying a hard brake
- Acceleration measurements
 - Uniaxial accelerometers
 - One accelerometers triad on top of the basket and another below trailer drop deck above rear axle

*Normal Conditions of Transport Truck Test of a Surrogate Fuel Assembly, FCRD-UFD-2014-000066, Rev 0.1

Over-the-Road Vibration Studies



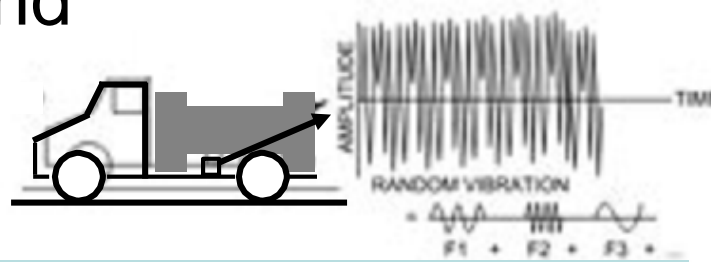
Over-the-Road Vibration Studies

- Measured maximum vertical accelerations
 - rod acceleration
 - 21.96 g, 1000 Hz filtered
 - 6.07 g, 100 Hz filtered
 - basket acceleration
 - 5.6 g, 1000 Hz filtered
 - below trailer bed, above axle acceleration
 - 11.8 g, 1000 Hz filtered, including crossing railroad tracks
 - 19.8 g, 1000 Hz filtered, including applying a hard brake

HBF Bending and Fatigue Tests

Background

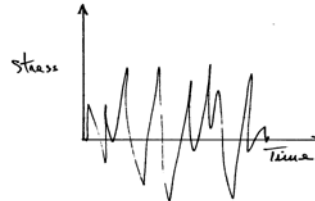
A transportation cask will experience some level of oscillation due to normal conditions of transport.



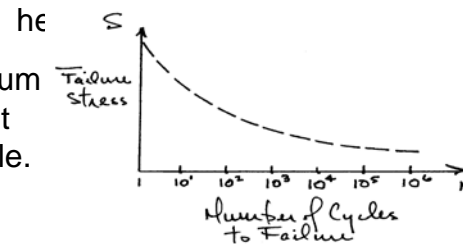
That oscillation will be transmitted in some way to the contents of the cask, the fuel elements.



The oscillation transmitted to the fuel elements will result in local stresses



The fuel cladding has the potential for fatigue failure if a large number of cycles are seen during transport, even if the maximum stresses seen by the cladding are far below the yield stress of the material. High burnup material in particular may be highly brittle. In addition, it is not clear how the ceramic fuel will affect the potential for cladding failure.

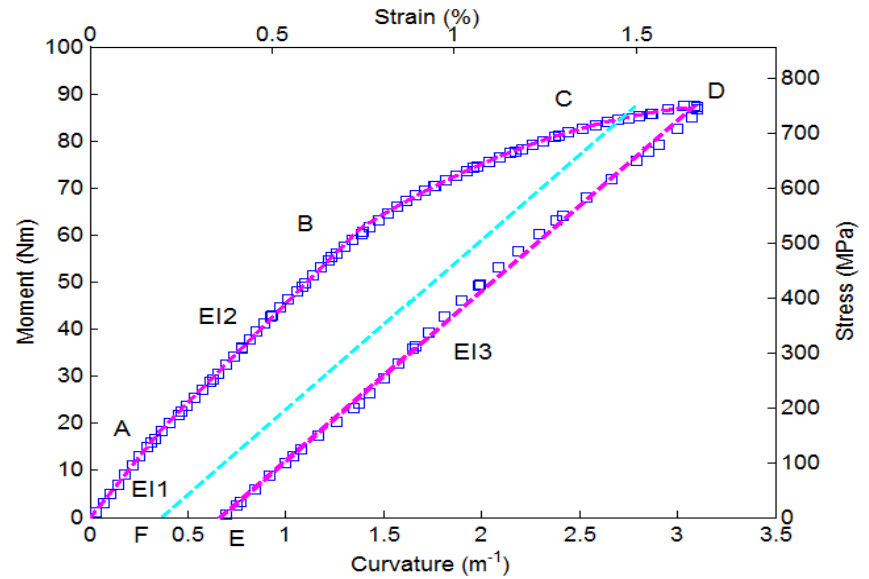
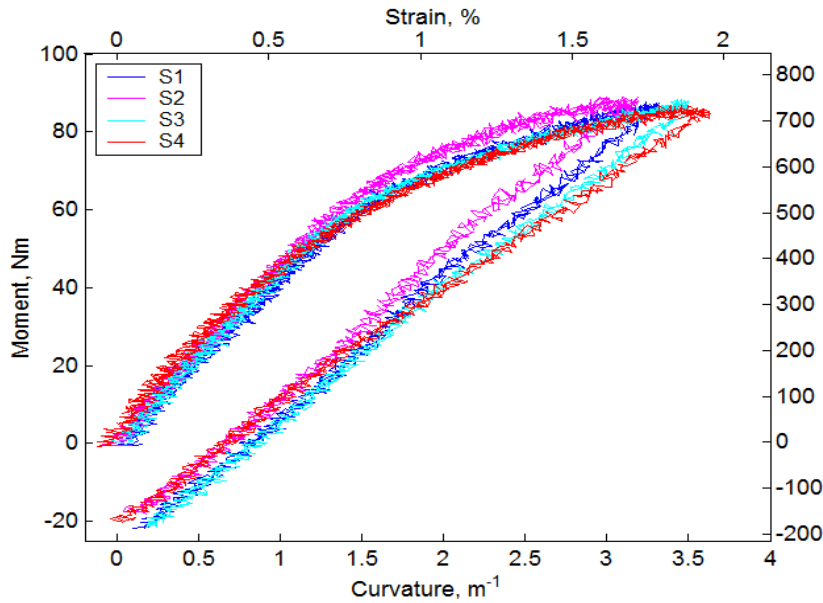


HBF Bending and Fatigue Tests

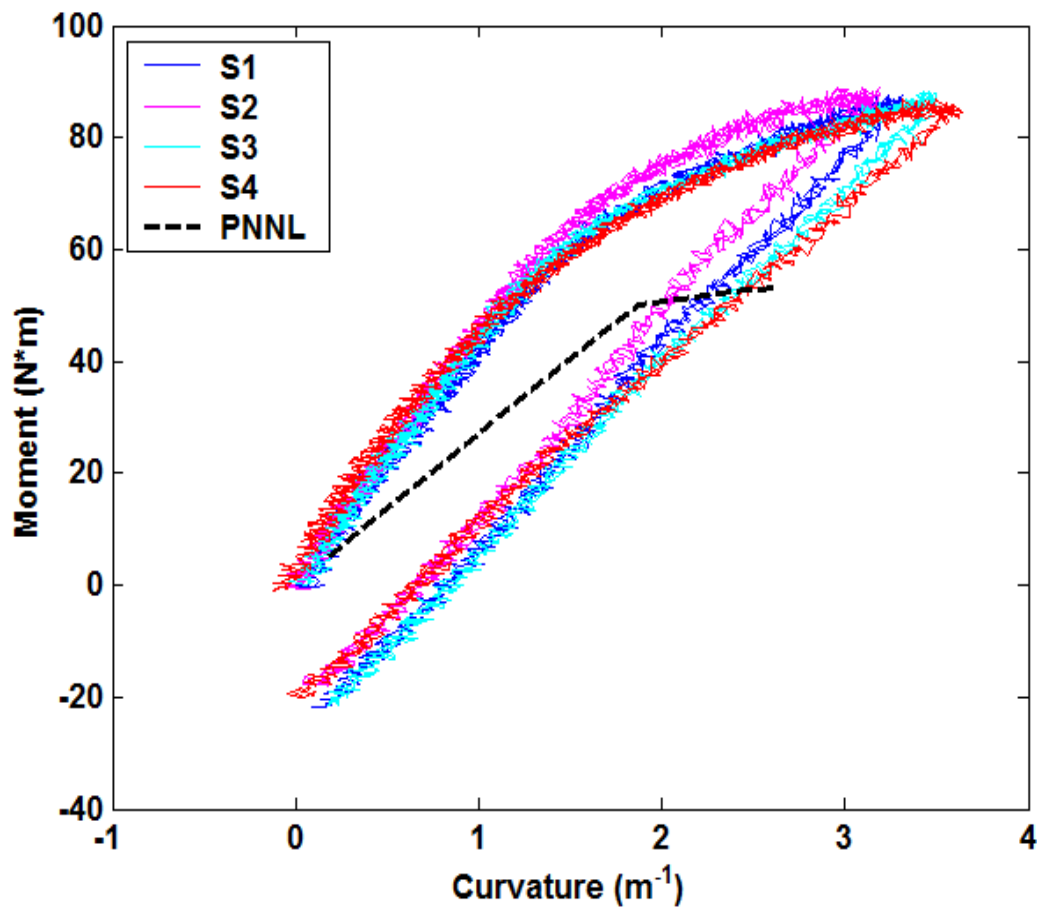
- PWR spent nuclear fuel (SNF) with Zircaloy-4 cladding
 - Burnup ranged from 63.8 to 66.8 GWd/MTU
- NRC Phase 1 test (non-reoriented HBF samples) program
 - Static bend tests have been completed on 4 samples
 - Vibration fatigue tests have been completed on 16 samples, at a wide range of bending moment amplitudes
- NRC Phase 2 test (reoriented HBF samples) program
 - Static bend tests will be performed on 1 sample
 - Vibration fatigue tests will be performed on 3 samples, at a range of bending moment amplitudes

Phase 1 Static Results

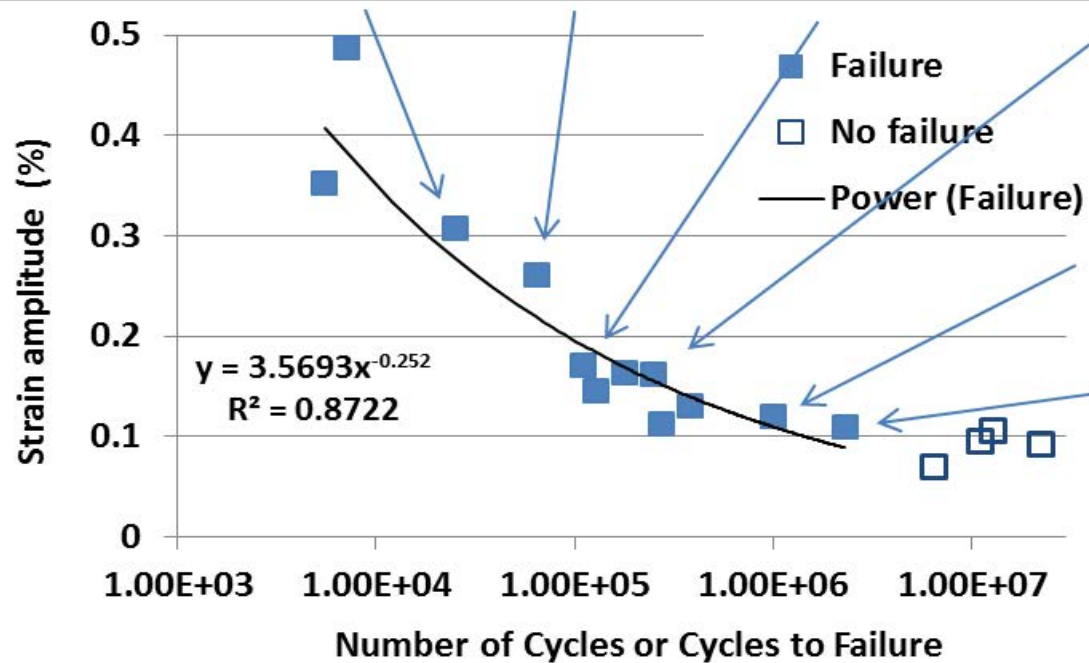
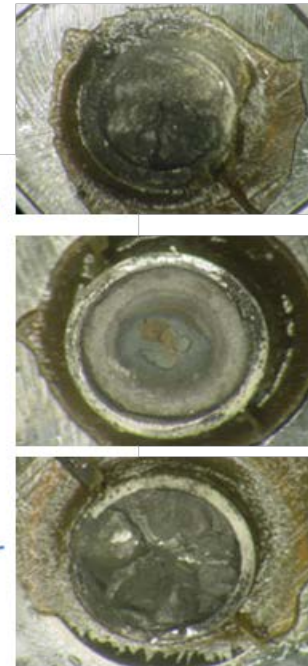
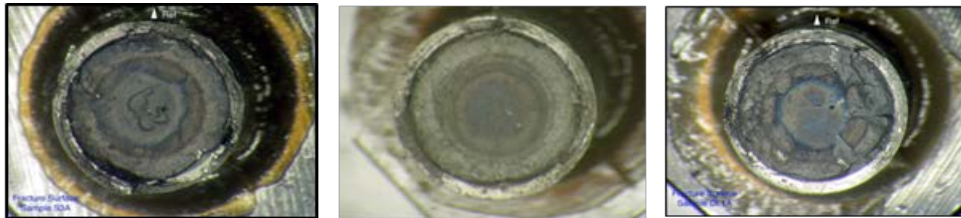
Varied Fuel Rod Flexural Rigidity



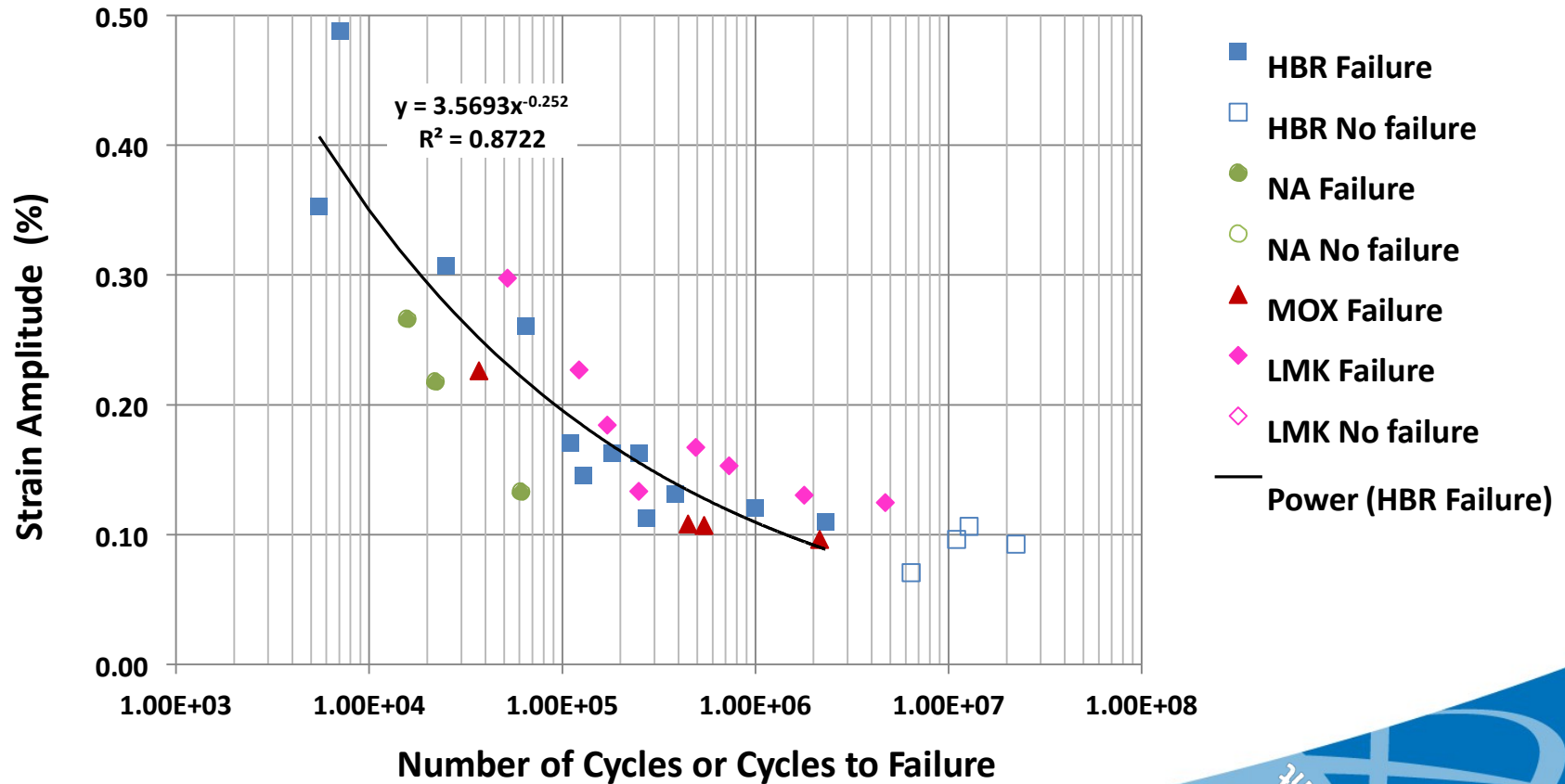
Phase 1 Static Results - Compared to Response, Cladding Only



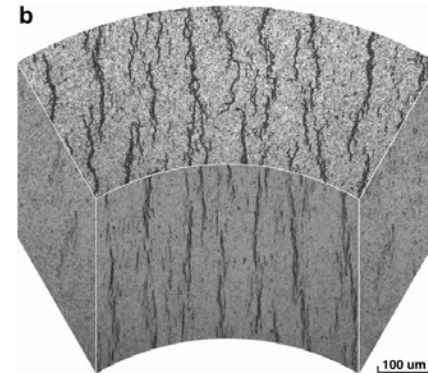
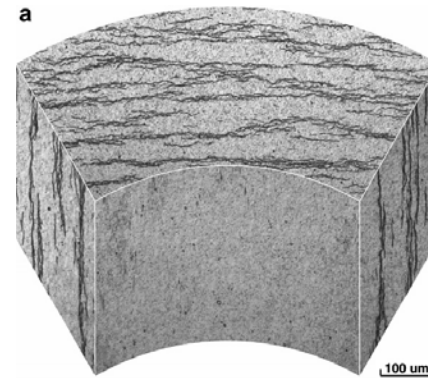
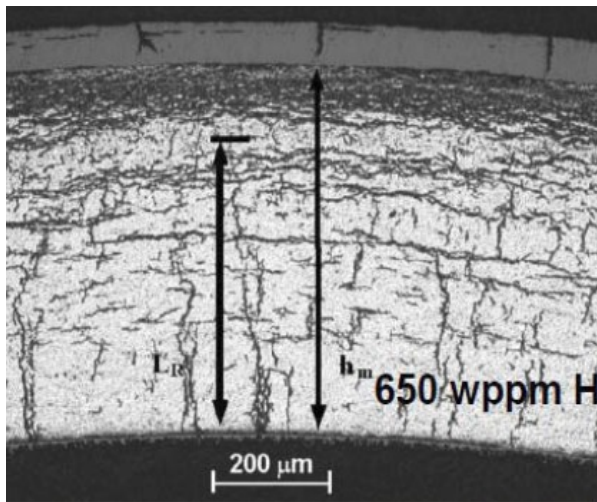
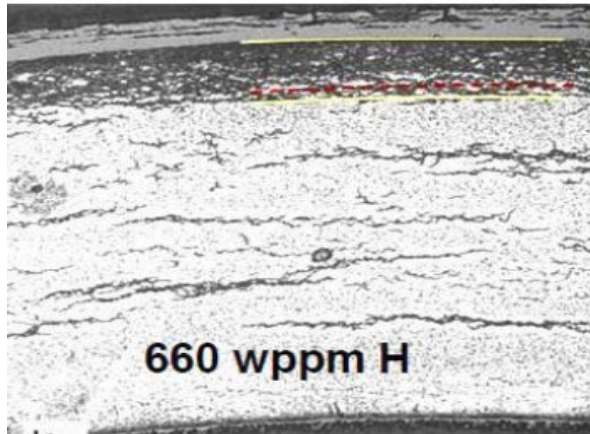
Phase 1 Cyclic Test Results



Ongoing Testing on CIRFT



Effect of Hydride Re-orientation



Licensing Review Implications

Side-Drop G-Load Equivalent*

- Three-moment equation solution for continuous beam
- W 15x15, nominal cladding geometry, Zirc-4 material
 - Assembly weight = 1420 lb.; No. of spacers = 7
 - No. of rods = 204; Fueled length = 144 in.
 - Side-drop lateral loading at 1 g = $1420/(204 \times 144) = 0.04834$ lb/in
 - M_{\max} = maximum fuel clad bending moment
 - $M_{\max}/g = 0.1058wl^2/g = 2.9459$ lb-in/g = 0.3328 N-m/g ($l = 24$ in)
 - CIRFT g-load amplitude equivalent at 1 N-m
 - $1g/(0.3328\text{N-m}) = 3$ g/N-m

* Calculation based on LLNL UCID-21246, "Dynamic Impact Effects on Spent Fuel Assembly,"
October

Licensing Review Implications

- Fuel cladding side-drop endurance limit
 - Nominal cladding thickness: 15 g
 - Net cladding thickness: 12 g (100 μm oxidation)
- CIRFT applied moment for the cladding to yield
 - Moment amplitude = $84 \text{ g}/(3 \text{ g/N-m}) = 28 \text{ N-m}$
 - Moment amplitude = $71 \text{ g}/(3 \text{ g/N-m}) = 24 \text{ N-m}$ (100 μm oxidation)
- CIRFT applied moment for the fueled rod to yield
 - Undefined - static test moment to 85 N-m
- Fuel rod bending endurance limit: 5.08 to 8.89 N-m
 - Lateral inertia load equivalent of 15 to 27 g

Conclusions

- NCT vibration performance margin
 - Fueled rod endurance limit of 15 g \gg 0.42 g considered by a cask vendor, for a closure bolt fatigue analysis, per NUREG 766510*
 - Fuel cladding unlikely to fail undergoing NCT vibration
 - 1-ft cask side drop quasi-static g-load of about 20 g is bounded by the HBF bending and fatigue tests
- Comparable phase 1 results expected of the HBF with hydride re-orientation in phase 2 testing
- Test results are being considered by the staff for developing review guidance to license HBF for storage and transportation accident conditions

* Magnuson CF and LT Wilson, "Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks," SAND76-0427, NUREG 766510, Sandia National Laboratories, Albuquerque, New Mexico, 1977

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Questions?