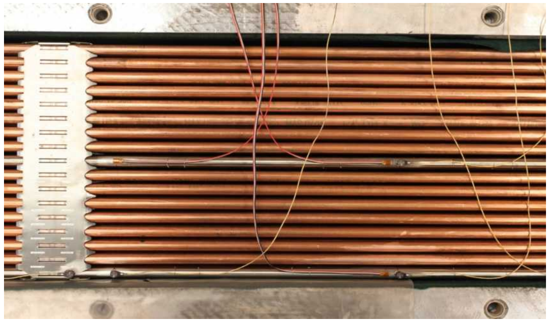
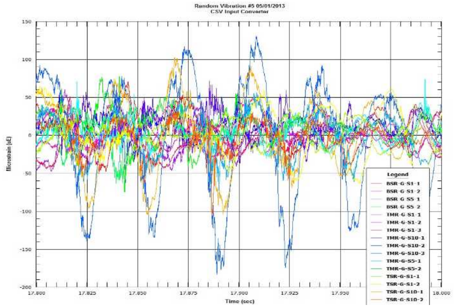
SAND2014-2043C

*Exceptional service in the national interest*

Sandia National Laboratories






# Determination of Loadings on Spent Nuclear Fuel Assemblies During Normal Conditions of Transport

## International Symposium on Spent Nuclear Fuel (SNF) Management

Ken Sorenson

March 26, 2014

SAND2013-XXXXP

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

**There has been much R&D work over the last 4 decades related to cask response to severe accident conditions…………**

**Most of this work relates to understanding cask response and its ability to remain leak-tight after severe mechanical and thermal loadings are applied…………**

RAIL1.AVI

RAIL2.AVI

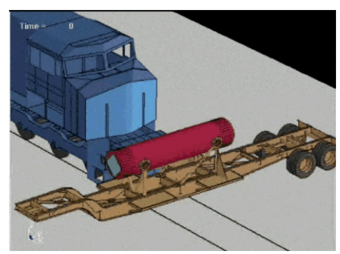
grade_cross_collision2.avi

TRUCK84.AVI

FIRE.AVI

Rail Impact Test
- 74-ton package
- 81 mph impact

Locomotive Impact Test
- 25-ton package
- 120-ton locomotive
- 81 mph impact



Locomotive Impact Analysis
- 25-ton package
- 120-ton locomotive
- 80 mph impact

Truck Impact Test
- 22-ton package
- 84 mph impact

Calorimeter Fire Test
- 30 minutes
- Fully engulfing

U.S.NRC
United States Nuclear Regulatory Commission
*Protecting People and the Environment*

NUREG-2125

**Spent Fuel Transportation Risk Assessment**

Final Report

Manuscript Completed: September 2013
Date Published: January 2014

John R. Cook, NRC Project Manager

Office of Nuclear Materials Safety and Safeguards

Sandia National Laboratories

**In January 2014, the US NRC published NUREG-2125 which affirmed the safety of transport. This study states that there is only a 1 in 1 billion chance of radioactive material release in the event of an accident.**

**However, while we are confident that we can accurately analyze cask response during severe mechanical and thermal loadings, we have limited knowledge of how the spent fuel itself will respond, even during normal conditions of transport…….**

## In the United States, two unrelated factors have focused attention on the integrity of high burnup spent fuel (i.e., > 45 GWD/MTU) during storage and transportation operations:

| Cessation of the Yucca Mountain repository licensing activities |
|---|

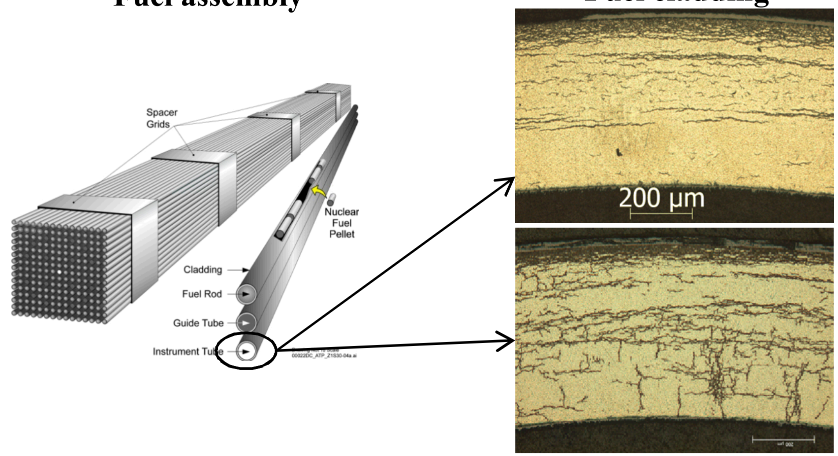
(www.pubs.usgs.gov)

**Impact:**

- **Spent fuel may be stored for periods well beyond the current licensing timeframe**
- **Long term degradation mechanisms are not validated**

| Efficiencies in US reactor operations have resulted in higher fuel burnups |
|---|

**Fuel assembly** **Fuel cladding**




(Billone, Argonne Nat'l Lab Presentation to EPRI/ESCP Dec 5, 2013)

**Impact:**

- **Longer duty cycles result in more hydrogen being absorbed into the fuel cladding**
- **Operational drying cycles may result in hydride re-orientation, thereby reducing cladding ductility**

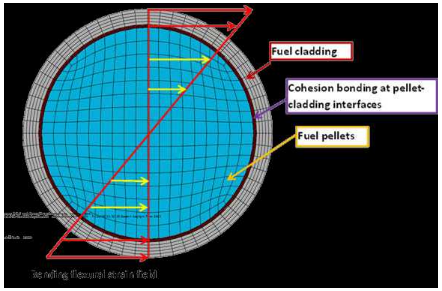
# A technical basis is needed to demonstrate our understanding of high burnup fuel response to retrieval from storage and to transport.

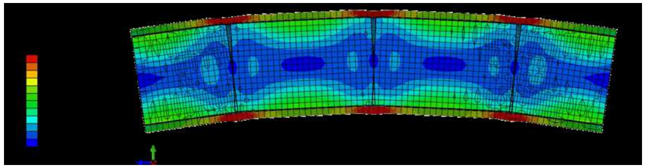
**This requires validation of the integrity of high burnup spent fuel through a combination of testing and analysis to demonstrate actual performance.**

Fundamentally: **applied stress/strain < material strength**

**Requires determination of:**
- Loads
- Applied strains
- Calculated stresses

**Requires determination of:**
- Material properties
  - Yield/ultimate strength
  - Ductility
  - Fracture toughness
- Constitutive relationships
- Pellet-clad interaction



Jiang, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

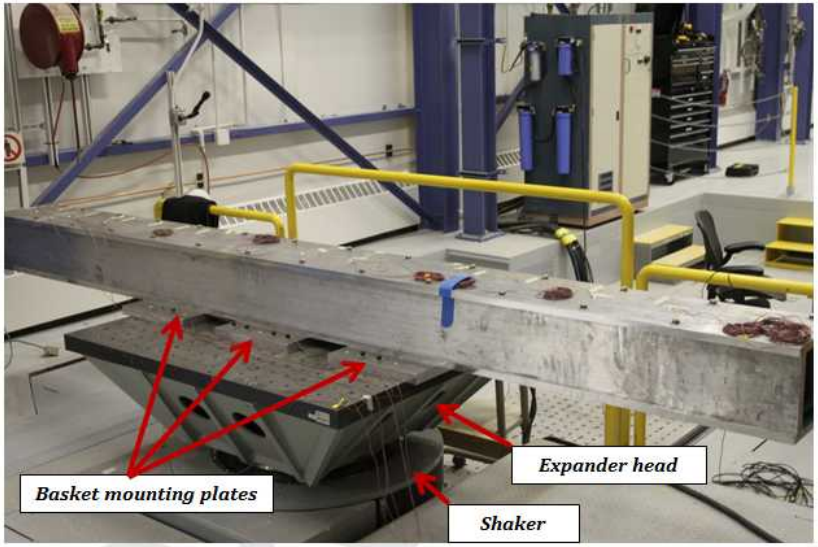
**The US DOE storage and transportation R&D program is developing this technical basis. Sandia is the lead lab for determining loads transferred to the fuel during Normal Conditions of Transport.**

# Assembly Shaker Test

**Sandia conducted a series of shaker table tests in April 2013 as a first step in determining loads transmitted to fuel during Normal Conditions of Transport**

Objectives

1. Simulate normal conditions of transport loading on a surrogate PWR fuel assembly by applying vibration and shock loadings that the assembly would experience during truck transport.
2. Instrument the fuel cladding to measure accelerations and strains imposed by the vibration and shock loadings resulting from normal condition of transport.

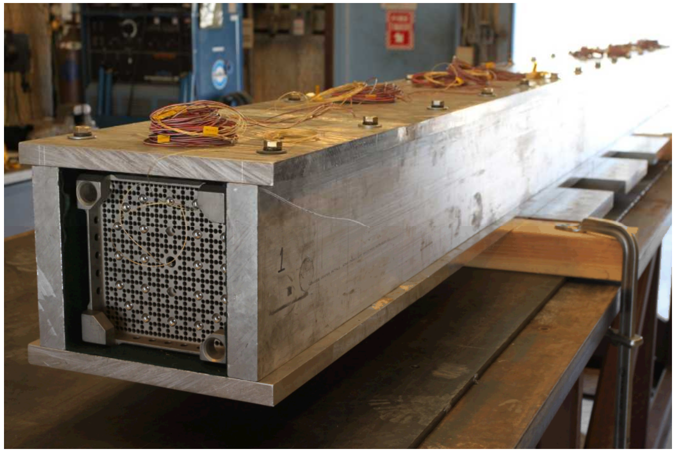


# Test Configuration

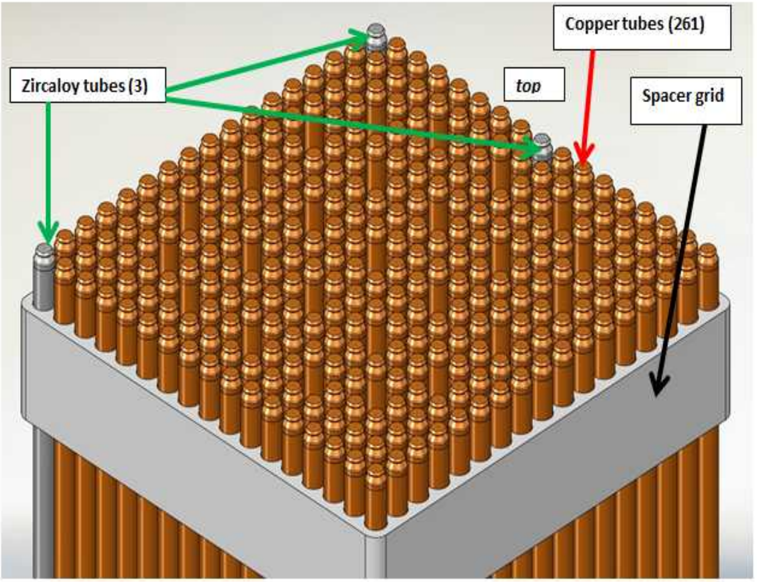
- The test unit included a fully loaded assembly and a basket.
- The test configuration was based upon the geometries of the NAC-LWT truck cask with a PWR basket.
- The assembly was placed in a basket which was placed on a shaker. The basket was bolted to the shaker. The clearances between the assembly and the basket matched those of the assembly/basket for the NAC-LWT design.
- The assembly had the same lateral and vertical freedom of motion as it would have in an actual cask.
- The mass and stiffness of the surrogate assembly match well with a real fresh fuel PWR 17x17 assembly

Basket Specifications

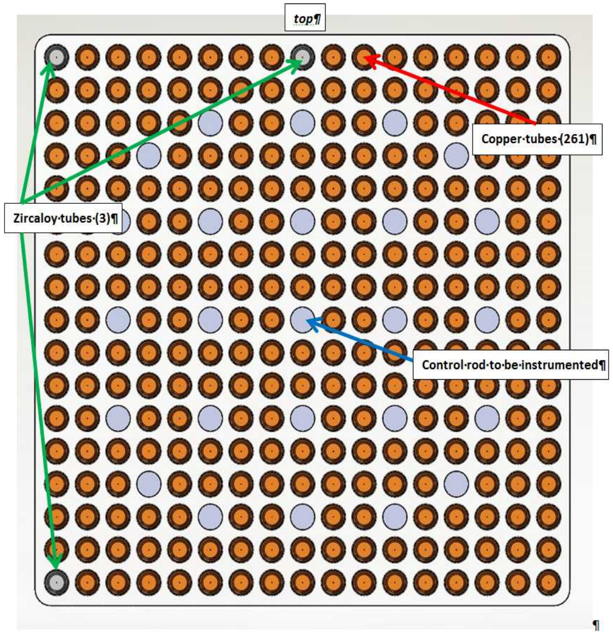
- 6061 Aluminum Basket
- Sides 1.5 inches thick
- Top/bottom 1 inch thick
- Length 161.5 inches
- Weight 837 pounds



# Surrogate 17x17 PWR Experimental Assembly




Isometric View of Fuel Rods



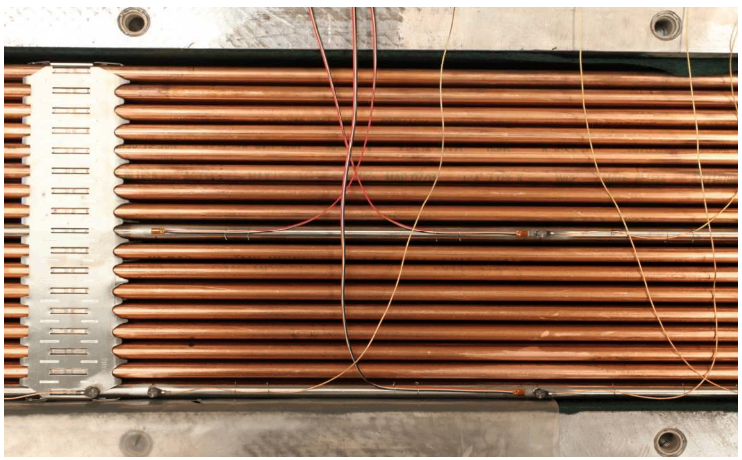

Top View of Assembly

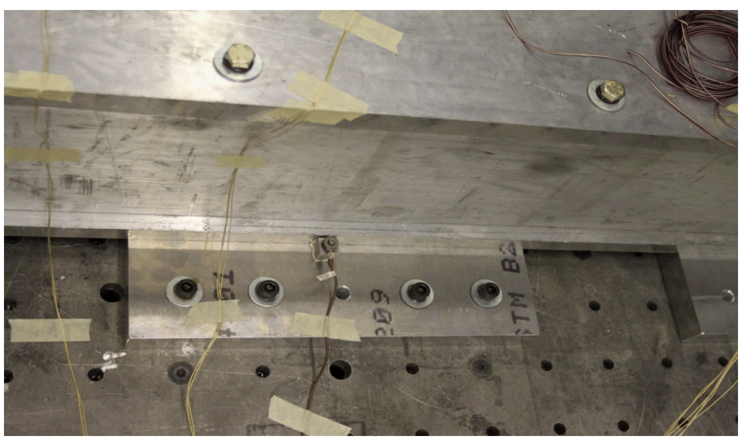
**Surrogate rod:**

- **Three Zr-4 rods**
- **Remainder: Copper**
- **All filled with lead rope**
- **Mass simulates fresh $U0_2$ fuel**

# Instrumentation

- Instrumentation placement based on pre-test finite elements analyses
- Only the Zr-4 rods and spacer grids were instrumented
  - 16 strain gages
  - 18 accelerometers on rods and grids
  - 7 accelerometers on basket and shaker table





# Applied Loadings for the Tests

- Input for the shaker was derived from data in "Shock and Vibration Environments for a Large Shipping Container During Truck Transport (Part II)", NUREG/CR-0128, 1978, SAND78-0337
- NUREG/CR-0128 details:
  - Vibration and shock data were measured by accelerometers over a 700-mile journey. Two tests, two casks, 56000 and 44000 pounds.
  - Measurements taken on the external body of the casks.
  - Speeds ranged from 0 to 55 mph.

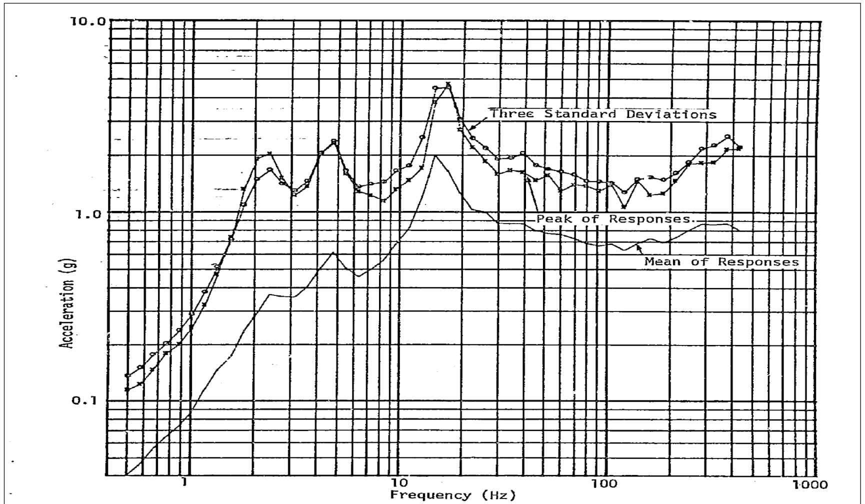



Figure 5. Superimposed Shock Response Spectra, 3% Damping, Vertical Axis

Figure 3.0-1: Recommended Random Vibration Test Specification

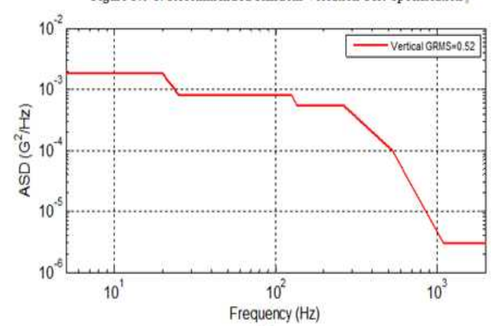



Table 3.0-1: Vibration Breakpoints

| Frequency (HZ) | ASD (G^2/Hz) |
|---|---|
| 5 | 1.8e-3 |
| 20 | 1.8e-3 |
| 25 | 8.0e-4 |
| 125 | 8.0e-4 |
| 135 | 5.5e-4 |
| 265 | 5.5e-4 |
| 530 | 1.0e-4 |
| 1100 | 3.0e-6 |
| 2000 | 3.0e-6 |

Figure 4.0-1: Recommended Shock Test Specification

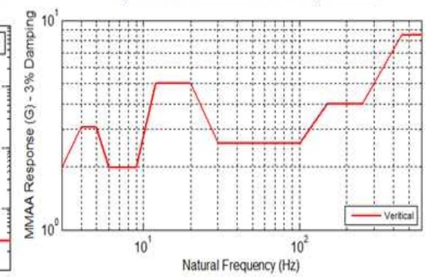
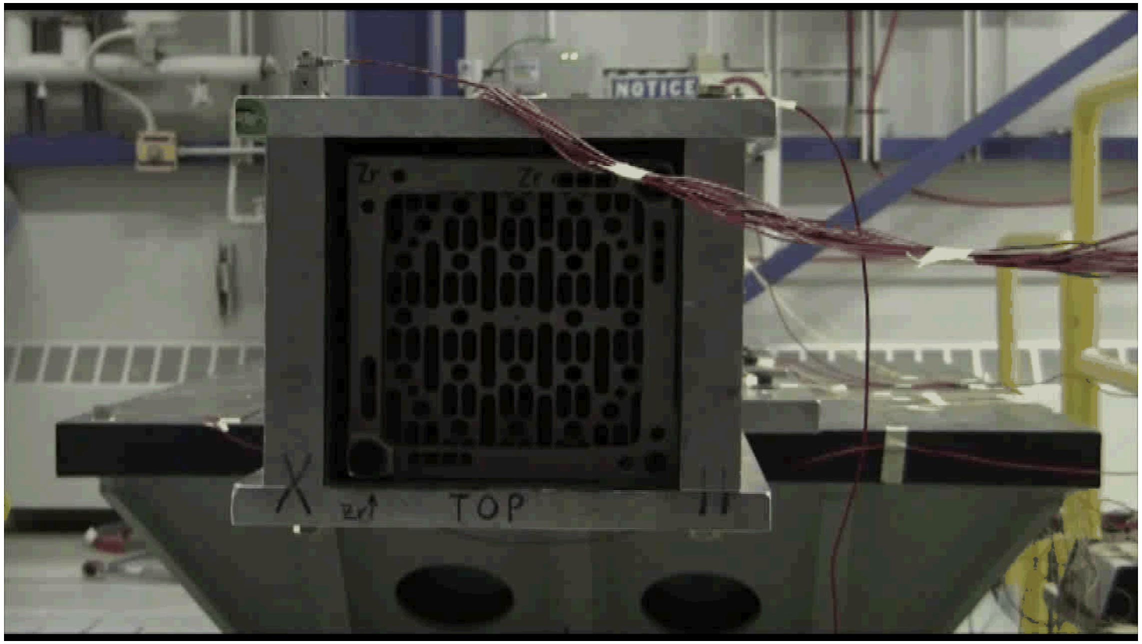


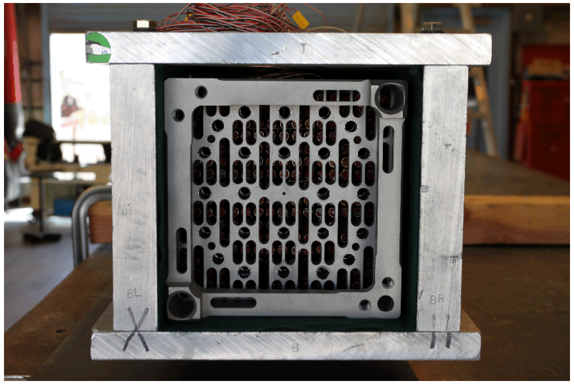

Table 4.0-1: Reference Shock Breakpoints

| 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 |

Shock response spectra: NUREG/CR-0128 ⟶ Spectral density input to the shaker table

# Mounted assembly and basket on the shaker table

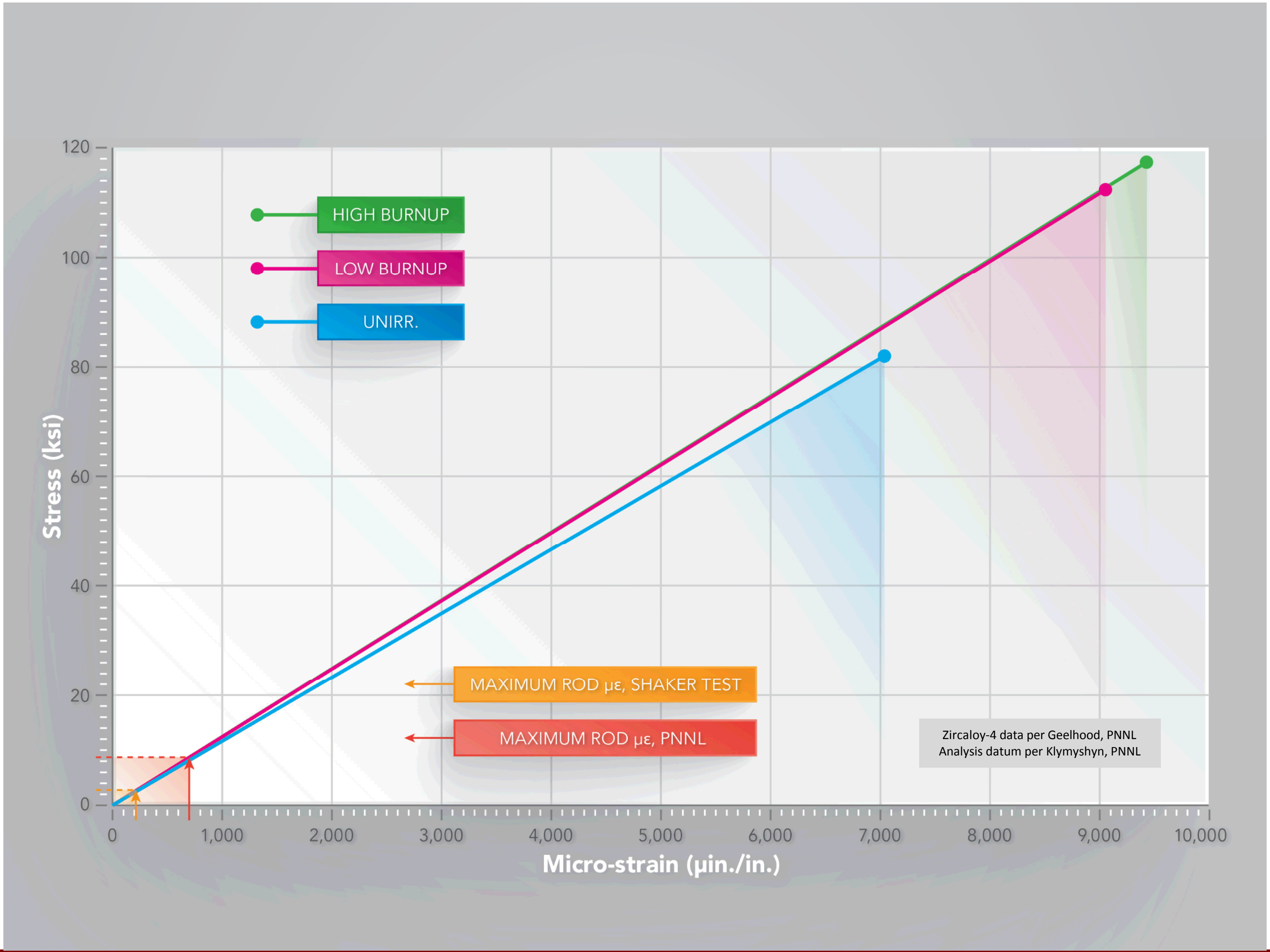


- 6 vibration tests
- 5 shock tests
- Loading in vertical direction only
- Maximum measured strain was 213 με

# Results

## Measured Strains are Very Low Relative to the Elastic Limit of Zr-4



# Maximum Micro-strains on Fuel Rods during Shock Test

| Maximum Strains on Zircaloy Fuel Rods, Shock Test #1 | | | |
|---|---|---|---|
| **Rod Location** | **Assembly Span** | **Position on Span** | **Maximum Strain (µin./in.)** |
| Top-middle rod | Bottom-end | Adjacent to spacer grid | 90 |
| Top-middle rod | Bottom-end | Mid-span | 131 |
| Top-middle rod | Bottom-end | Adjacent to spacer grid | 171 |
| Top-middle rod | Mid-assembly | Adjacent to spacer grid | 104 |
| Top-middle rod | Mid-assembly | Mid-span | 97 |
| Top-middle rod | Top-end | Adjacent to spacer grid | 127 |
| Top-middle rod | Top-end | Mid-span | **199** |
| Top-middle rod | Top-end | Adjacent to spacer grid | 70 |
| Top-side rod | Bottom-end | Adjacent to spacer grid | **54** |
| Top-side rod | Bottom-end | Mid-span | 107 |
| Top-side rod | Top-end | Mid-span | 117 |
| Top-side rod | Top-end | Adjacent to spacer grid | 113 |
| Bottom-side rod | Bottom-end | Mid-span | 62 |
| Bottom-side rod | Bottom-end | Adjacent to spacer grid | 121 |
| Bottom-side rod | Mid-assembly | Adjacent to spacer grid | 110 |
| Bottom-side rod | Mid-assembly | Mid-span | 115 |

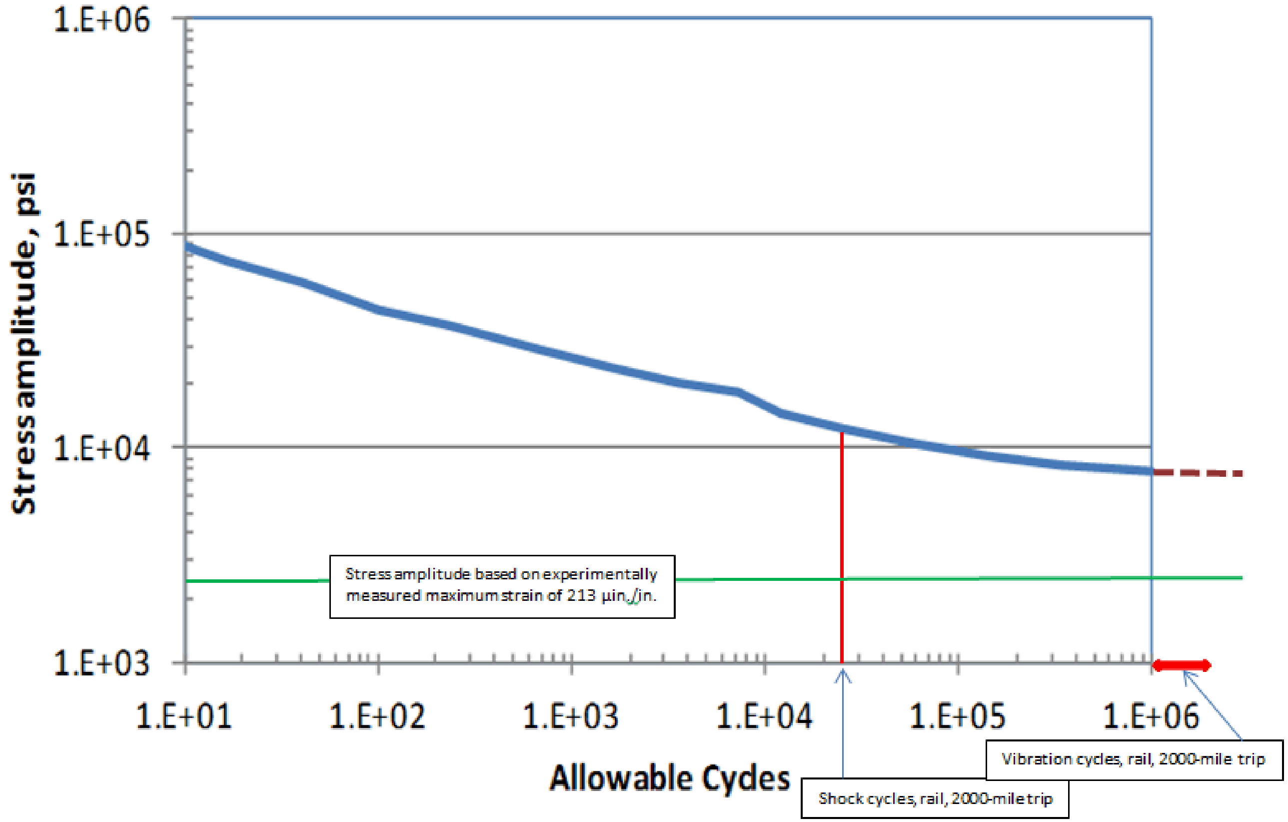
| | |
|---|---|
| **Average of All Strain Gages** | **112** |
| **Average Top-middle Rod** | **124** |
| **Average Top-side Rod** | 98 |
| **Average Bottom-side Rod** | 102 |
| **Average Bottom-end Span** | 105 |
| **Average Mid-assembly Span** | 107 |
| **Average Top-end Span** | **125** |
| **Average Mid span** | **118** |
| **Average Adjacent to Spacer Grid** | 107 |

# Average Accelerations and Average Peak Accelerations during Random Vibration Test

| Average Accelerations, $g_{RMS}$, and Average Peak Accelerations, $g_{peak}$, Random Vibration Test #5 | | | | |
|---|---|---|---|---|
| Location | Span | Position on Span | Average ($g_{RMS}$) | Average ($g_{peak}$) |
| SHAKER | | | 0.5 | 0.7 |
| Top-middle | 1 | On spacer grid | 1.3 | 1.8 |
| Top-middle | 1 | Adjacent to spacer grid | 2.0 | 2.8 |
| Top-middle | 1 | Mid-span of rod | 2.0 | 2.8 |
| Top-middle | 1 | Adjacent to spacer grid | 0.3 | 0.4 |
| Top-middle | 1 | On spacer grid | 0.7 | 1.0 |
| Top-middle | 5 | On spacer grid | 1.2 | 1.7 |
| Top-middle | 5 | Adjacent to spacer grid | 3.7 | 5.2 |
| Top-middle | 5 | Mid-span of rod | 4.0 | 5.7 |
| Top-middle | 5 | Adjacent to spacer grid | 3.9 | 5.5 |
| Top-middle | 5 | On spacer grid | 0.6 | 0.8 |
| Top-side | 10 | On spacer grid | 0.6 | 0.8 |
| Top-side | 10 | Adjacent to spacer grid | 3.8 | 5.4 |
| Top-side | 10 | Mid-span of rod | 4.3 | 6.1 |
| Top-side | 10 | Adjacent to spacer grid | 4.6 | 6.5 |
| Top-side | 10 | On spacer grid | 1.0 | 1.4 |
| Control rod, bottom end | 1 | On control rod | 0.7 | 1.0 |
| Control rod, top end | 10 | On control rod | 0.9 | 1.3 |
| Basket, bottom end | ≈ 1 | On top edge of basket | 1.9 | 2.7 |
| Basket, mid-span | ≈ 5 | On top edge of basket | 0.9 | 1.3 |
| Basket, top end | ≈ 10 | On top edge of basket | 1.7 | 2.4 |
| Mounting plate, vertical | ≈ 5 | Near mid-span of basket | 1.0 | 1.4 |
| Mounting plate, lateral | ≈ 5 | Near mid-span of basket | 0.08 | 0.1 |
| Mounting plate, long. | ≈ 5 | Near mid-span of basket | 0.09 | 0.1 |

# Fracture Mechanics & Fatigue Assessments Based Upon Experimentally-Measured Strains

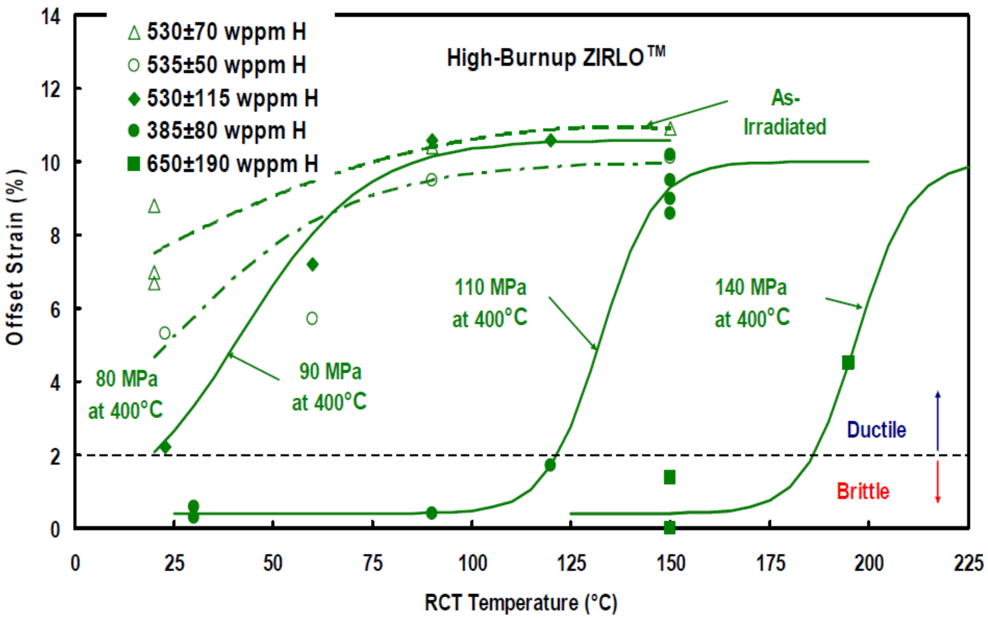
| Crack depth/Zircaloy-rod wall thickness | Applied stress intensity at crack tip, (MPa-√m) | Lower bound Zircaloy-4 fracture toughness, (MPa-√m) |
|---|---|---|
| 0.10 | 0.3 | 20 - 30 |
| 0.25 | 0.4 | |
| 0.50 | 0.6 | |



# Next Steps

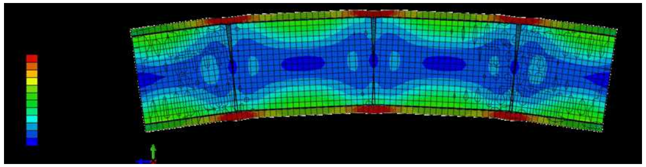
**Preliminary results look promising in demonstrating that high burnup fuel can maintain its integrity during Normal Conditions of Transport. However, more work needs to be done:**

- **Verify NRC NUREG/CR-0128 shock and vibrations loadings for NCT**
- **Test at lower frequencies: ~ 1 Hz (current test range 3 Hz to 1500 Hz)**
- **Conduct test to simulate 30 cm drop?**
- **Conduct similar tests for rail conditions**
- **Integrate materials testing results into evaluations (e.g., DBTT, PCI)**




Billone, Argonne National Laboratory, EPRI ESCP Meeting, Dec. 2013

Relating curvature to flexural rigidity:
EI = M/κ



Jiang, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

# Danke schön für Ihnen Aufmerksamkeit!