Fuel Assembly Vibration/Shock Test Simulating Normal Truck Transport

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Assembly Shaker Test

The objectives of this test program are to:

- Simulate over-the-road tests on a full-scale representative fuel assembly by applying loadings that used nuclear fuel cladding would experience during normal conditions of transport (NCT).
- Instrument the cladding to directly capture accelerations and strains imposed by the shock and vibration mechanical loadings resulting from the normal condition of transport criteria.
- Provide data to benchmark analyses.

Motivation for Assembly Test

Why is this test important?

There is little data on mechanical loadings that are subjected directly to the fuel pins during NCT.

For retrieval after storage, and subsequent transport, it is important to assess the ability of high burnup used fuel to maintain its integrity during NCT.

The margin of safety between the applied loads on fuel roads and the material properties of the high burnup-rods has not be quantified:

Is $\textit{applied stress}_{\textit{normal transport}} < \textit{yield strength}_{\textit{cladding}}$ **?**

Application of Test Results

The data from the assembly shaker test (fuel rod accelerations and applied strains) shall be used to validate finite element models of fuel assemblies being developed at Pacific Northwest National Laboratory (LS-DYNA).

Given clad degraded material properties from other DOE R&D experimental programs, conduct analyses to assess high burnup used fuel integrity during NCT.

The validated models can be used to analytically determine the loads on fuel rods for other basket configurations, cladding types and transport environments, particularly rail.

Experimental Compromises

Due to funding levels, several important compromises had to be implemented

Issue	Compromise
Actual truck casks too costly	Perform test without a cask Simulate truck transport with shaker table*
Available truck casks are contaminated	
Using UO_2 pellets not feasible	Use Pb filler as surrogate
Availability of Zircaloy tubes available, but limited	Use Cu tubes as surrogate
Surrogates possess material properties dissimilar to Zircaloy	Adjust wall thickness of Cu tubes so that $EI_{Cu} = EI_{Zirc}$ Adjust amount of Pb in tubes to that total assembly weight is that of actual assembly
Assembly is in a basket in a truck cask	Construct basket to simulate a NAC-LWT configuration. Affix basket to shaker.

***U.S. Nuclear Regulatory Commission, "Shock and Vibration Environments for a Large Shipping Container During Truck Transport (Part II)," NUREG/CR-0128 (SAND Report 78-0337), August 1978. (Referenced in *Section 2.5.6.5 Vibration* in NUREG-1609, "Standard Review Plan for Transportation Packages for Radioactive Material"**

Surrogate Material Response

- **SOLID**WORKS **simulation predicts a bending response difference of less than 5% between the Cu-Pb rod and Zircaloy-Pb rod**

10 lb Bending Test	
Configuration	Deformation (mm)
Zircaloy	29.9
Cu	28.9

- **Combined Modulus / Moment of Inertia properties were checked in order to get an idea on the combined stiffness of each rod**
  - $EI_{Cu\text{-}Pb} = 8.71\ K\text{-}in^2$
  - $EI_{Zirc\text{-}Pb} = 5.53\ K\text{-}in^2$

- **Conclusion: Cu tubing with Pb rod is slightly stiffer than Zircaloy-Pb**

Material Properties

Material Properties	ρ ($g \cdot cm^{-3}$)	E (GPa)
UO_2	10.98	200
Pb	11.34	16
Zircaloy	6.55	99
Cu	8.94	115

- Conclusions
  - UO_2 and Pb share very similar densities
  - UO_2 is considerably more stiff than Pb
  - Zircaloy is 30% less dense than Cu
  - Zircaloy shares a similar stiffness with Cu

- Although the material surrogates do not mimic the true material properties exactly, they are the best as far as availability, constructability, and cost.

- Because the mass and the stiffness between the surrogate and a real assemble are close, we expect the dynamic response of the assembly to represent that of a real fresh fuel assembly.

Experimental Assembly

- **Actual Assembly weighs approximately 1404 lbs**
- **Experimental assembly weighs approximately 1446 lbs**
- **NAC-LWT PWR basket weighs 840 lbs; test basket weigh 837 lbs**

- **Although the stiffness of the actual rods and experimental rods are not the same (mostly due to properties of the UO_2 *v*. Pb), the weights are nearly exact – weight is considered the most important parameter to simulate.**

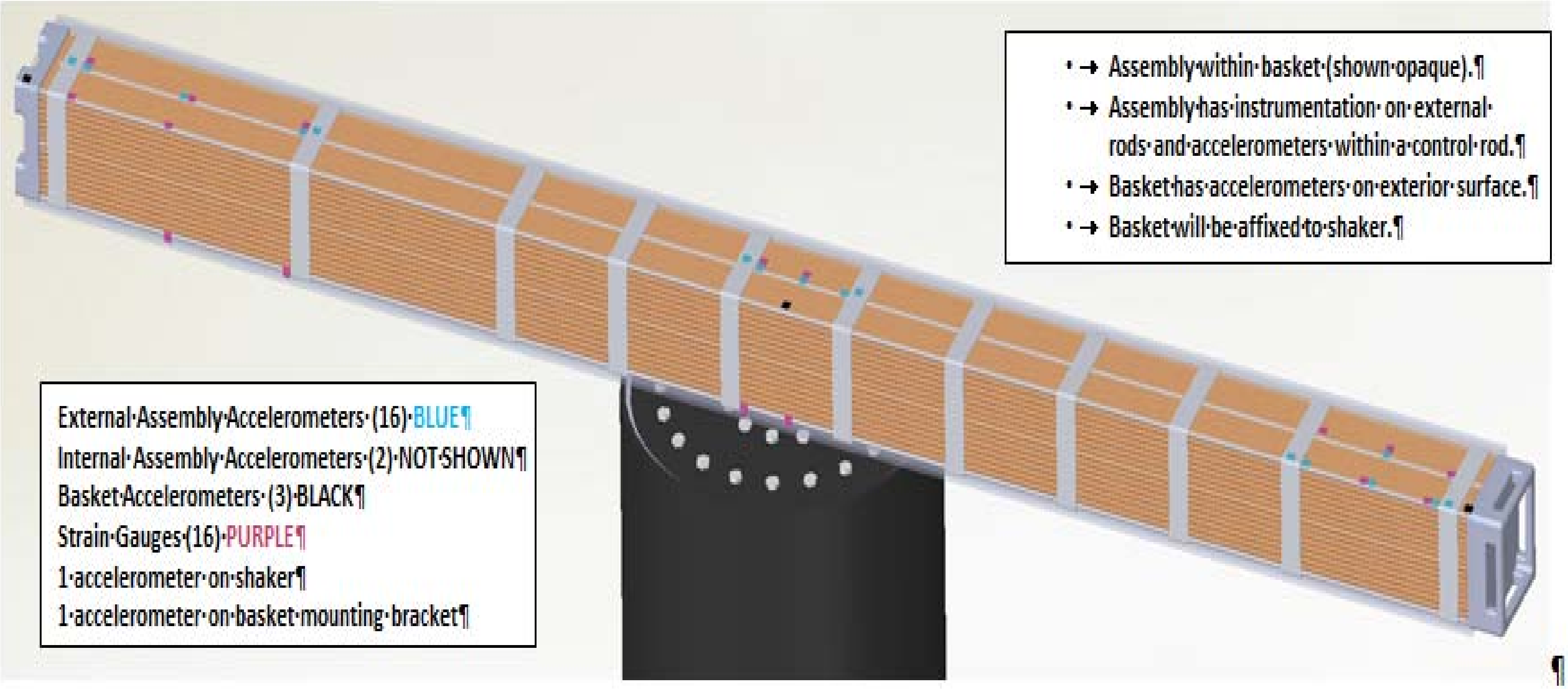
Test Configuration

- The test configuration is based upon the geometries of the NAC-LWT truck cask with a single PWR basket.

- The test hardware will include the fully loaded surrogate assembly and a mass-equivalent basket.

- The assembly shall be placed in the basket which will be placed on a shaker table. The basket will be bolted to the shaker table. The clearances between the assembly and the basket will match those of the assembly/basket for the NAC-LWT design.

Instrumentation Locations on Assembly

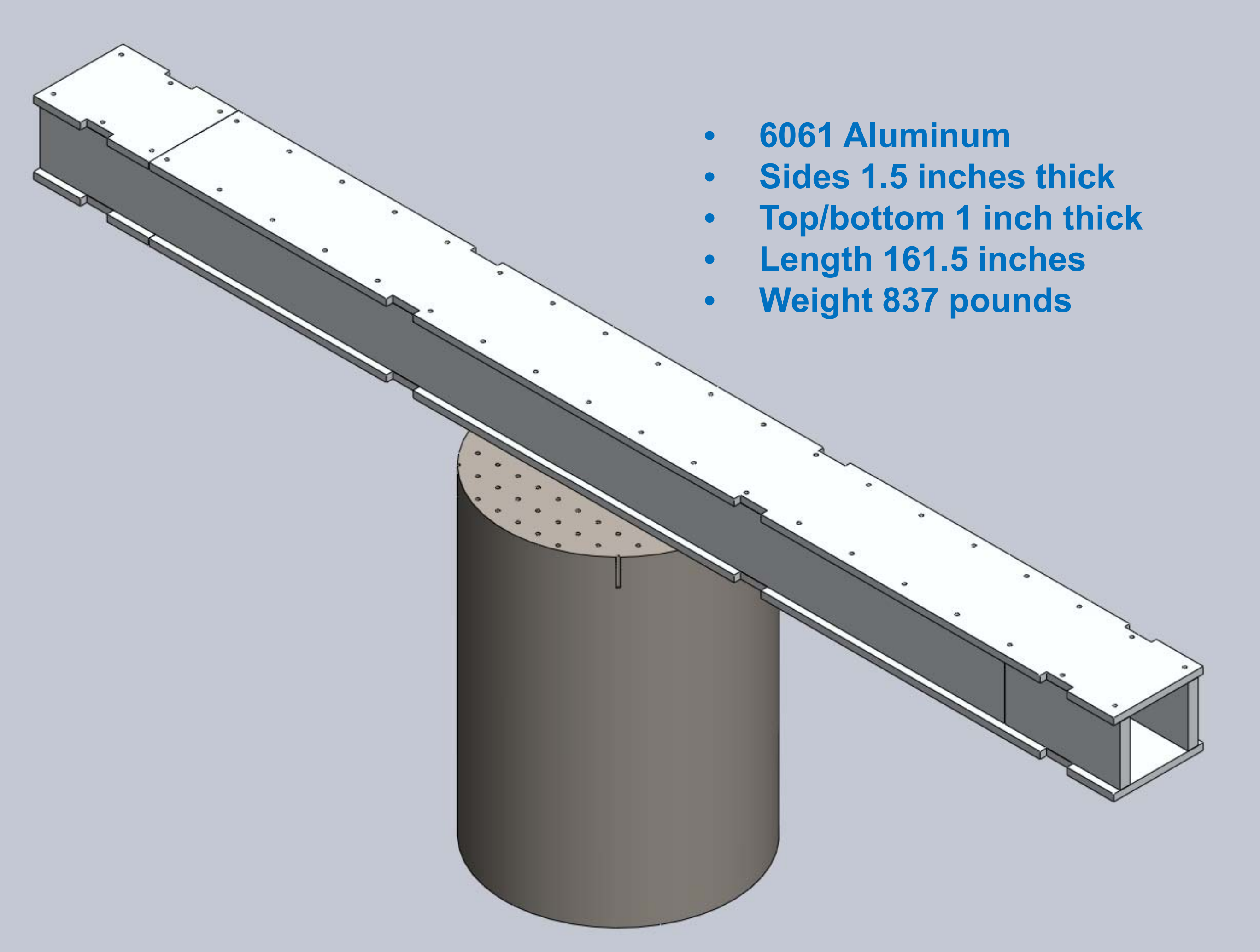


- Assembly within basket (shown opaque).
- Assembly has instrumentation on external rods and accelerometers within a control rod.
- Basket has accelerometers on exterior surface.
- Basket will be affixed to shaker.

External Assembly Accelerometers (16) BLUE
Internal Assembly Accelerometers (2) NOT SHOWN
Basket Accelerometers (3) BLACK
Strain Gauges (16) PURPLE
1 accelerometer on shaker
1 accelerometer on basket mounting bracket

Assembly will be placed within a basket which will be bolted to a 4’ x 5’ table (not shown) mounted to the shaker.

Basket



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

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Test Modifications

- Cu-tube/Pb-rods are used instead of Zircaloy-tube/UO_2-pellets, *except for three Zircaloy-Pb rods.*
- The Zircaloy-Pb rods will be instrumented.
- One Zr-Pb rod will be at the top-center of the assembly; one rod at the top-side; and one rod at the bottom-side.
- Holes will be cut along length of basket in order to provide access to instrumentation.

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pemccon, 4/22/2013

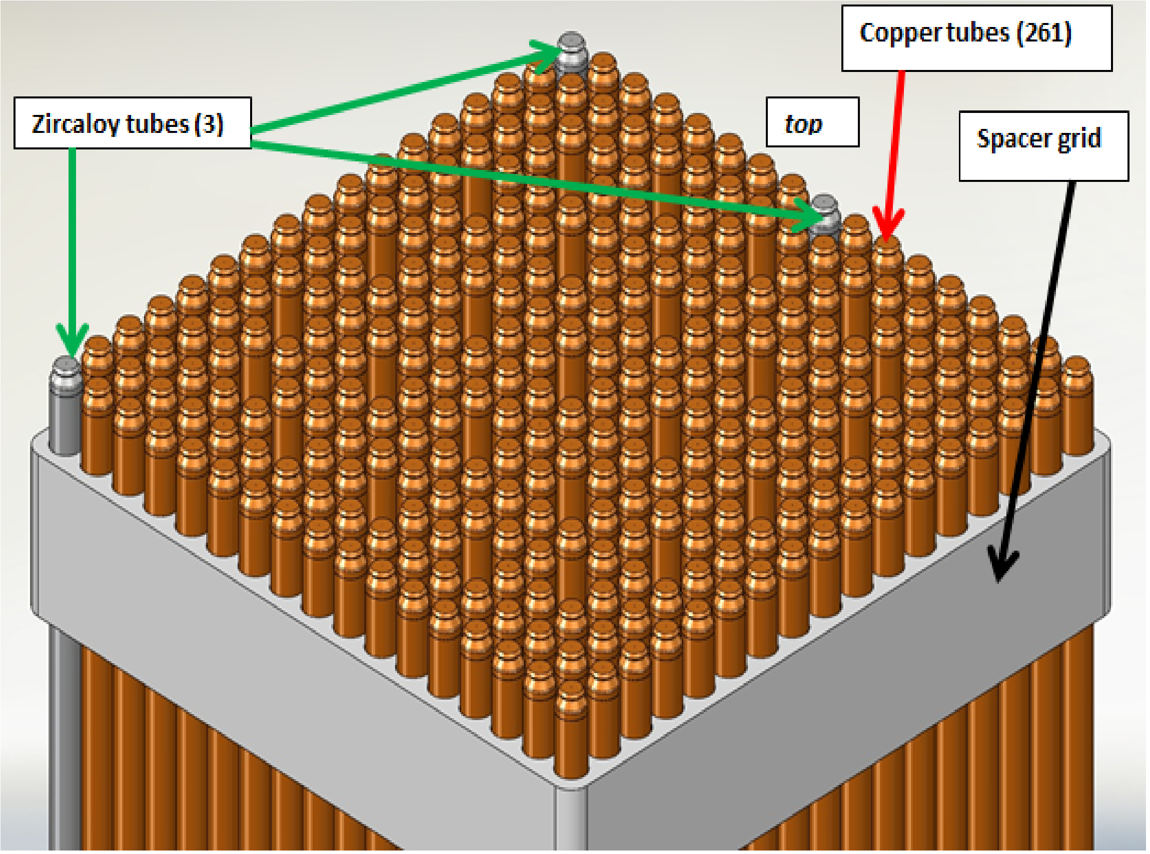
Applied Loading for the Test

Both vibrational and shock accelerations shall be applied to the assembly/basket via the shaker table.

The assembly/basket shall be subjected to vertical accelerations only – no longitudinal or lateral accelerations.

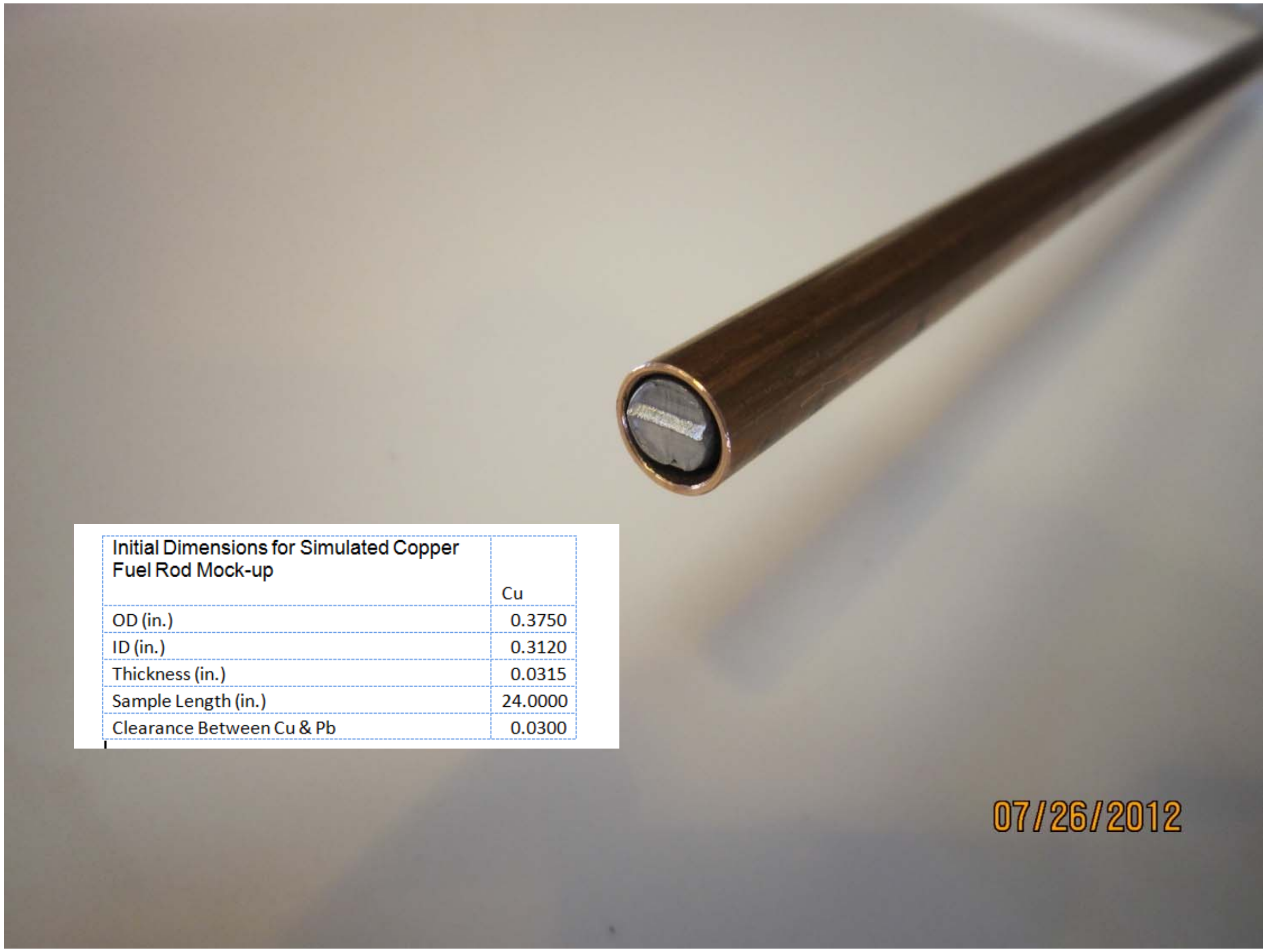
Over-the-road data for trucks show that vertical accelerations due to vibrations and shocks envelope accelerations in the other directions.

Experimental Assembly



Isometric View of Fuel Rods
(Top Nozzle and Basket not shown)

Lead rod within Copper tube



Initial Dimensions for Simulated Copper Fuel Rod Mock-up	Cu
OD (in.)	0.3750
ID (in.)	0.3120
Thickness (in.)	0.0315
Sample Length (in.)	24.0000
Clearance Between Cu & Pb	0.0300

07/26/2012

Model 2250A-10 accelerometers (18)

Inside center guide tube: 3 accelerometers:
- **1 at each end and middle (=3)**

Top, center rod: 10 accelerometers:
- **For portion of rod with *longest* spacing between spacer grids (58.4-cm span), 5 accelerometers**
  - **1 on each spacer grid (=2)**
  - **1 on rod adjacent to each spacer grid (=2)**
  - **1 at mid-span of rod (=1)**
- **For portion of rod with *shortest* spacing between spacer grids (25.8-cm span), 5 accelerometers**
  - **1 on each spacer grid (=2)**
  - **1 on rod adjacent to each spacer grid (=2)**
  - **1 at midspan of rod (=1)**

Top, side rod: 5 accelerometers:
- **For portion of rod with an *intermediate* spacing between spacer grids (26.2-cm span)**
  - **1 on each spacer grid (=2)**
  - **1 on rod adjacent to each spacer grid (=2)**
  - **1 at midspan of rod (=1)**

Top of basket above side wall: 4 accelerometers (*model tbd*)
- **1 at each end and middle (=3)**
- **1 on bracket that restrains basket motion**

A triaxial accelerometer shall be placed on shaker.

CEA-03-062UW-350 Strain gauges (16)

Top, middle rod – 8 strain gauges

For each end span between spacer grids – two spans – one gauge adjacent to each spacer grid and one gauge at mid-span between spacer grids (3 gauges per span).

For portion of rod with shortest spacing between spacer grids, 2 strain gauges: one strain gauge adjacent to a spacer grid, one strain gauge at mid-span

Top, side rod – 4 strain gauges

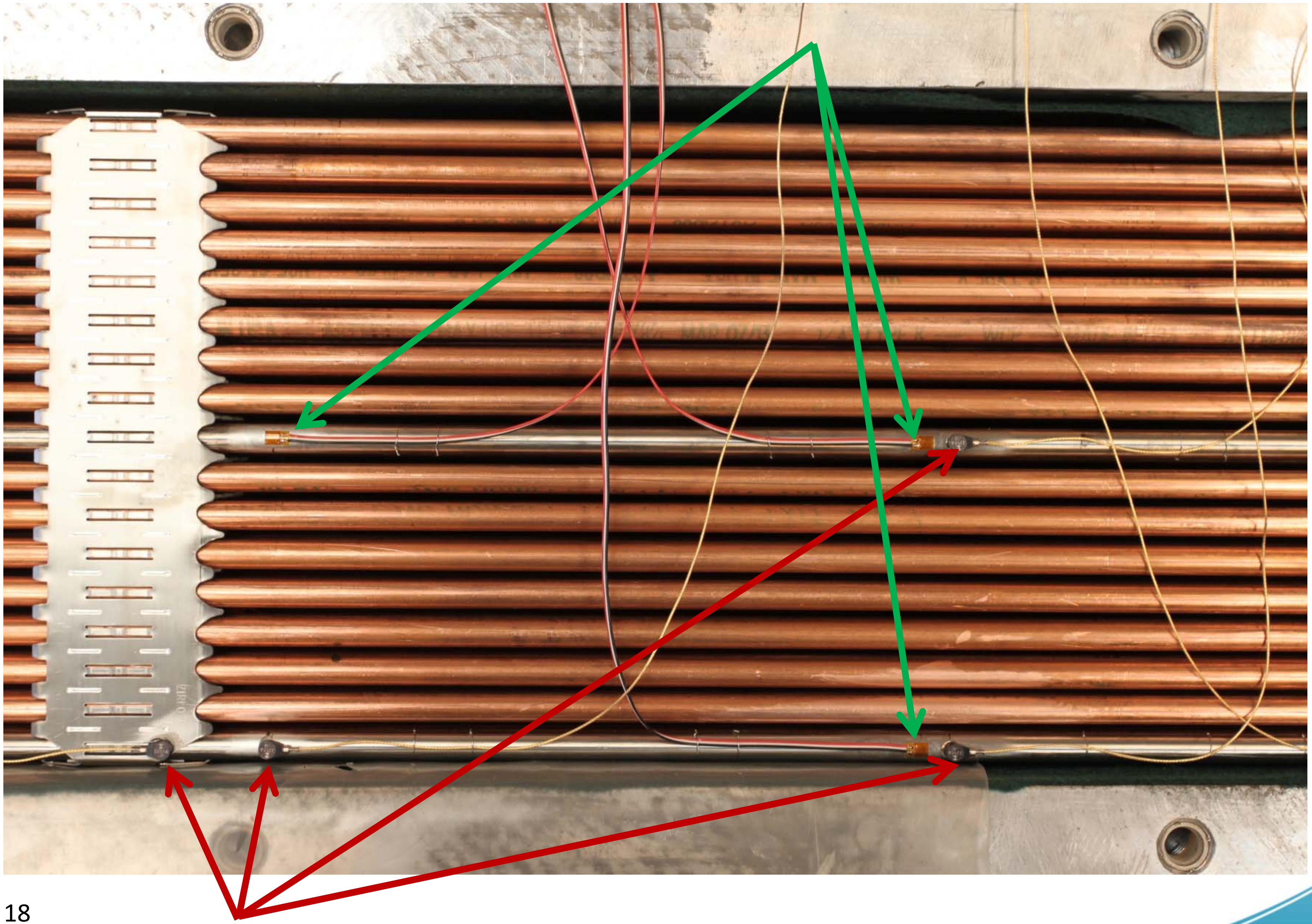
For each end span between spacer grids, one gauge adjacent to one spacer grid and one gauge at mid-span (2 gauges per span)

Bottom, side rod – 4 strain gauges

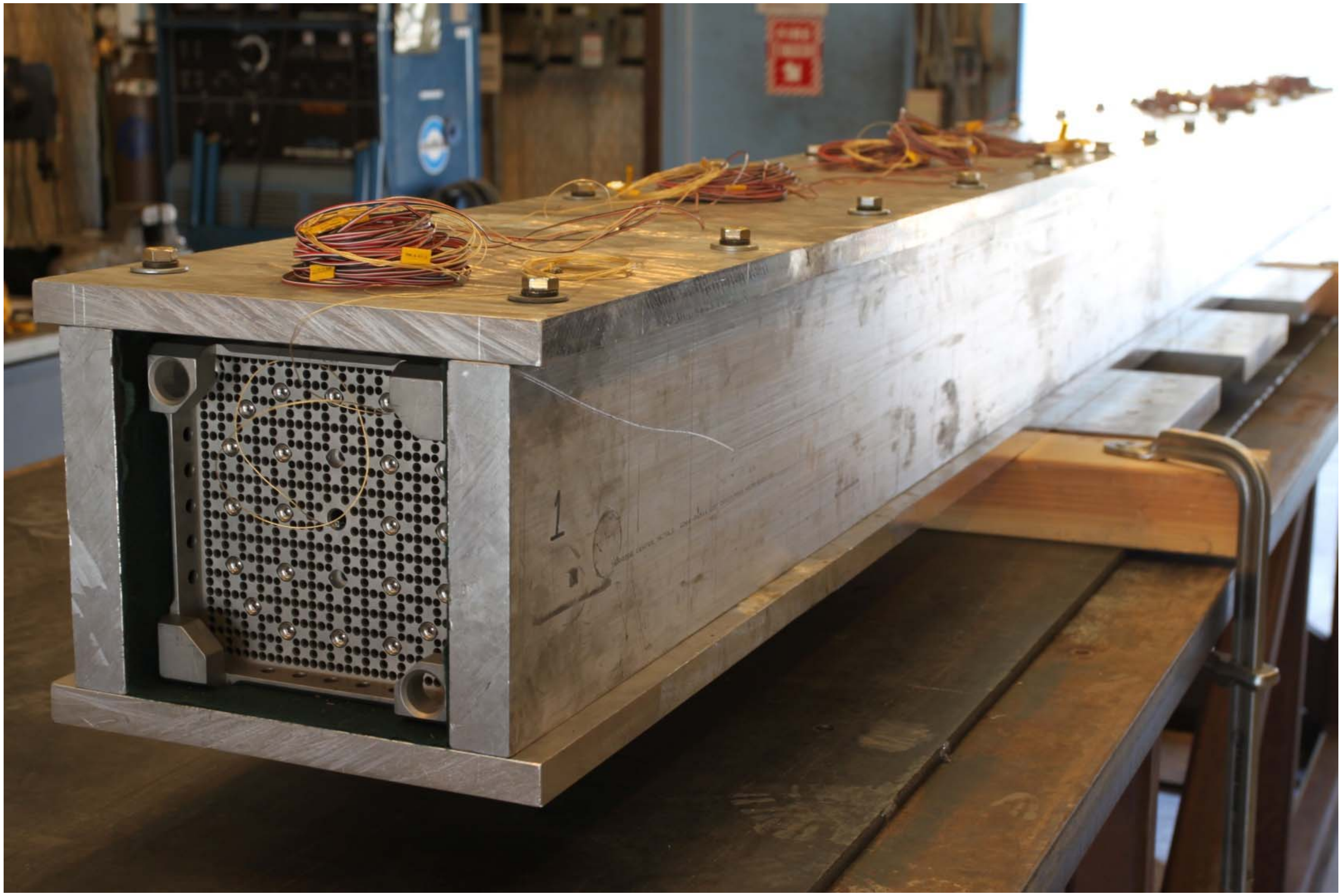
For one end span between spacer grids – two spans – one gauge adjacent to a spacer grid and one gauge at mid-span between spacer grids (2 gauges per span).

For portion of rod with shortest spacing between spacer grids, 2 strain gauges: one strain gauge adjacent to a spacer grid, one strain gauge at mid-span

Accelerometers and Strain Gauges on Top Middle and Top Side Zircaloy Tubes



Assembly in Basket



Technical Basis for Loading Inputs to Shaker for Vibration / Shock Tests of Fuel Assembly

Input Data

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 (SAND Report 78-0337), 1978.
(Referenced in *Section 2.5.6.5 Vibration* in NUREG-1609, "Standard Review Plan for Transportation Packages for Radioactive Material")

- **Report Details:**
  - **Vibration and shock data were measured by accelerometers over a 700-mile journey. Two tests, two casks.**
  - **56000-pound cask and 44000-pound cask.**
    - **Weight of loaded NAC-LWT is 51200 pounds**
  - **Measurements taken on the *external* body of the casks.**
  - **Speeds ranged from 0 to 55 mph.**

- **Using the most conservative data from the 1978 experiment, the shaker will simulate the vibration and shock experienced by the casks during normal transport.**

Vibration Data Converted to Spectral Density

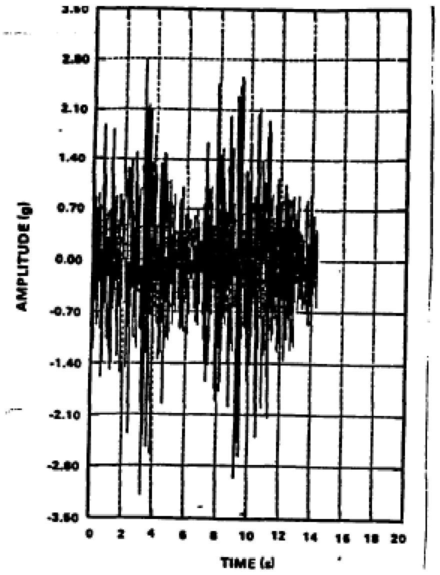


Figure 9a. Representative Time History

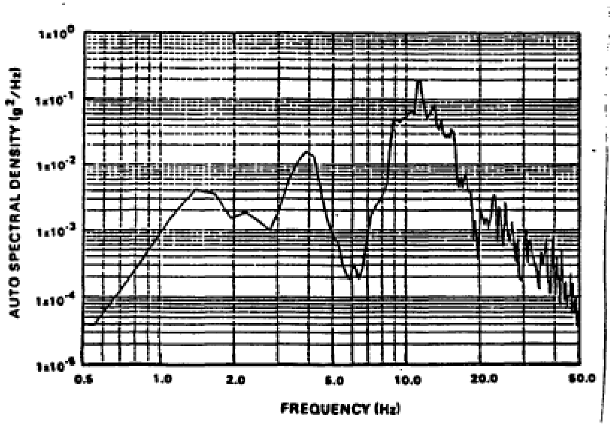


Figure 9b. Representative PSD

Shock Spectra from NUREG/CR-0128

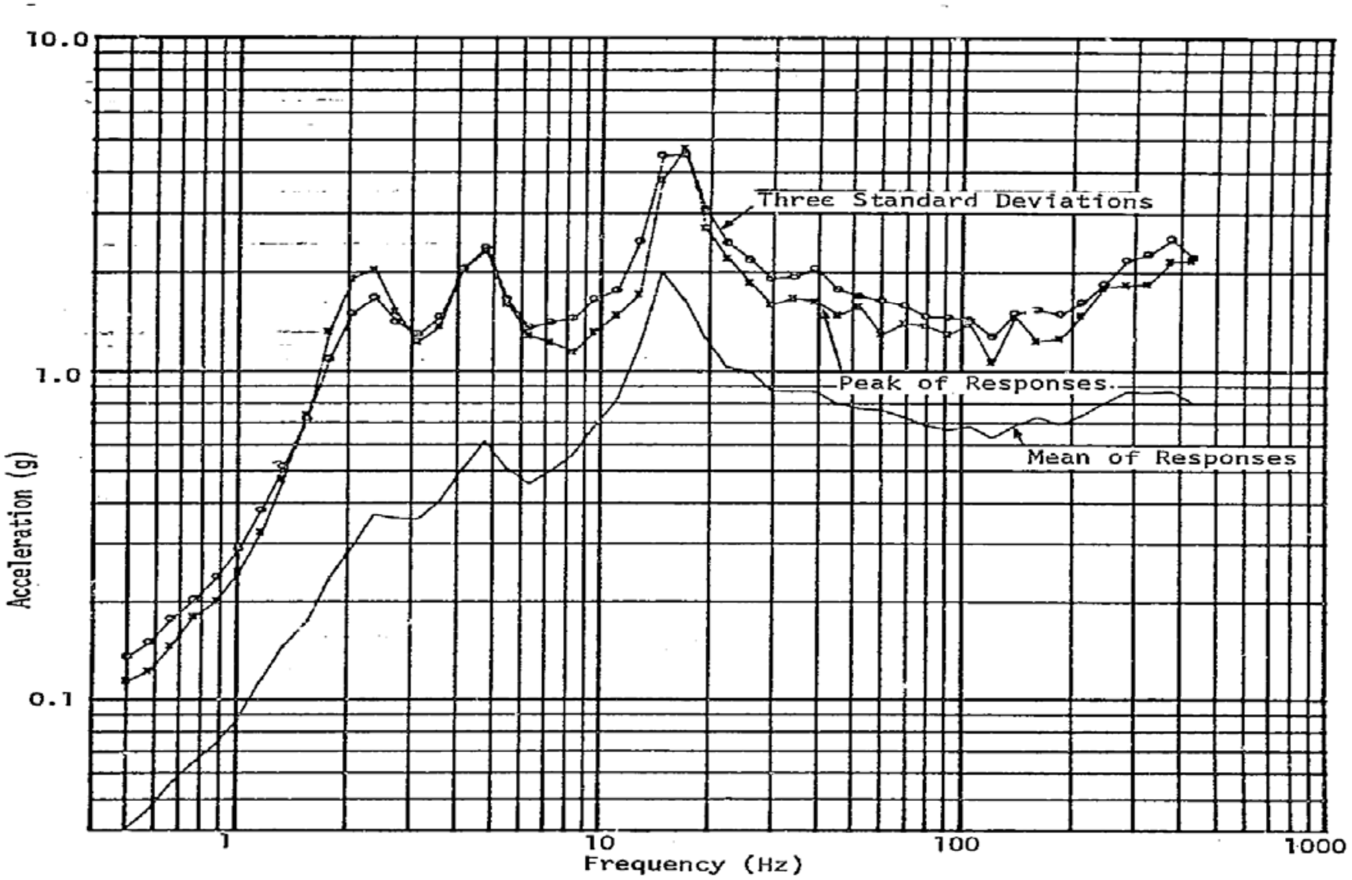


Figure 5. Superimposed Shock Response Spectra,
3% Damping, Vertical Axis

Inputs to Shaker

Figure 3.0-1: Recommended Random Vibration Test Specification

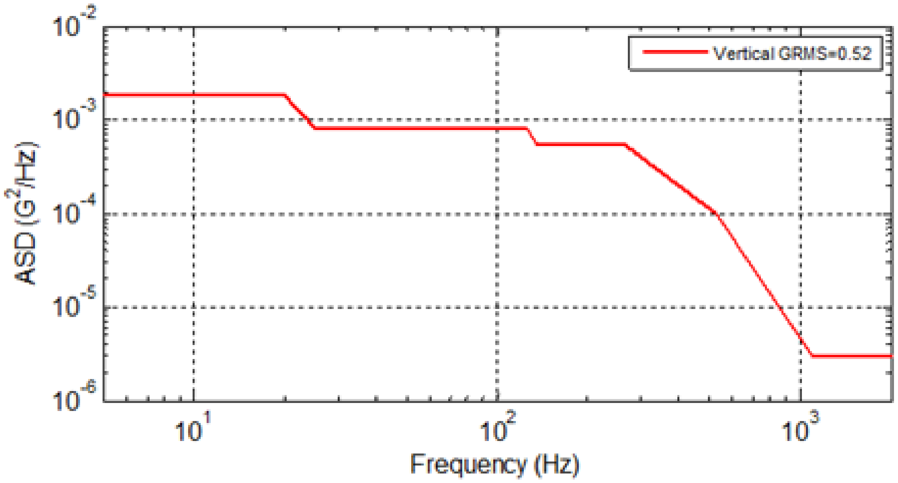
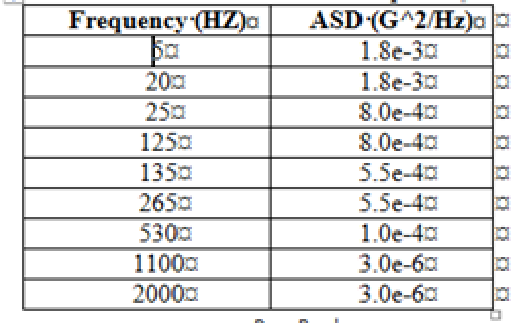


Table 3.0-.1: Vibration Breakpoints



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

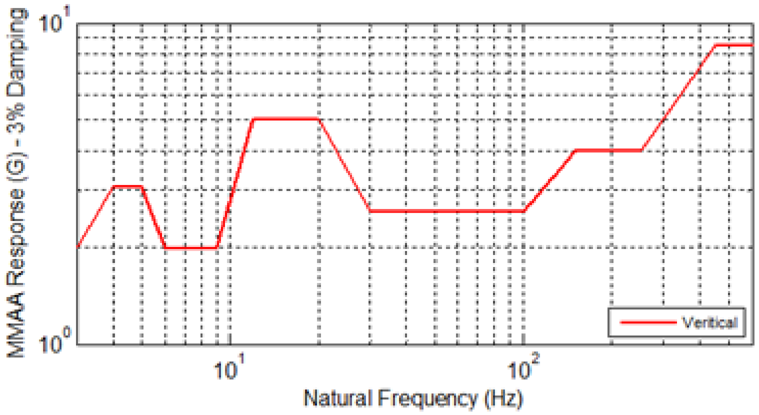
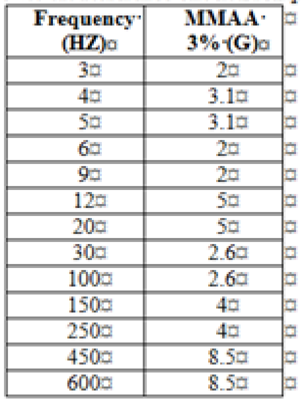


Table 4.0-.1: Reference Shock Breakpoints



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

Conclusions

- Direct loading functions on surrogate fuel pin cladding from NCT are being experimentally obtained.

- This data will be used to:
  - Benchmark analysis tools
  - Conduct finite element codes to estimate used fuel performance under NCT

- Further work is planned to:
  - Test more representative surrogate assemblies
  - Conduct shaker table tests with rail shock/vibration data

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