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Fuel Assembly Vibration/Shock Test Simulating Normal Transport

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BAM Bundesanstalt für Materialforschung und -prüfung

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NNSA National Nuclear Security Administration

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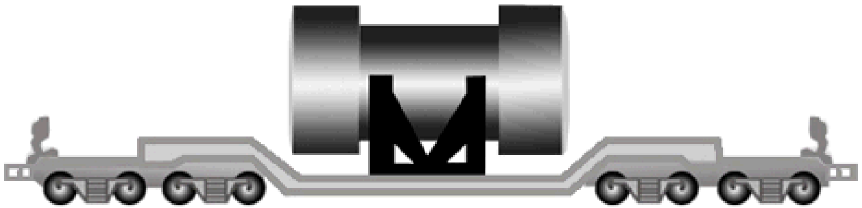
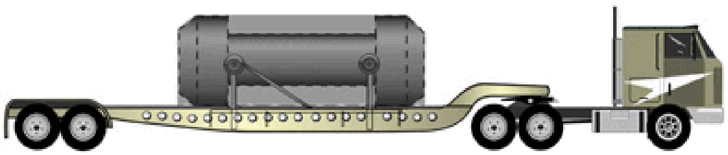
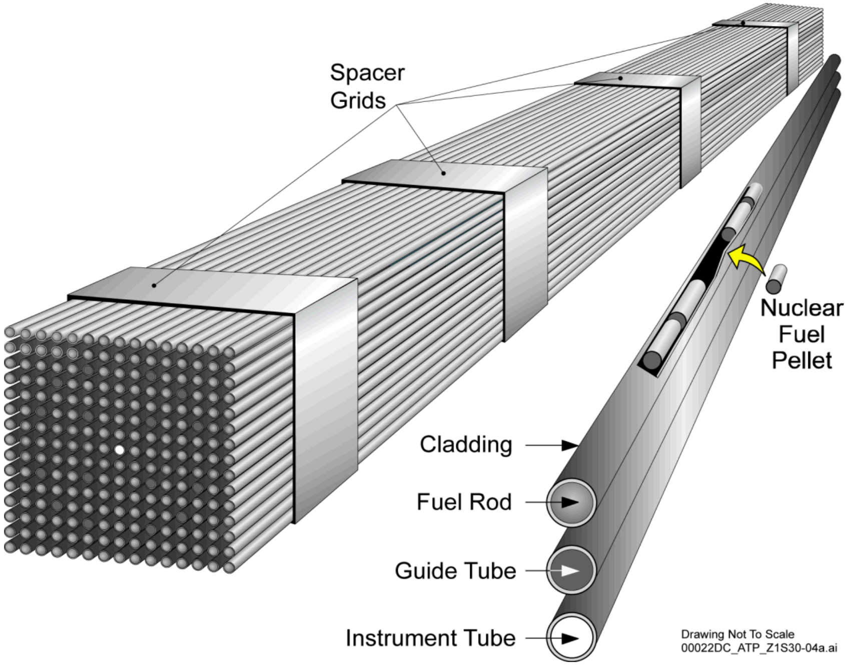
Part I: Assembly Shaker Test

Purpose: Measure the structural response directly on fuel rods in an 17 X 17 PWR fuel assembly when subjected to vibration and shock loads simulating those produced during normal transport by truck.

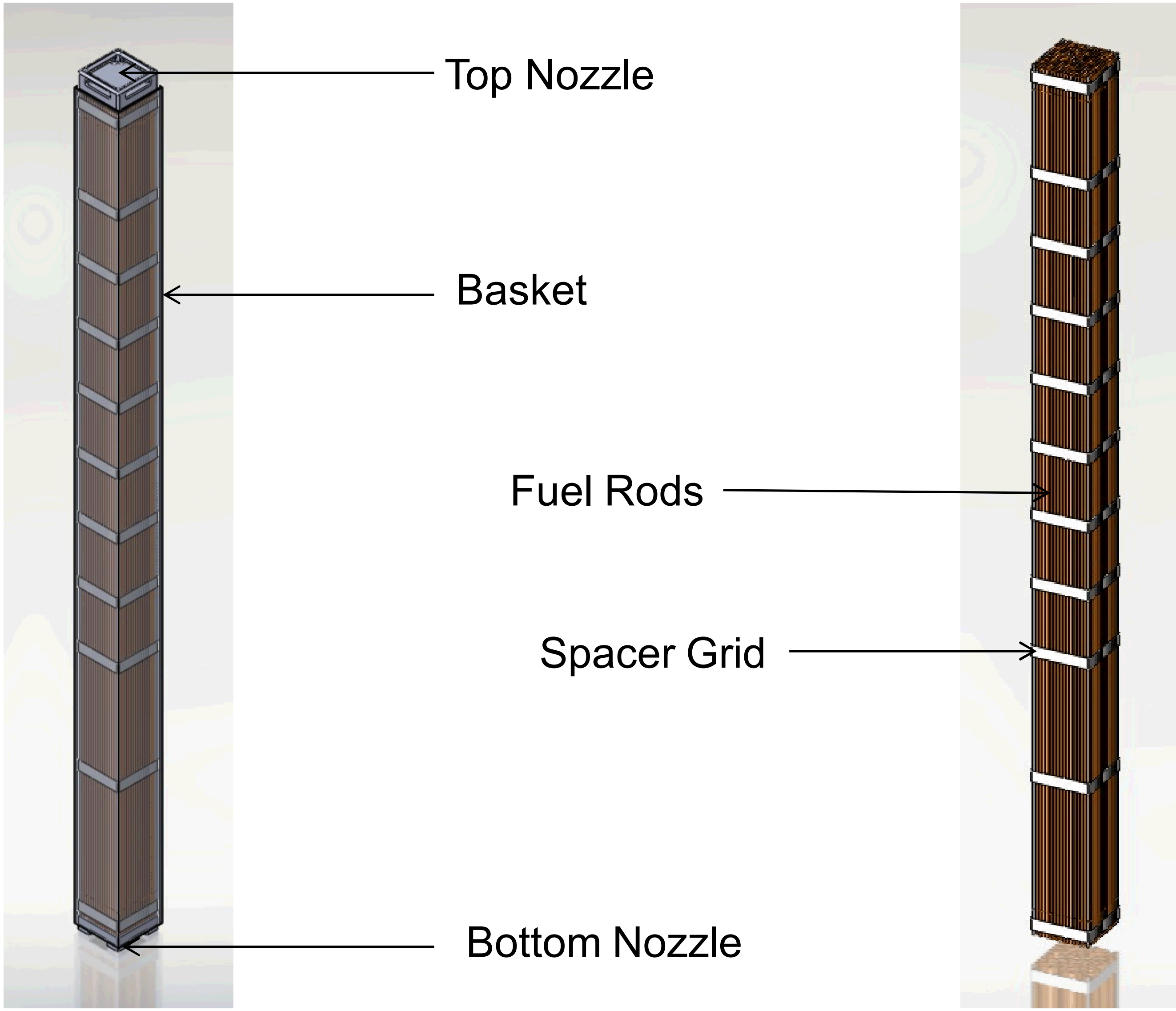
Normal Transport Modes







Experimental 17 x 17 PWR Assembly



Experimental Compromises

Experimental Problem	Solution
Actual truck casks too costly (NAC-LWT)	Perform test without a cask Simulate truck transport with shaker table*
Available truck casks are contaminated	
Using UO_2 pellets not feasible	Use Pb rods as surrogate
Availability of Zircaloy tubes 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 NAC-LWT specifications. Place assembly on "stiffeners" to ensure unrealistic bending does not occur about assembly midpoint

***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 tube matrix

Zirc and Surrogate Material Properties (Based on equivalent thickness and variable EI)

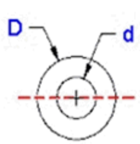
Zirc	
E_{zirc} (GPa)	99
E_{zirc} (ksi)	14359
ρ_{zirc} (g/cm^3)	6.55
ρ_{zirc} (g/in^3)	107
h (in)	151.79
Vol_{zirc} (in3)	3.77
Mass (g)	404.80
t (in)	0.0225
D_{zirc} (in)	0.374
d_{zirc} (in)	0.329
EI (k*in2)	5.532
Zirc Rod (lbs)	0.891

Aluminum	
E_{Al} (GPa)	70
E_{Al} (ksi)	10153
ρ_{Al} (g/cm^3)	2.7
ρ_{Al} (g/in^3)	44
h (in)	144
Vol_{Al} (in3)	5.38
Mass (g)	238.19
t (in)	0.03500
D_{Al} (in)	0.375
d_{Al} (in)	0.305
EI (k*in2)	5.543
Al Rod (lbs)	0.525

Brass	
E_{Brass} (GPa)	110
E_{Brass} (ksi)	15954
ρ_{Brass} (g/cm^3)	8.5
ρ_{Brass} (g/in^3)	139
h (in)	151.79
Vol_{Brass} (in3)	5.67
Mass (g)	790.42
t (in)	0.03500
D_{Brass} (in)	0.375
d_{Brass} (in)	0.305
EI (k*in2)	8.710
Brass Rod (lbs)	1.739

Carbon Steel	
E_{SS} (GPa)	205
E_{SS} (ksi)	29733
ρ_{SS} (g/cm^3)	7.85
ρ_{SS} (g/in^3)	129
h (in)	151.79
Vol_{SS} (in3)	5.67
Mass (g)	729.98
t (in)	0.03500
D_{SS} (in)	0.375
d_{SS} (in)	0.305
EI (k*in2)	16.232
CS Rod (lbs)	1.606

Copper	
E_{Cu} (GPa)	115
E_{Cu} (ksi)	16679
ρ_{Cu} (g/cm^3)	8.94
ρ_{Cu} (g/in^3)	147
h (in)	151.79
Vol_{Cu} (in3)	5.67
Mass (g)	831.34
t (in)	0.03500
D_{Cu} (in)	0.375
d_{Cu} (in)	0.305
EI (k*in2)	8.710
Cu Rod (lbs)	1.829



$$\text{Moment of Inertia} = I = \frac{\pi(D^4 - d^4)}{64}$$

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} = $8.71\ K\text{-}in^2$
  - EI_{Zirc} = $5.53\ K\text{-}in^2$

- **Conclusion: Cu tubing is slightly stiffer than Zircaloy**

Material Properties

Material Properties	ρ (g·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.**

- **We expect the dynamic response of the assembly to represent that of a real fuel assembly.**

Experimental Assembly

- **Actual Assembly weighs approximately 1404 lbs**
- **Experimental assembly weighs approximately 1446 lbs**
  - **A 3% difference in weight between the actual and experimental assemblies**
- **Although the stiffness of the actual 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.**

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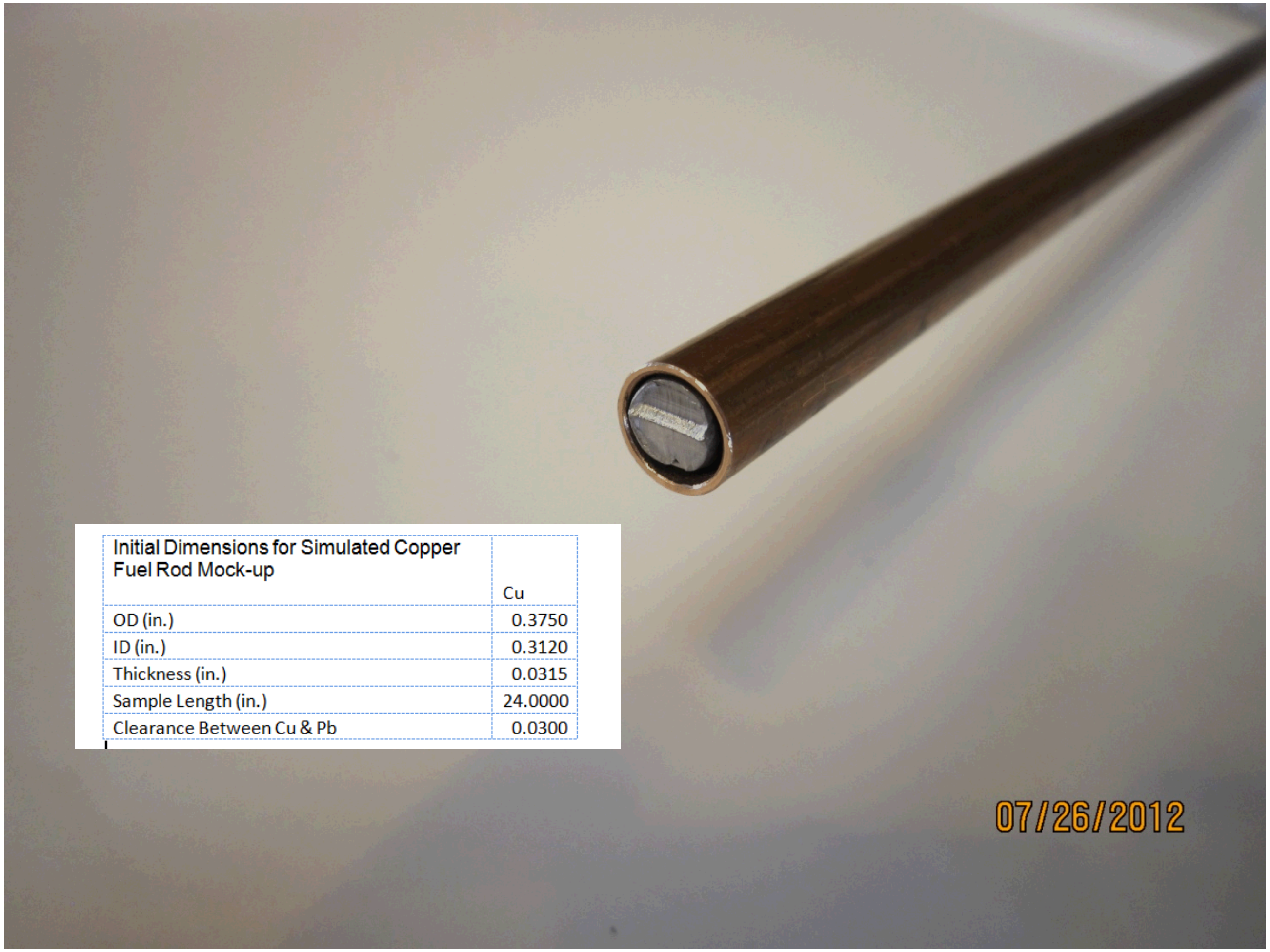
Lead rod within Copper tube



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

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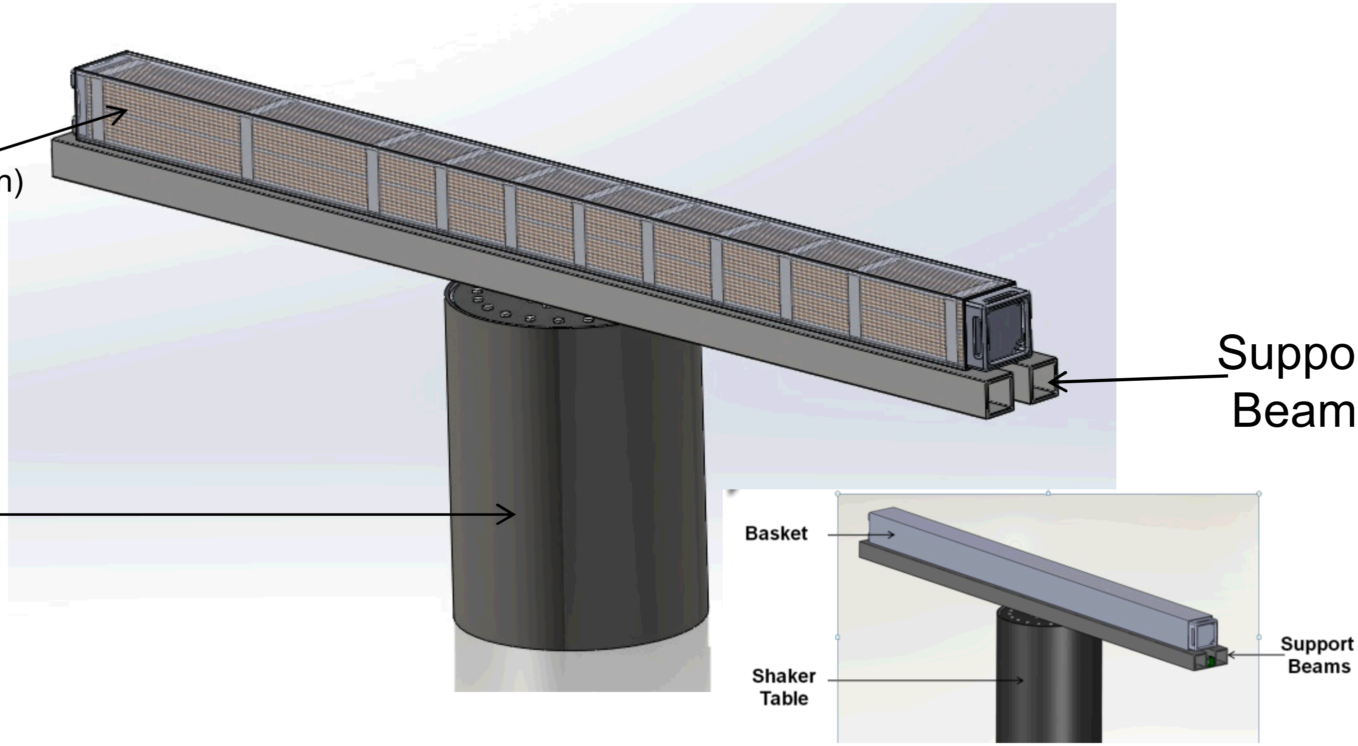
Shaker and Assembly

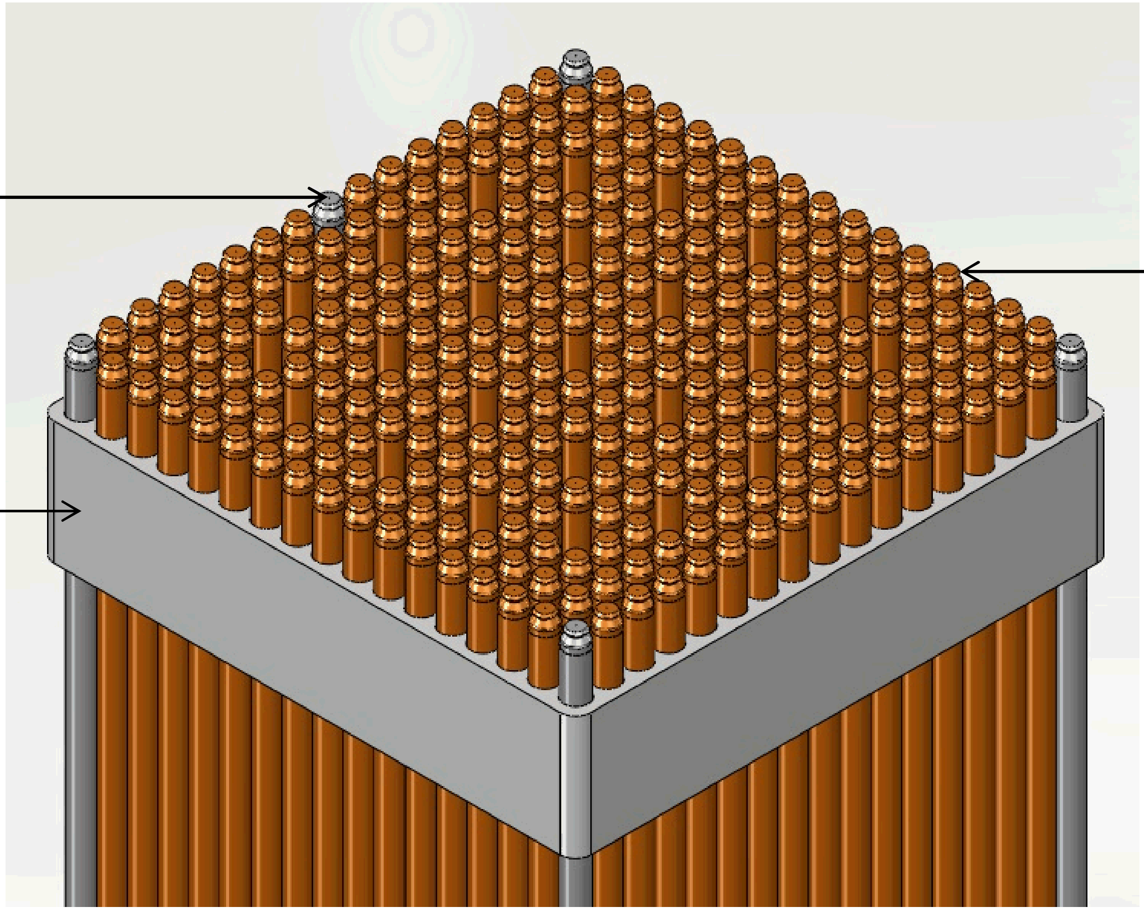


Note: Shaker table is not long enough to support entire assembly. Beams to be used to simulate rigidity of an *assembly-within-a-basket-within-a-cask-affixed-to-a-trailer* under normal transport conditions.

Test Modifications

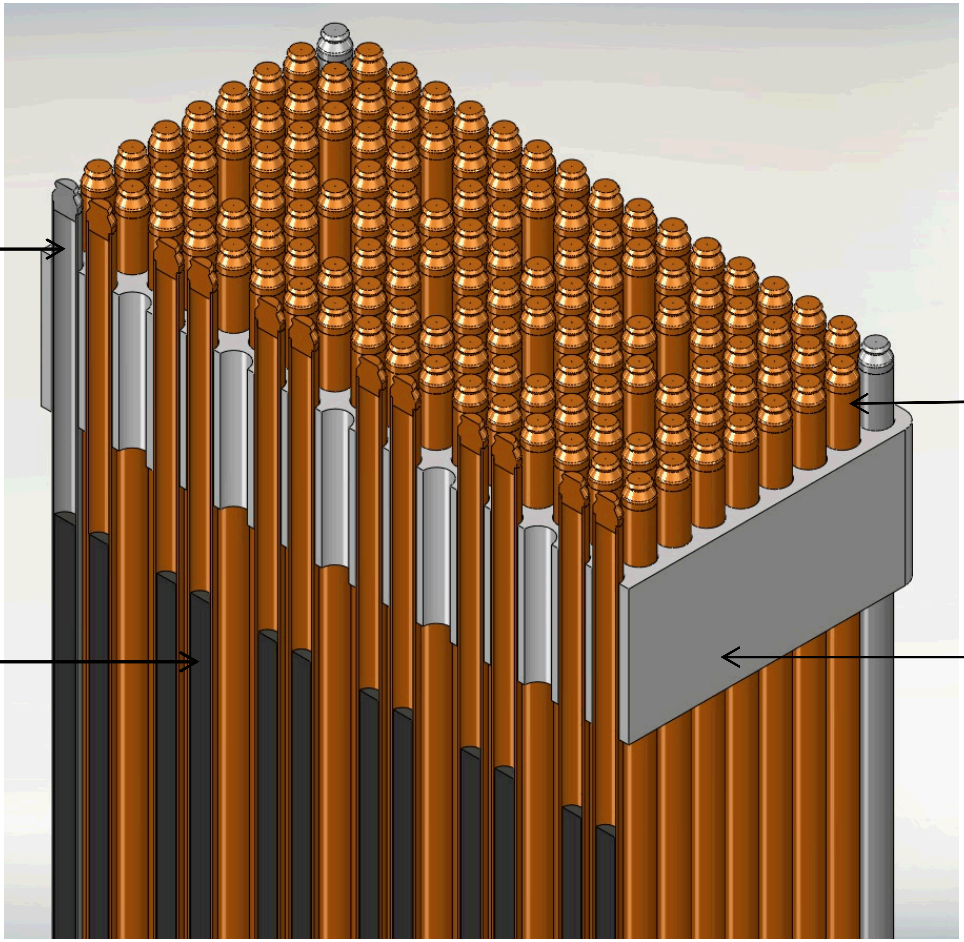
- **Beams will be used for full support of the assembly in order to avoid bending from cantilevered ends**
- **Holes will be cut along length of basket in order to provide access to instrumentation**
- **Cu-tube / Pb-rods will be used instead of Zircaloy-tube / UO_2-pellets *except for five Zircaloy-Pb rods* – the Zircaloy rods shall be instrumented**

Experimental Assembly



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

Experimental Assembly



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

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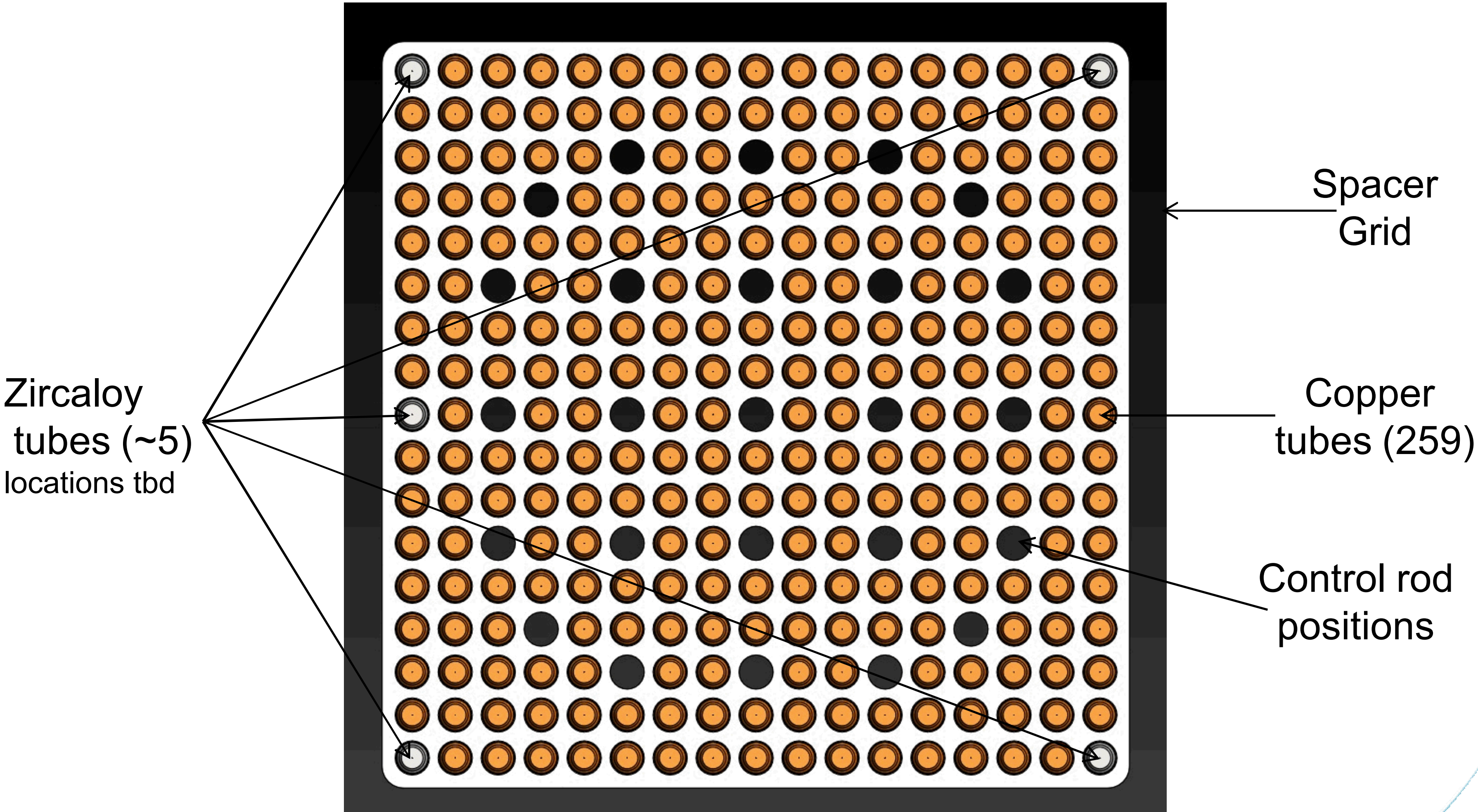
Experimental Assembly

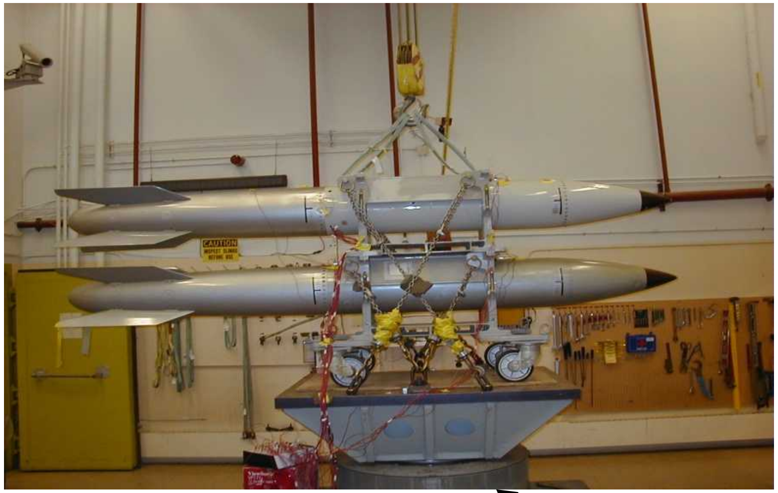


Top View of Assembly
(Top Nozzle and Basket not shown)

Excitation Equipment (Shakers)

Shakers at Sandia used for system level tests of full-scale assemblies or items requiring high vibration levels.

Shown is the Unholtz-Dickie Corporation T4000 electrodynamic shaker for vertical testing **<http://www.udco.com/largetseries.shtml>**

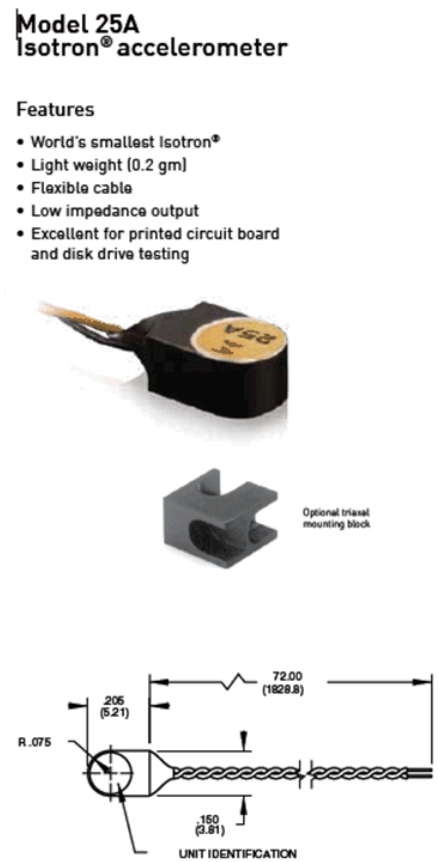


Vertical Shaker

Instrumentation

- **Accelerometers will be placed along the length of the <u>Zircaloy rods</u> in order to measure shock and vibration**

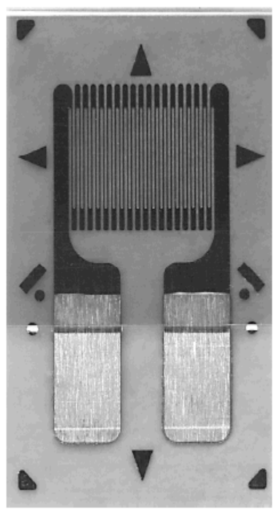
- **Accelerometers shall measure the dynamic response of the system and provide the boundary conditions for the modeling of the test**



Instrumentation

- Strain gauges will be placed along the length of the rods in order to measure strain at specific points on the rods
- The stress state of the fuel rods will be calculated based on the strain gauge readings and used to benchmark the model

GAGE PATTERN DATA




actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS)	OPTIONS AVAILABLE See Note 2
CEA-XX-062UW-120	120 ± 0.3%	**P2**
CEA-XX-062UW-350	350 ± 0.3%	**P2**

DESCRIPTION

General-purpose gage. Exposed solder tab area is 0.07 x 0.04 in [1.8 x 1.0 mm].

GAGE DIMENSIONS Legend: ES = Each Section; S = Section (S1 = Sec 1); CP = Complete Pattern; M = Matrix; inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.062	0.220	0.120	0.120	0.31	0.19
1.57	5.59	3.05	3.05	7.9	4.8

GAGE SERIES DATA See Gage Series data sheet for complete specifications.

Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±3%	−100° to +350°F [−75° to +175°C]

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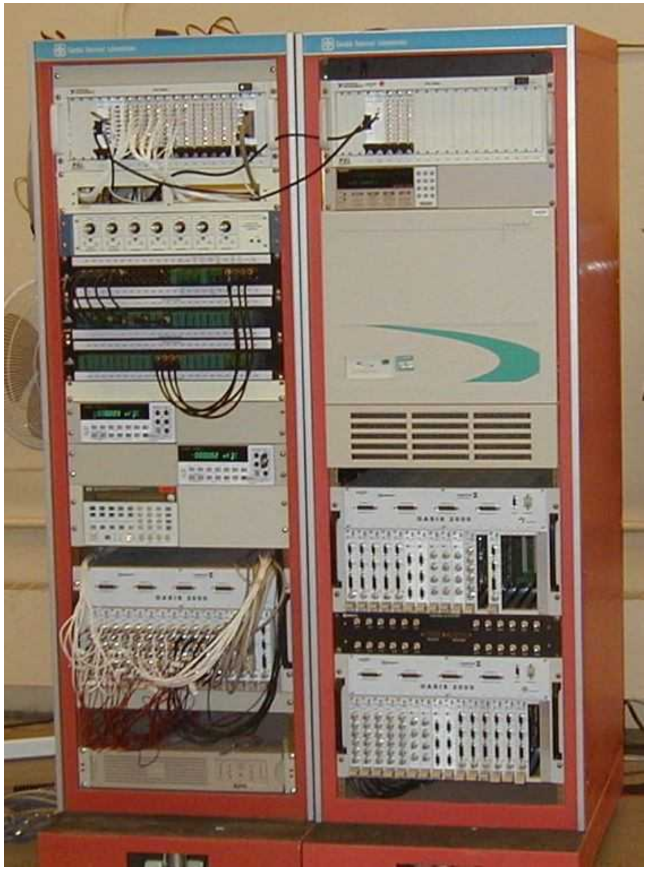
Control and Data Acquisition

- State-of-the-art Digital Vibration Controller
  - 38 input channels available for control, limiting, or real-time monitoring
  - Average, maximum, or minimum spectrum control options
- Computer controlled signal conditioning system
  - Over 200 channels
  - Conditions various types of sensors (e.g., strain gage, force, displacement)
- Data Acquisition and Analysis System
  - 208 channels
  - 102.4 kilo-samples/s, 24-bit resolution
  - Data streaming to disk array for long duration recording

Control and Data Acquisition



Part II

Basis for Inputs to Shaker Table 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.**
  - **Measurements taken on the *external* body of the casks.**
  - **56000-pound cask and 44000-pound cask.**
  - **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.**

NUREG/CR-0128 http://rampac.energy.gov/NRCinfo/NUREG_0128.pdf

SHOCK AND VIBRATION ENVIRONMENTS
FOR A LARGE SHIPPING CONTAINER
DURING TRUCK TRANSPORT (PART II)

Clifford F. Magnuson

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Sandia National Laboratories

NUREG/CR-0128 (SAND Report 78-0337)

ABSTRACT

The purpose of this study was to obtain vibration and shock data during truck shipment of heavy cargo. These data were for use in determining any trends of vibration and shock environments with increased cargo weight. The new data were obtained on a "piggyback" basis during truck transport of 249 100N (56,000-pound) cargo which consisted of a spent fuel container and its supporting structure. The truck was driven from Mercury, Nevada, to Albuquerque, New Mexico. The routes traveled were US 95 from Mercury, Nevada, to Las Vegas, Nevada; US 93 from Las Vegas to Kingman, Arizona; and I-40/US 66 from Kingman to Albuquerque, New Mexico. Speeds varied from very slow to 88 km/hr (55 mph). A comparison of data from similar experiments with cargo weights varying from no-load to this load shows that the zero-to-peak acceleration amplitude levels of vibration are highest when trucks carry relatively light loads. This is true for the longitudinal and vertical axes of the vehicles in most frequency bands and for the transverse axis above 700 Hz. The shock response acceleration amplitudes for heavier cargo weights were less severe above 3 Hz in the vertical axis and higher between 8 and 20 Hz in the transverse axis. The highest acceleration amplitude of shock response in the longitudinal axis below about 20 Hz was produced in a trailer having a spring suspension system and carrying the 249 100N (56,000 pounds) load.

Vibration Data from NUREG/CR-0128

Truck Vibration 249 100N (56,000-Pound) Cargo

Frequency Band (Hz)	Input to Cargo (g); 99% Level of Zero-to-Peak Amplitude		
	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.27	0.10	0.52
5-10	0.14	0.07	0.27
10-20	0.19	0.19	0.37
20-40	0.10	0.07	0.19
40-80	0.10	0.10	0.37
80-120	0.07	0.10	0.37
120-180	0.07	0.10	0.52
180-240	0.05	0.10	0.52
240-350	0.07	0.14	0.52
350-500	0.05	0.07	0.37
500-700	0.05	0.02	0.10
700-1000	0.05	0.02	0.10
1000-1400	0.14	0.05	0.10
1400-1900	0.03	0.02	0.10

Shock Spectra from NUREG/CR-0128

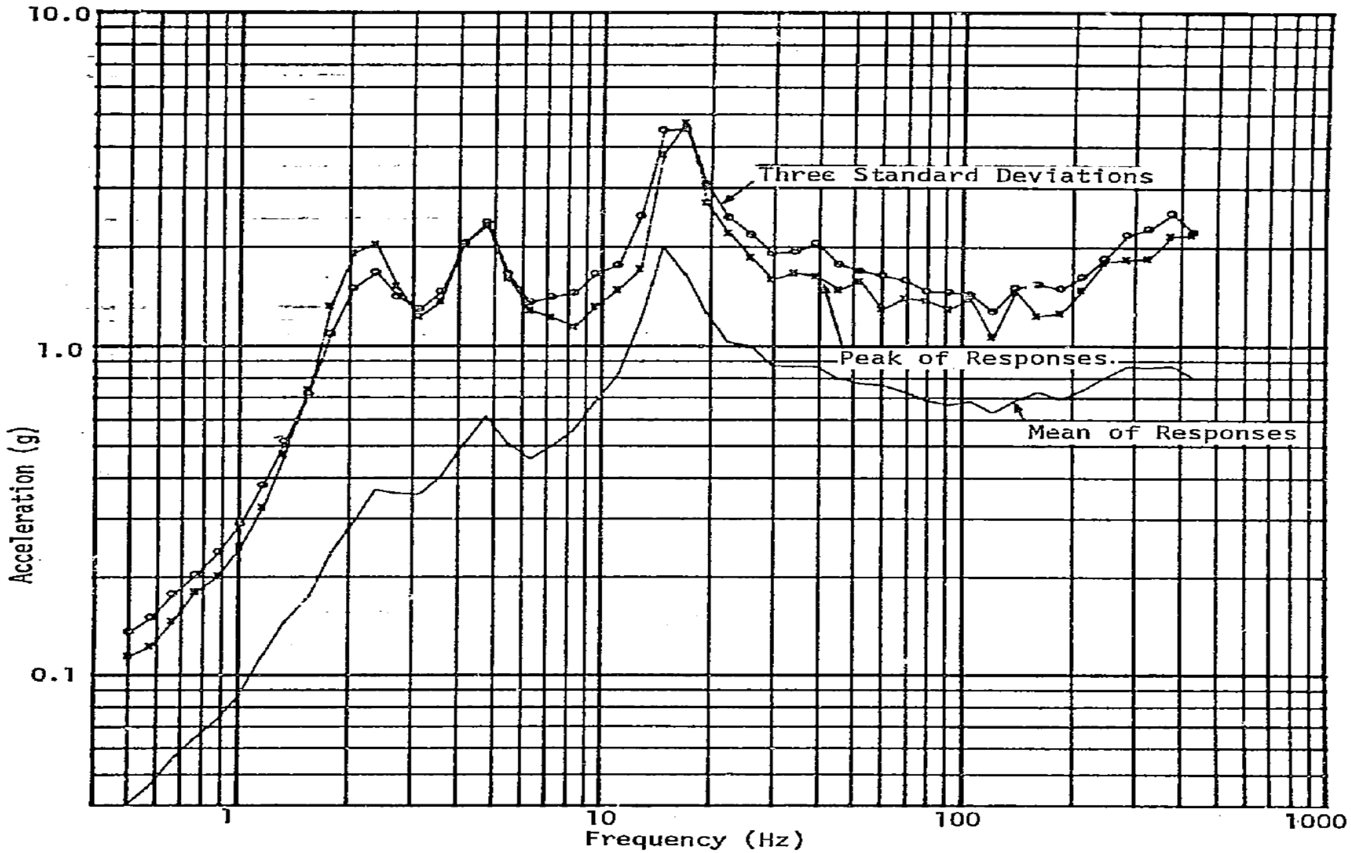

Figure 5. Superimposed Shock Response Spectra, 3% Damping, Vertical Axis

Vibration & Shock Inputs Derived for Shaker

The Environments Engineering Group at Sandia National Laboratories derived a set of set of random vibration and shock test specifications for a laboratory test of a reactor fuel assembly.

These specifications were derived from the vibration and shocks presented in NUREG/CR-0128. The purpose of the laboratory test is to measure loads during normal highway transportation.

Test specifications are for the vertical axis only since it is the direction which will maximally affect the loading.

Vibration Data Converted to Spectral Density

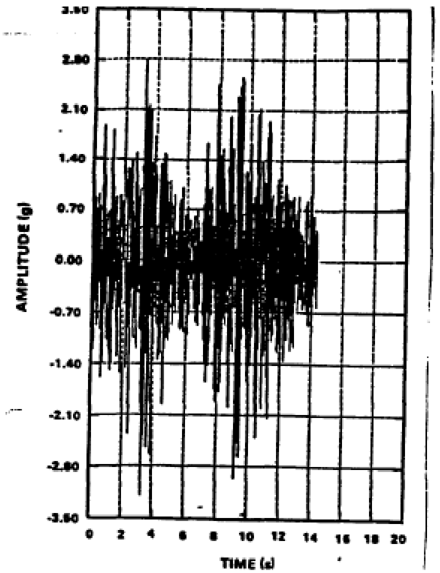

Figure 9a. Representative Time History

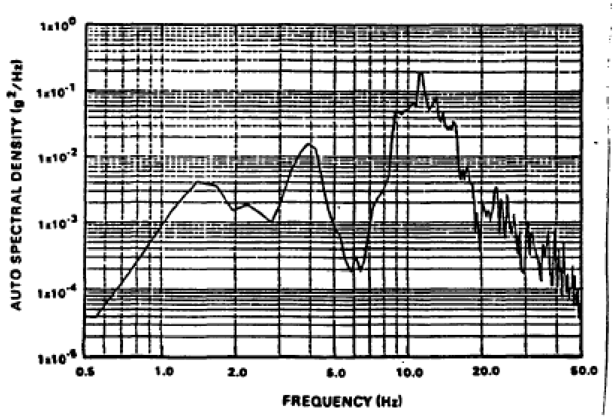

Figure 9b. Representative PSD

Inputs to Shaker

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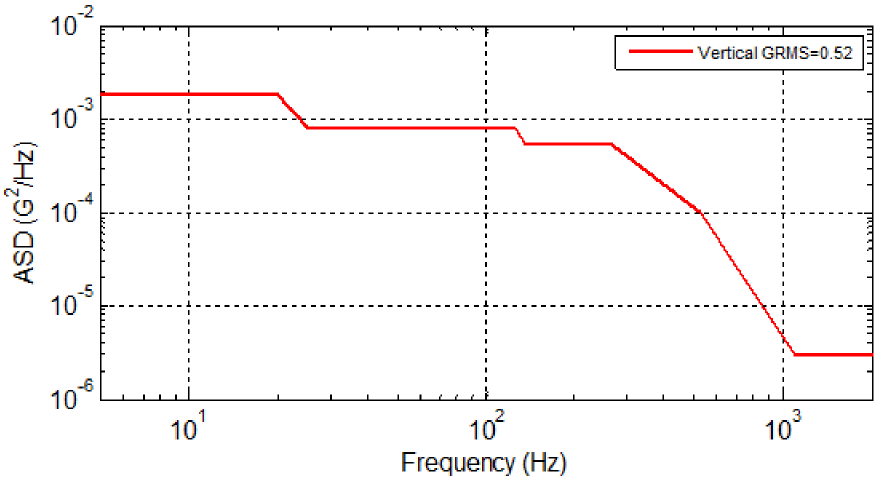
Figure·3.0-1:·Recommended·Random·Vibration·Test·Specification¶



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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

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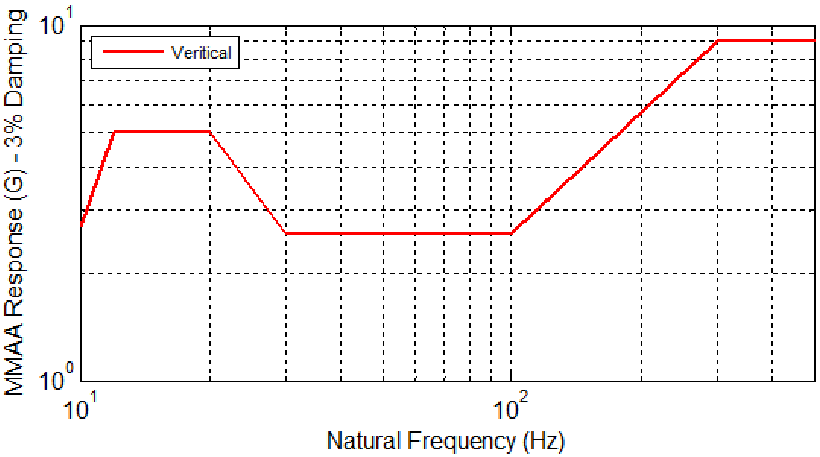
Figure·4.0-1:·Recommended·Shock·Test·Specification·¶



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Table·4.0-.1:·Reference·Shock·Breakpoints¶

Frequency·(HZ)	MMAA·3%·(G)
10	2.7
12	5.0
20	5.0
30	2.6
100	2.6
300	9.0
600	9.0

¶

The Units g^2/Hz *v*. Hz

- Accelerometers record g *v*. seconds
- Power Spectral Density describes how the power of a signal (such as random vibration) is distributed with frequency
- The Power Spectral Density curve is plotted on axes of g^2/Hz *v*. Hz
- The unit g^2/Hz results from the Fourier Transformation of a signal (g *v*. s) which gives the frequency and amplitude (g^2/Hz) of the waves that when summed form the time domain signal
- The <u>energy</u> of vibration is the area under the Power Spectral Density curve
- The energy of a signal is the same whether calculated from the time (seconds) domain (g *v*. s) or the frequency (Hz) domain (g^2/Hz *v*. Hz)
- Shakers use the Power Spectral Density curve rather than g *v*. s for vibration to input the power due to vibration to a component over the entire frequency domain.

Part III: Modeling the Assembly Tests

Pacific Northwest National Laboratory Analysis Support

Westinghouse 17x17 PWR Assembly Shaker Simulation Modeling

- A LS-DYNA structural model of a detailed W 17x17 assembly will be refined and modified to include specific details for the Sandia test assembly and basket that will be utilized to impose the loading time history during the actual shaker testing.
- Scoping pre-test evaluations will be performed to identify appropriate data collection sites within and about the test assembly. This information will help finalize the test design and provide baseline analyses for future benchmarking and validation of modeling techniques involving LS-DYNA.
- A script will be written that converts LS-DYNA fuel assembly specific geometric data and shall port it to Sandia's PRESTO Structural Dynamics code. This tool will help provide baseline analyses for future benchmarking and validation of modeling techniques involving PRESTO as well as cross-comparison between LS-DYNA and PRESTO.