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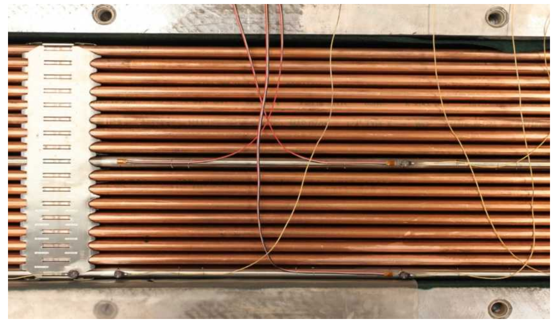
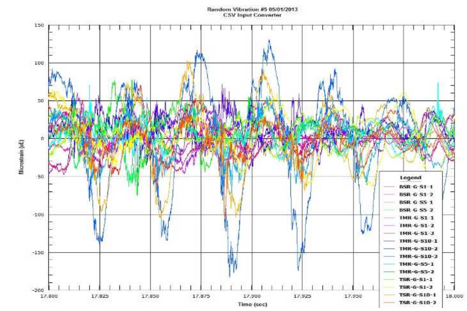




Loading on Fuel Rods in a Surrogate PWR Assembly Subjected to Simulated Normal Conditions of Truck Transport

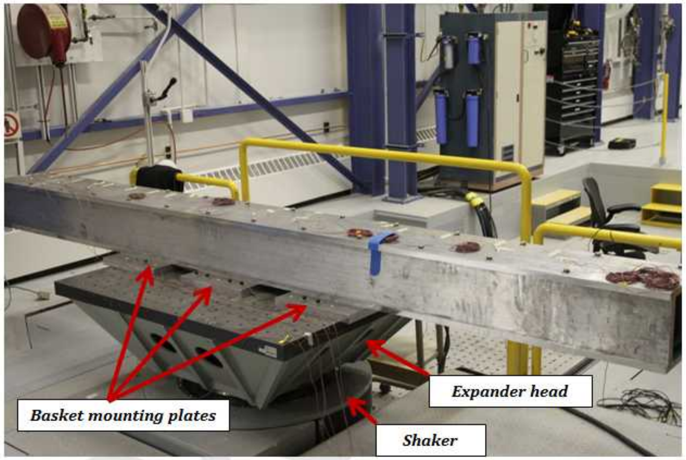
Paul McConnell, Doug Ammerman, Ken Sorenson

PATRAM 2013, 22 August 2013

Assembly Shaker Test - Objectives

1. Simulate normal conditions of truck transport on a surrogate PWR fuel assembly by applying 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.

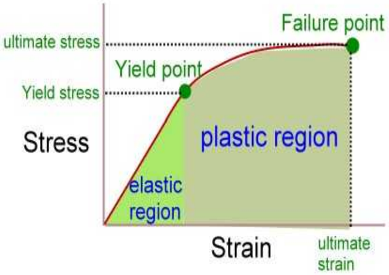


Motivation for Assembly Shaker Test

The margin of safety between the applied loads on fuel rods and the material properties of the Zircaloy rods has not been quantified.

Fuel rods subjected to high burnups may be sufficiently embrittled so that loads applied to the rods during normal transport could result in rod failure.

$$\textbf{applied stress}_{\textit{normal transport}} > \textbf{yield strength}_{\textit{cladding}} \textbf{?}$$



Application of Test Results (1)

The assembly shaker test provides a data point – the applied stresses on the rods - related to the issue of the margin of safety:

applied stress$_{\text{normal transport}}$

Material property test programs at the DOE national laboratories shall measure properties of high burnup cladding:

yield strength$_{\text{cladding}}$

Are the stresses and strains applied to the fuel
during normal conditions of transport
less than the yield strength of the fuel rods?

Application of Test Results (2)

- The data from the assembly shaker tests can be used to validate finite element models of fuel assemblies.
- The validated models can be used to predict the loads on fuel rods for other basket configurations and transport environments, particularly rail.

Constraints and compromises to an ideal test

Ideal Experimental Design	Constraint	Compromise Solution for Test	Comments
Use actual cask	• Available truck casks contaminated • Rail casks unavailable	**Simulate truck transport with a shaker**	Applicable shock/vibration data available from NUREG/CR-0128
Use actual PWR assembly	Use of an irradiated assembly not feasible	**PWR assembly was available**	
Use zirconium alloy rods	Limited number of Zircaloy-4 rods available	• **Use copper alloy tubes for most assembly locations** • **Use Zircaloy-4 rods for those rods to be instrumented**	Among many materials evaluated for surrogates for Zircaloy-4 and UO_2, copper and lead had best combination of material properties (elastic modulus and density, respectively), availability, and cost
Use UO_2 pellets in rods	UO_2 pellets unavailable	**Use lead rods as surrogate**	
Rods have same material properties as used in an actual assembly	• Limited number of Zircaloy-4 rods available • UO_2 pellets unavailable	• **Adjust wall thickness of copper tubes so that $EI_{Cu} \approx EI_{Zircaloy\text{-}4}$** • **Adjust amount of lead in tubes so total assembly weight is that of an actual assembly**	

Constraints and compromises to an ideal test

Ideal Experimental Design	Constraint	Compromise Solution for Test	Comments
Assembly is in an actual basket which is within a cask	Actual basket unavailable	**Construct a basket to contain assembly**	
Basket within a truck cask has some freedom of motion	Experimentally unviable to allow basket to move shaker due to shaker control constraints	**Attach basket to shaker to prevent motion**	
Assembly in basket has freedom of motion	None	**Fuel assembly allowed same freedom of motion as an assembly within an actual NAC-LWT PWR basket**	Within the basket, the assembly had 0.45 in. (1.14 cm) clearance at the top and 0.225 in. (0.57 cm) along the sides
Assembly subjected to actual truck transport environment	Truck cask unavailable	**Derive inputs for shaker from truck vibration/shock data**	• Vibration data and shaker inputs ranged from 5 Hz to 2,000 Hz • Shock data ranges from 0.5 Hz to 420 Hz. Shaker inputs for shock ranged from 4 Hz to 600 Hz
Basket/ assembly within an actual truck cask	Truck cask unavailable	• **Basket constructed to conform to material (aluminum), weight, and internal dimensions of NAC-LWT PWR basket** • **Basket affixed to shaker**	
Instrument assembly and basket (accelerometers and strain gages)	None	• **Apply expert judgment and analyses to define location of instruments** • **Instrument selected rods**	• All rods are expected to respond in a similar manner (per analyses) • Used 16 strain gages and 25 accelerometers

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 single PWR basket.
- The assembly was placed in the 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 freedom of motion as it would have in an actual cask: 0.45 inches in the vertical direction.

Applied Loading for the Test

- Both vibrational and shock vertical accelerations were applied to the assembly/basket via the shaker.

- Over-the-road data for trucks shows that vertical accelerations due to vibrations and shocks envelope accelerations in the other directions and truck accelerations envelope those of rail transport.

Inputs to shaker control system

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 (SAND77-1110).**
    - **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 experiments, the shaker simulated the vibration and shock experienced by the casks during normal transport.**

Vibration & Shock Inputs Derived for Shaker

- A set of set of vibration and shock test specifications were derived from the vibration and shocks presented in NUREG/CR-0128 for normal conditions of truck transport.

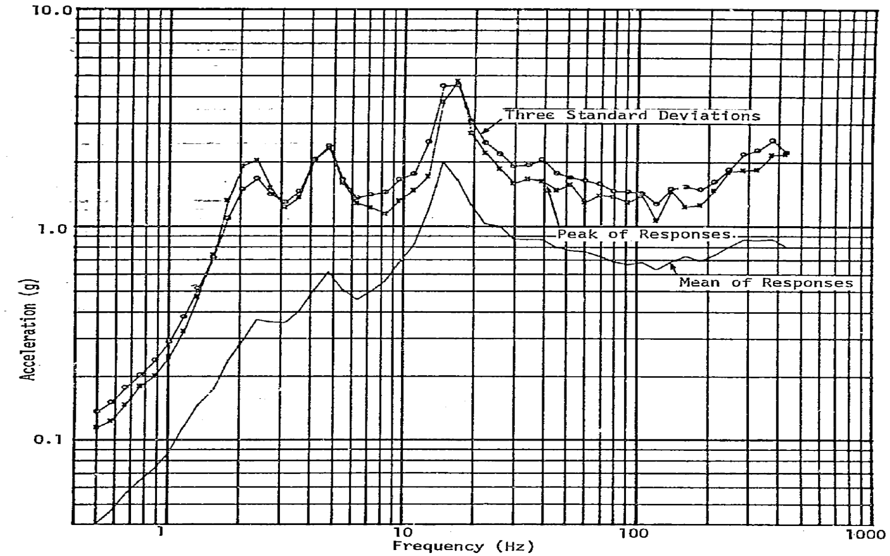


Figure 5. Superimposed Shock Response Spectra, 3% Damping, Vertical Axis

Truck Vibration
195 700 N (44,000 Pound) Cargo

Frequency Band - Hz	Input to Cargo (g) 99% Level of 0 to Peak Amplitude: Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.14	0.14	0.27
5-10	0.19	0.19	0.19
10-20	0.27	0.27	0.27
20-40	0.10	0.27	0.27
40-80	0.14	0.14	0.52
80-120	0.07	0.10	0.52
120-180	0.07	0.10	0.52
180-240	0.05	0.10	0.52
240-350	0.05	0.10	0.52
350-500	0.05	0.05	0.14
500-700	0.04	0.04	0.07
700-1000	0.03	0.07	0.07
1000-1400	0.01	0.04	0.05
1400-1900	0.01	0.05	0.05

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

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Inputs to Shaker

Figure 3.0-1: Recommended Random Vibration Test Specification

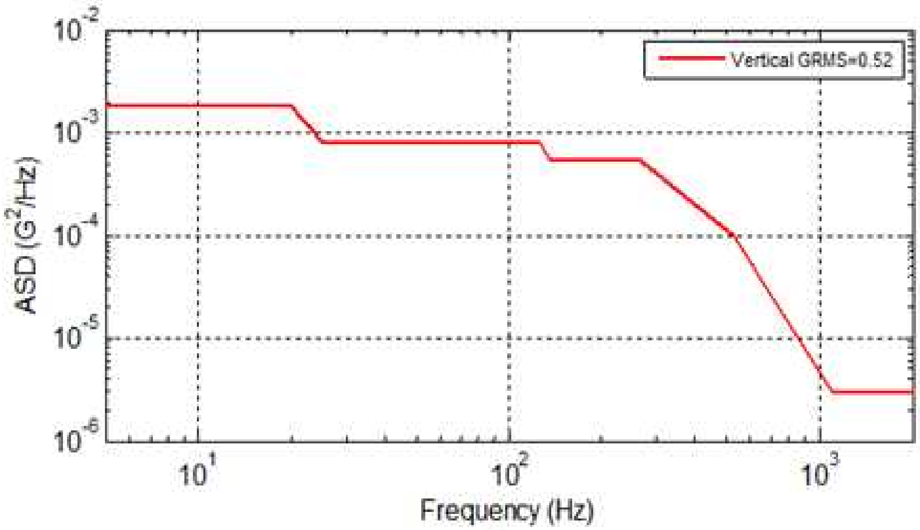

Table 3.0-1: Vibration Breakpoints

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

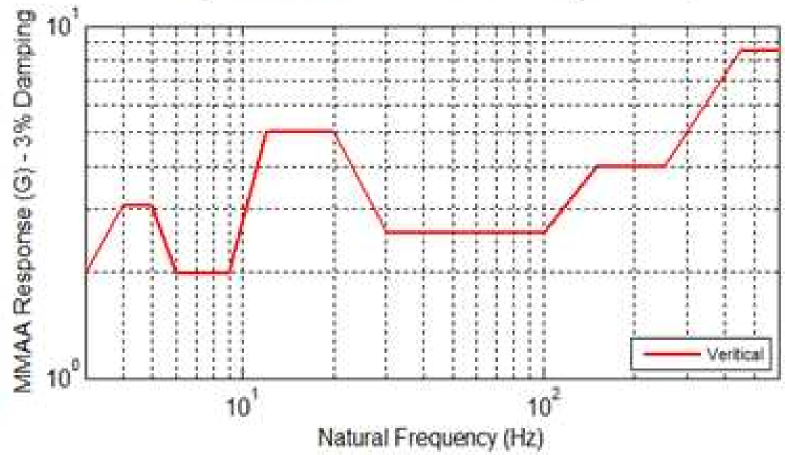

Table 4.0-1: Reference Shock Breakpoints

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

Slide 12

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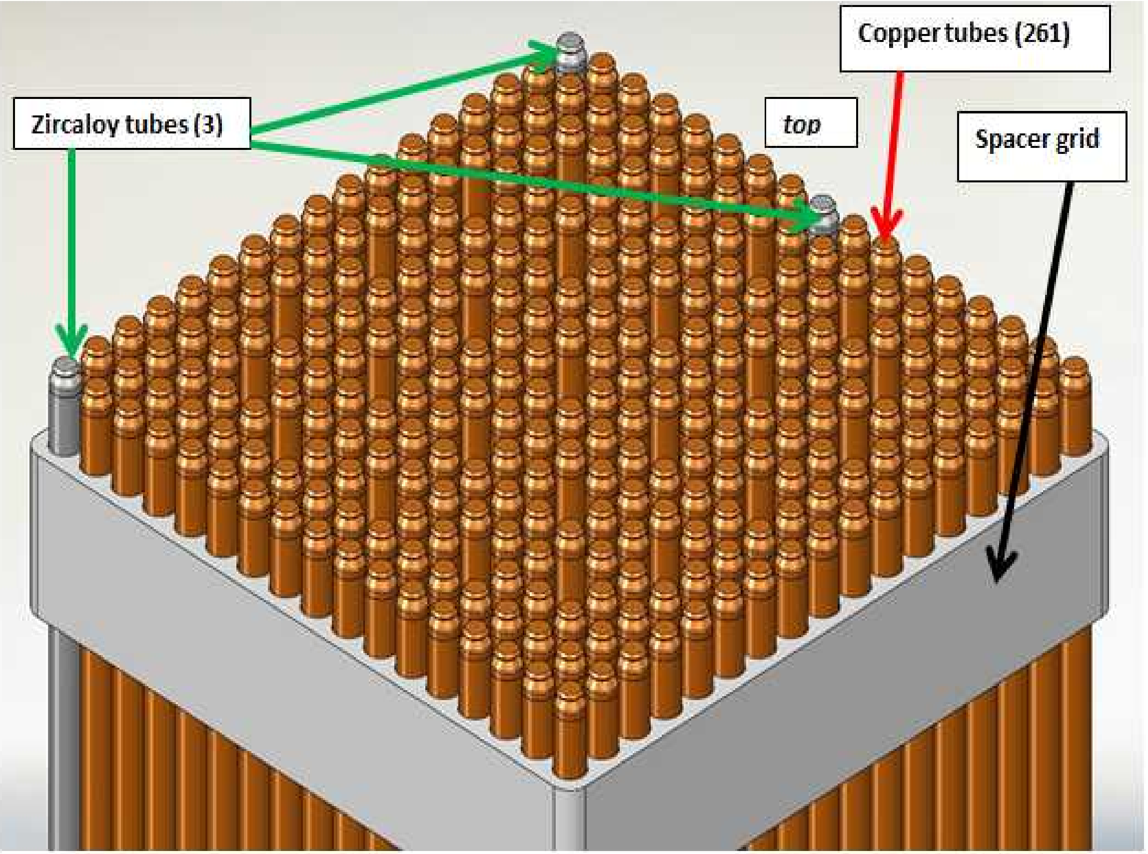
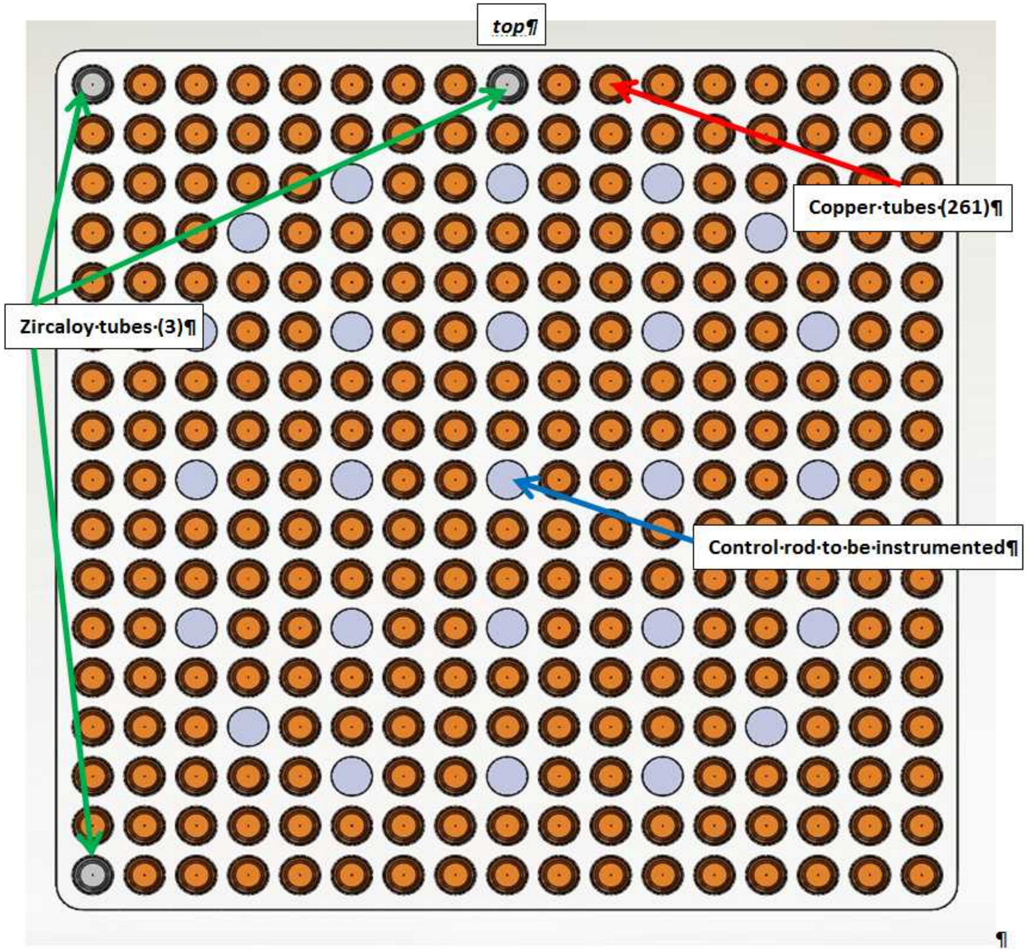
Experimental Assembly



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

Experimental Assembly

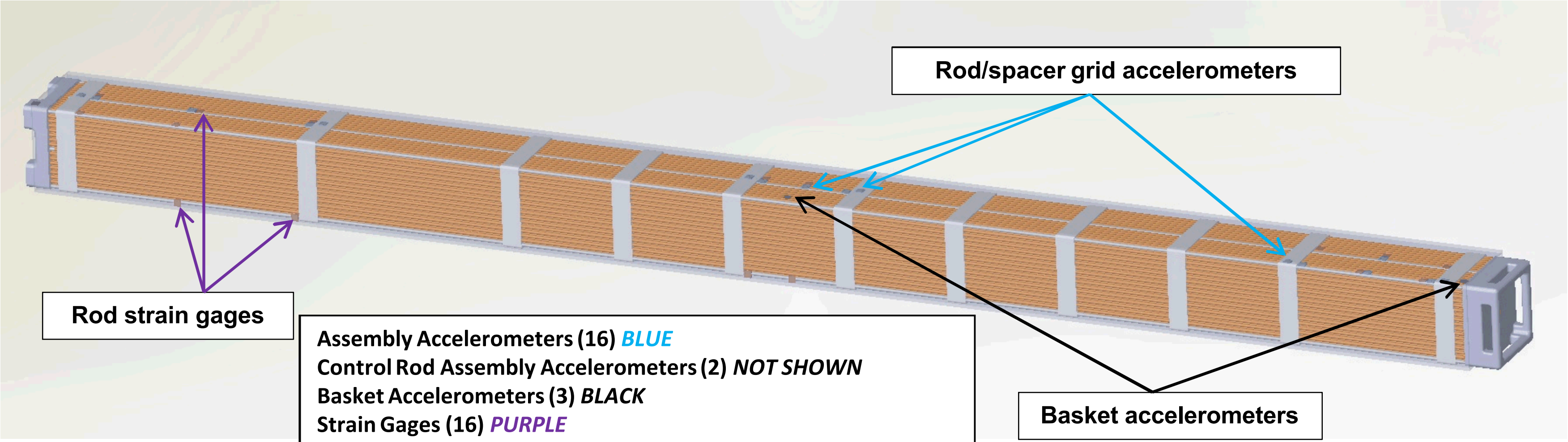


Top View of Assembly
(Top Nozzle and Basket not shown)

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

Instrumentation Locations on Test Unit

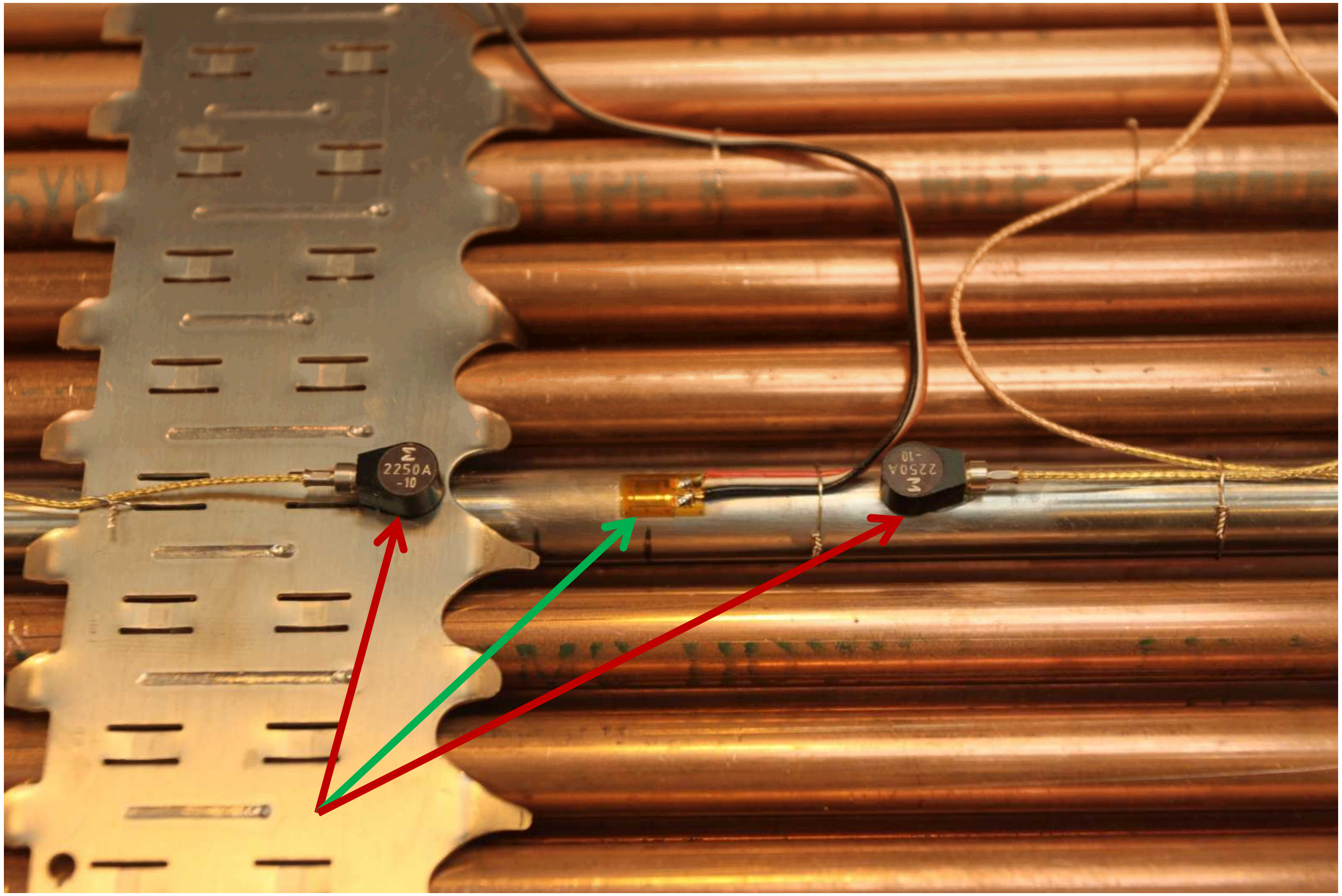


Assembly Accelerometers (16) *BLUE*
Control Rod Assembly Accelerometers (2) *NOT SHOWN*
Basket Accelerometers (3) *BLACK*
Strain Gages (16) *PURPLE*
Triaxial accelerometer on basket mounting plate (=3) and
1 INPUT/CONTROL accelerometer on shaker *NOT SHOWN*

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

Assembly within Open Basket

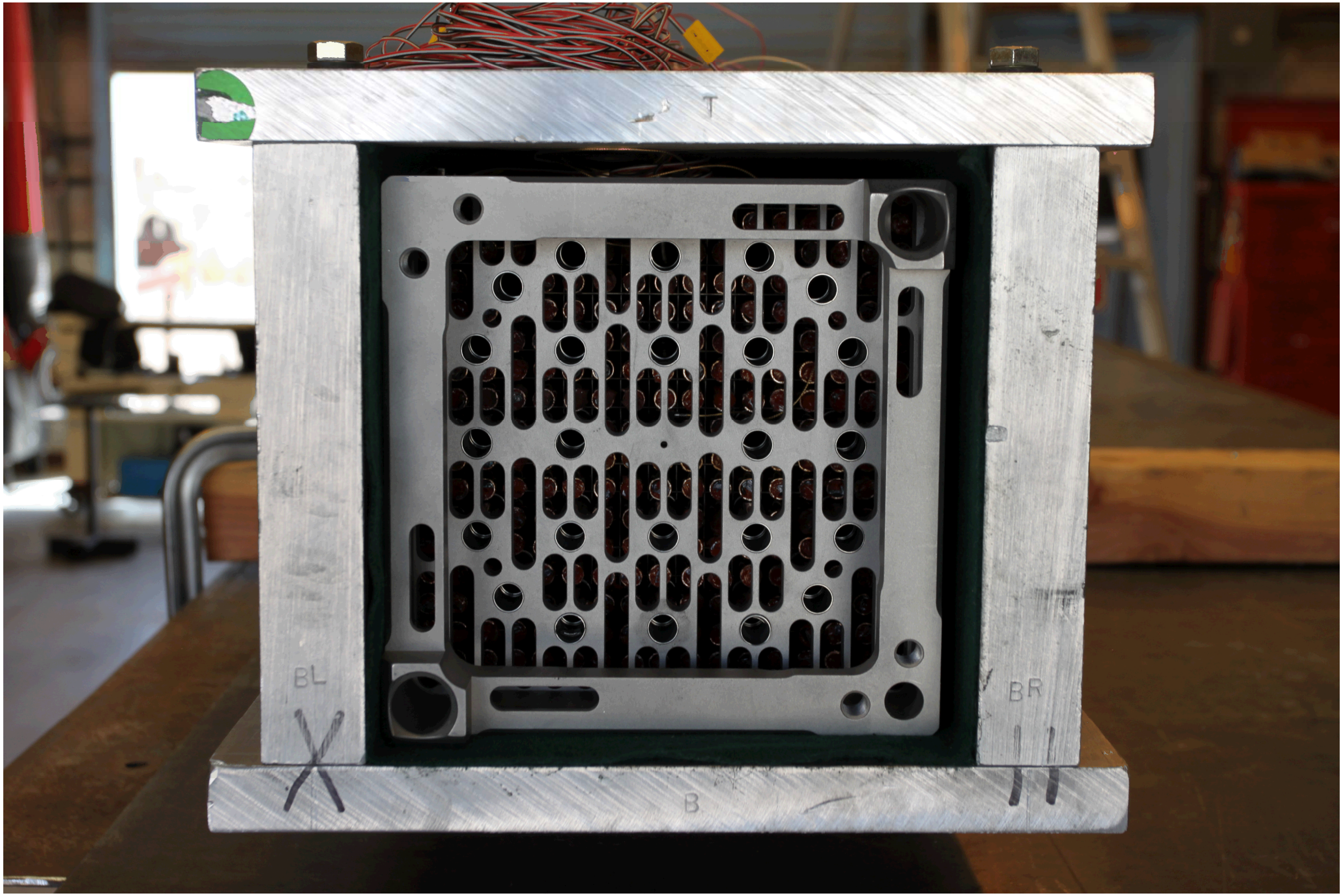
Accelerometers and Strain Gauge on Top-Center Zircaloy Tube



Assembly in Basket

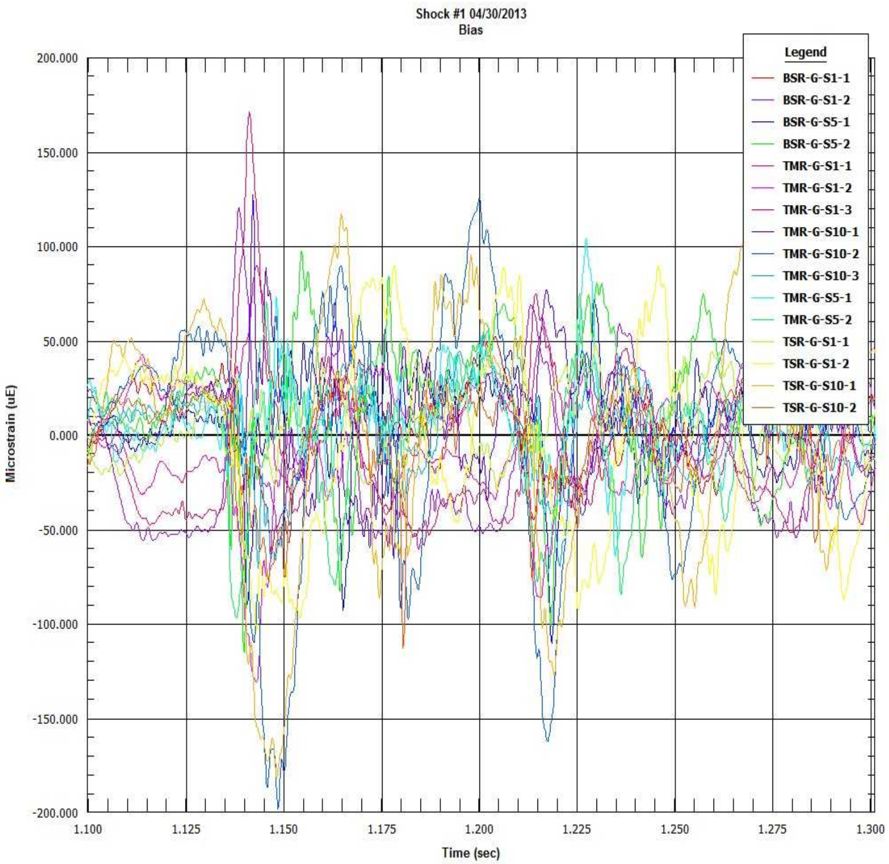
- 6061 Aluminum Basket
- Sides 1.5 inches thick
- Top/bottom 1 inch thick
- Length 161.5 inches
- Weight 837 pounds

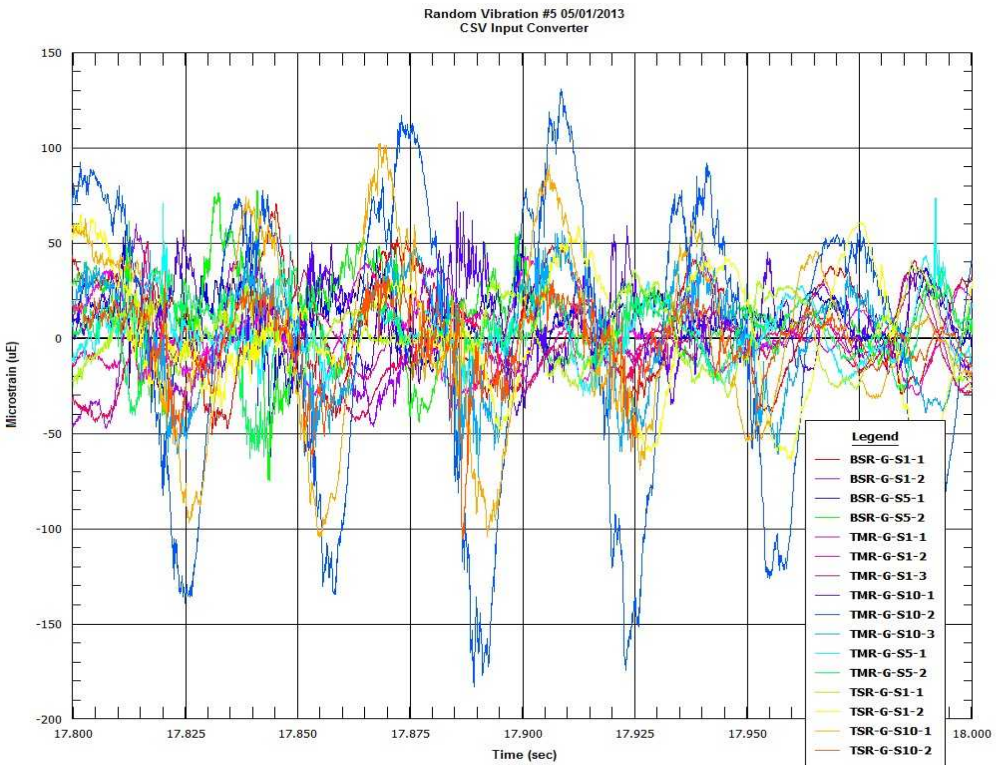
Bottom-end of assembly within basket. Note copper rods behind end nozzle.



Basket / Assembly on Shaker

Shock and vibration time-histories, micro-strains v. time





Maximum Micro-strains on Zircaloy Fuel Rods during Shock Test #1

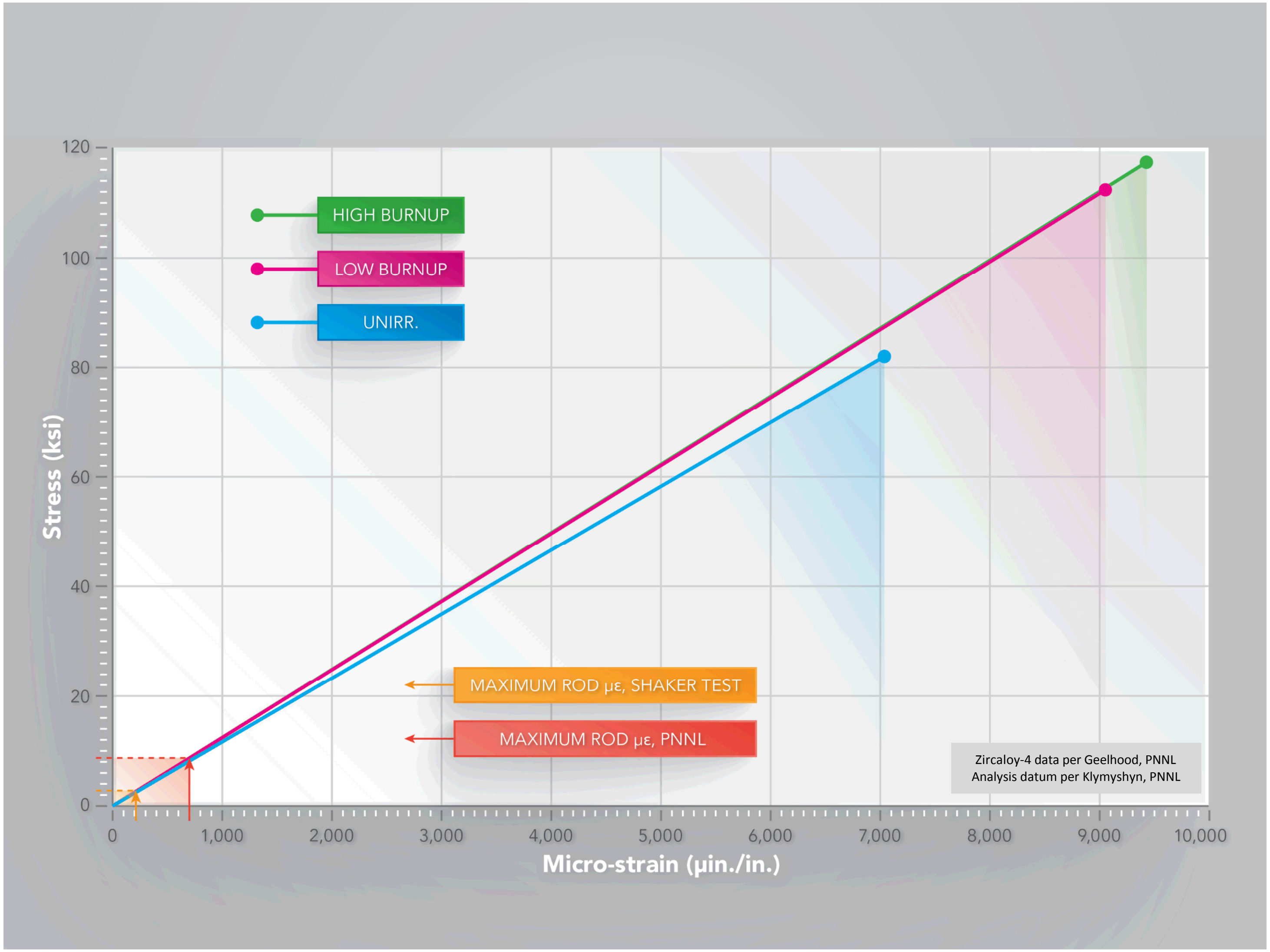
Maximum Strains on Zircaloy Fuel Rods, Shock Test #1			
Rod Location	**Assembly Span**	**Position on Span**	**Maximum Strain (µin./in.)**
Top-middle rod	Bottom-end	Adjacent to spacer grid	90
Top-middle rod	Bottom-end	Mid-span	131
Top-middle rod	Bottom-end	Adjacent to spacer grid	171
Top-middle rod	Mid-assembly	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

Maximum Strains, Average Strains ($\mu\varepsilon_{RMS}$), and Average Peak Strains ($\mu\varepsilon_{peak}$) on Zircaloy Fuel Rods Random Vibration Test #5

Sandia National Laboratories

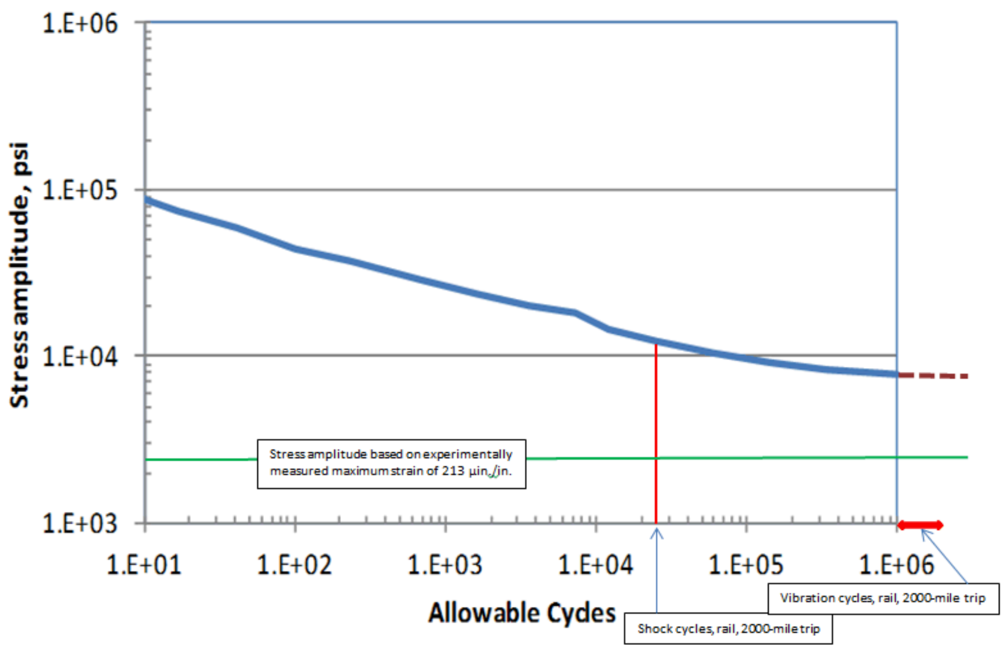
Maximum Strains, Average Strains ($\mu\varepsilon_{RMS}$), and Average Peak Strains ($\mu\varepsilon_{peak}$) on Zircaloy Fuel Rods Random Vibration Test #5					
Rod Location	**Span**	**Position on Span**	**Maximum Strain (µin./in.)**	**Average ($\mu\varepsilon_{RMS}$) (µin./in.)**	**Average ($\mu\varepsilon_{peak}$) (µin./in.)**
Top-middle	Bottom-end	Adjacent to spacer grid	70	19	27
Top-middle	Bottom-end	Mid-span	75	21	30
Top-middle	Bottom-end	Adjacent to spacer grid	81	19	27
Top-middle	Mid-assembly	Adjacent to spacer grid	145	15	21
Top-middle	Mid-assembly	Mid-span	80	19	27
Top-middle	Top-end	Adjacent to spacer grid	98	14	20
Top-middle	Top-end	Mid-span	**183**	**42**	**59**
Top-middle	Top-end	Adjacent to spacer grid	74	16	23
Top-side	Bottom-end	Adjacent to spacer grid	**60**	13	18
Top-side	Bottom-end	Mid-span	128	26	37
Top-side	Top-end	Mid-span	153	41	58
Top-side	Top-end	Adjacent to spacer grid	113	15	21
Bottom-side	Bottom-end	Mid-span	74	17	24
Bottom-side	Bottom-end	Adjacent to spacer grid	71	19	27
Bottom-side	Mid-assembly	Adjacent to spacer grid	106	**11**	**16**
Bottom-side	Mid-assembly	Mid-span	92	13	18
		Average All Strain Gages	**100**	**20**	**28**
		Average Top-middle Rod	101	21	30
		Average Top-side Rod	**114**	**24**	**34**
		Average Bottom-side Rod	86	15	21
		Average Bottom-end Span	80	19	27
		Average Mid-assembly Span	106	15	21
		Average Top-end Span	**124**	**26**	**37**
		Average Mid-span	**112**	**26**	**37**
		Average Adjacent to Spacer Grid	91	16	23

Measured strains are very low relative to the elastic limit of Zircaloy-4



Fracture mechanics and 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	0.2 - 0.3	20 - 30
0.25	0.4 - 0.4	
0.50	0.5 - 0.6	



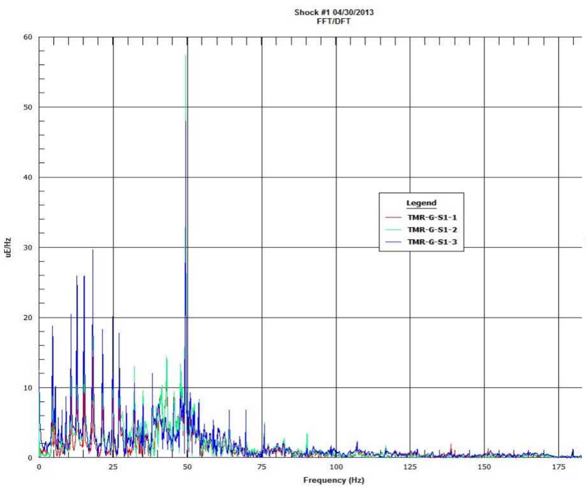
Average Accelerations and Average Peak Accelerations during Random Vibration Test #5

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		Adjacent to spacer grid	2.0	2.8
Top-middle		Mid-span of rod	2.0	2.8
Top-middle		Adjacent to spacer grid	0.3	0.4
Top-middle		On spacer grid	0.7	1.0
Top-middle	5	On spacer grid	1.2	1.7
Top-middle		Adjacent to spacer grid	3.7	5.2
Top-middle		Mid-span of rod	4.0	5.7
Top-middle		Adjacent to spacer grid	3.9	5.5
Top-middle		On spacer grid	0.6	0.8
Top-side	10	On spacer grid	0.6	0.8
Top-side		Adjacent to spacer grid	3.8	5.4
Top-side		Mid-span of rod	4.3	6.1
Top-side		Adjacent to spacer grid	4.6	6.5
Top-side		On spacer grid	1.0	1.4
Control rod, bottom end	1	On control rod	0.7	1.0
Control rod, top end	10		0.9	1.3
Basket, bottom end	≈ 1	On top edge of basket	1.9	2.7
Basket, mid-span	≈ 5		0.9	1.3
Basket, top end	≈ 10		1.7	2.4
Mounting plate, vertical	≈ 5	Near mid-span of basket	1.0	1.4
Mounting plate, lateral			0.08	0.1
Mounting plate, long.			0.09	0.1

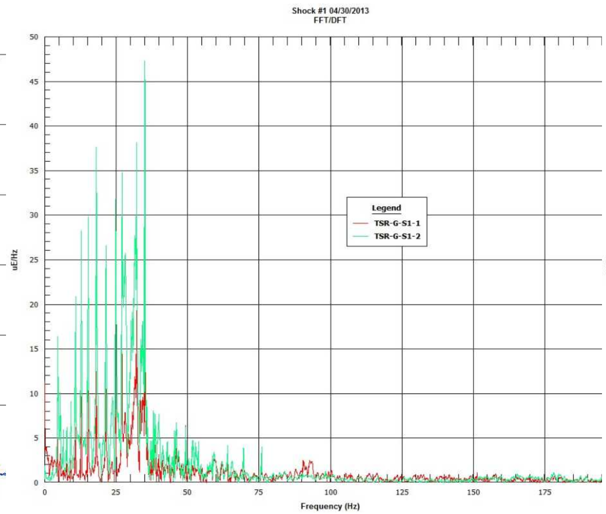
Maximum Micro-Strains, Each Strain Gage, Duplicative Tests

Maximum Strains (µin./in.), Each Strain Gage, Duplicative Tests												
Gage	Vibration #4		Vibration #5		Vibration #6		Shock #1		Shock #2		Shock #5	
	Max	Min	**Max**	Min	**Max**	Min	**Max**	Min	**Max**	Min	**Max**	Min
TM-1-1	69	−60	70	−59	65	−56	90	−46	91	−49	64	−43
TM-1-2	69	−74	67	−75	64	−77	48	−130	56	−119	63	−119
TM-1-3	73	−64	81	−65	71	−57	172	−53	138	−84	148	−75
TM-5-1	156	−66	145	−57	145	−61	104	−64	90	−83	114	−61
TM-5-2	61	−82	70	−80	64	−97	75	−97	99	−88	89	−119
TM-10-1	90	−55	98	−48	83	−47	127	−66	91	−62	107	−77
TM-10-2	138	−207	131	−183	121	−172	126	−199	169	−213	101	−184
TM-10-3	74	−89	67	−74	62	−76	53	−70	69	−71	42	−80
TS-1-1	55	−41	60	−40	70	−45	53	−36	71	−42	85	−67
TS-1-2	97	−122	89	−128	93	−105	107	−110	114	−139	134	−150
TS-10-1	110	−143	113	−153	101	−146	118	−181	130	−153	149	−198
TS-10-2	45	−113	42	−113	45	−106	35	−112	42	−119	45	−115
BS-1-1	67	−69	74	−61	46	−67	55	−62	74	−70	61	−81
BS-1-2	68	−72	71	−58	62	−56	121	−60	116	−74	85	−75
BS-5-1	65	−108	106	−94	70	−97	71	−111	56	−102	60	−120
BS-5-2	94	−98	90	−92	94	−105	97	−115	88	−111	94	−91

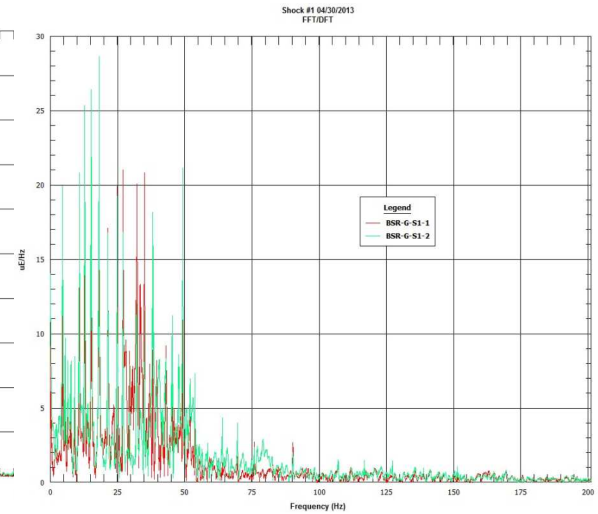
Shock Test FFT, με/Hz, v. Hz



Top-middle rod

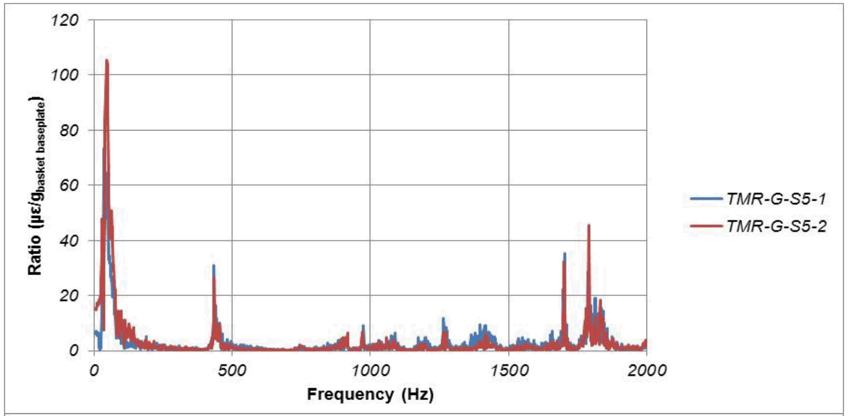


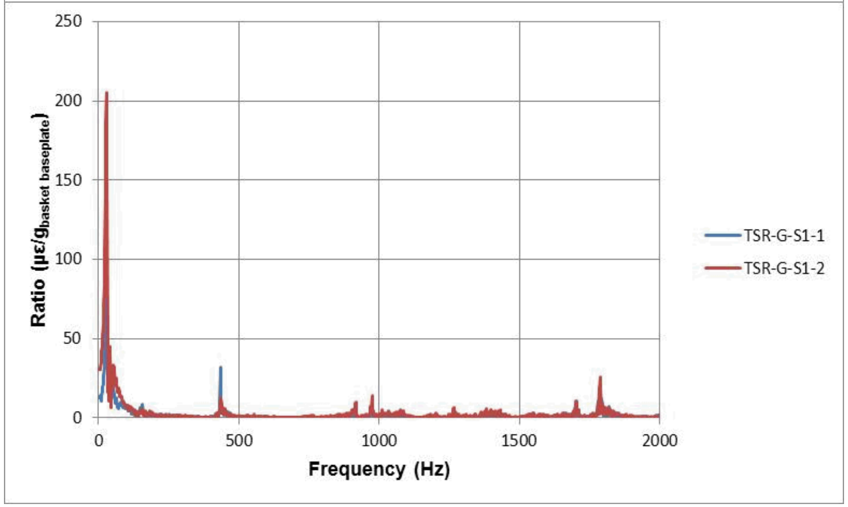
Top-side rod

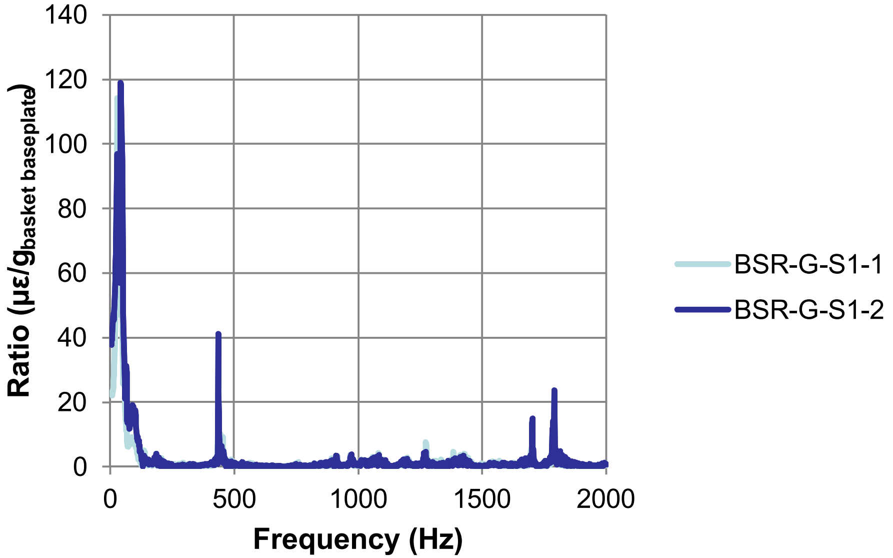


Bottom-side rod

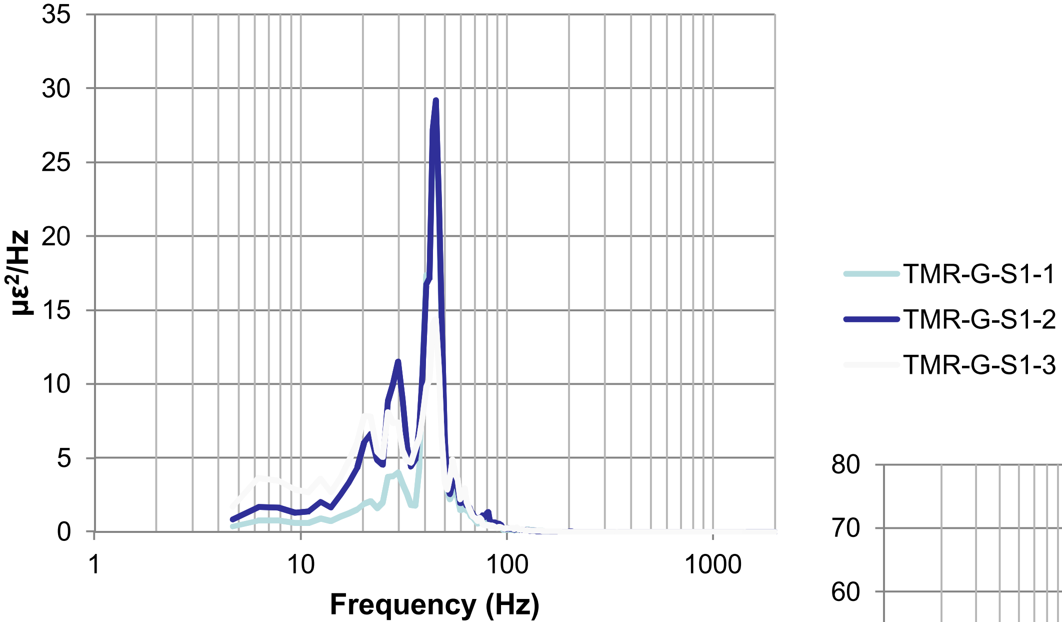
Vibration Test Ratio of micro-strains to baseplate vertical acceleration, με/g, *v*. Hz.

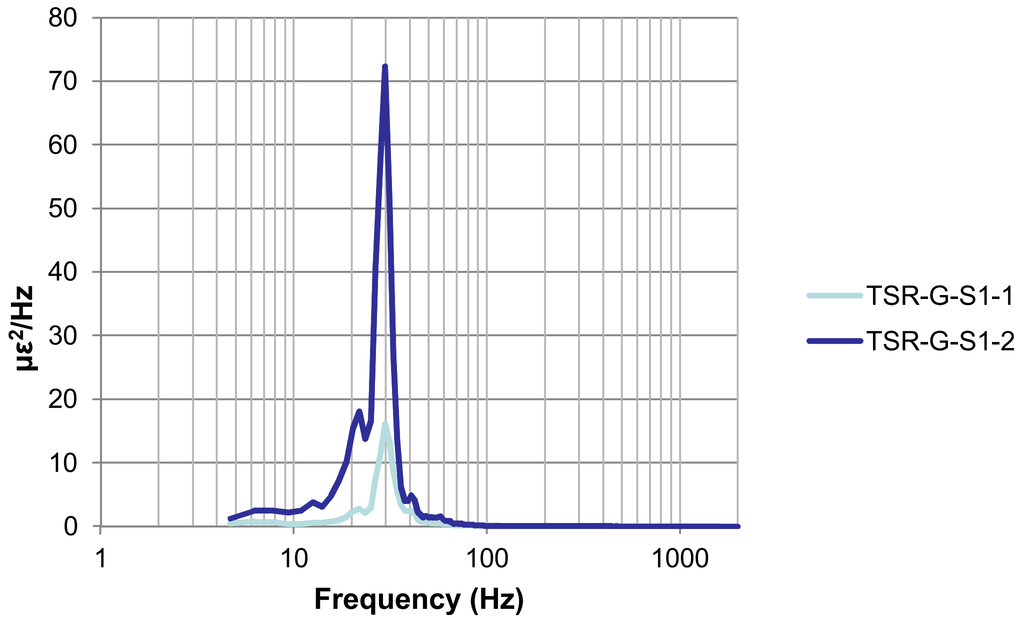




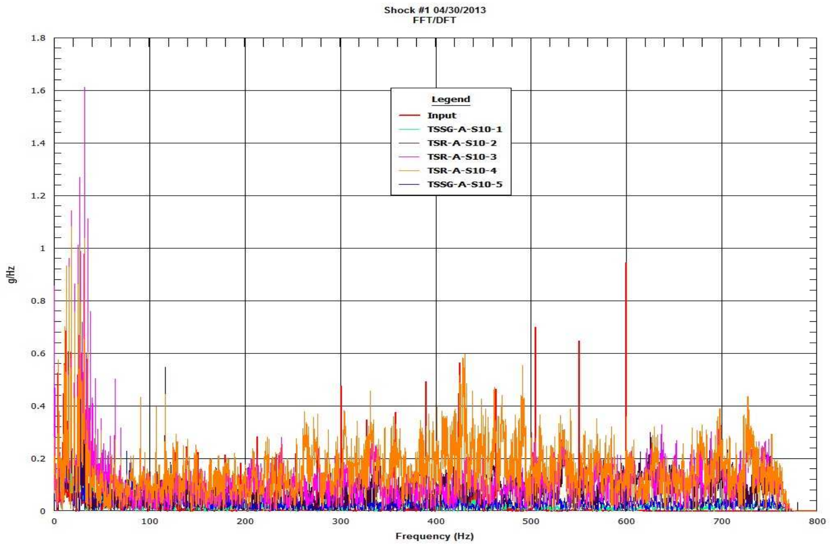


Vibration Test Micro-strain Power Spectral Density, $\mu\varepsilon^2$/Hz, *v*. Hz.

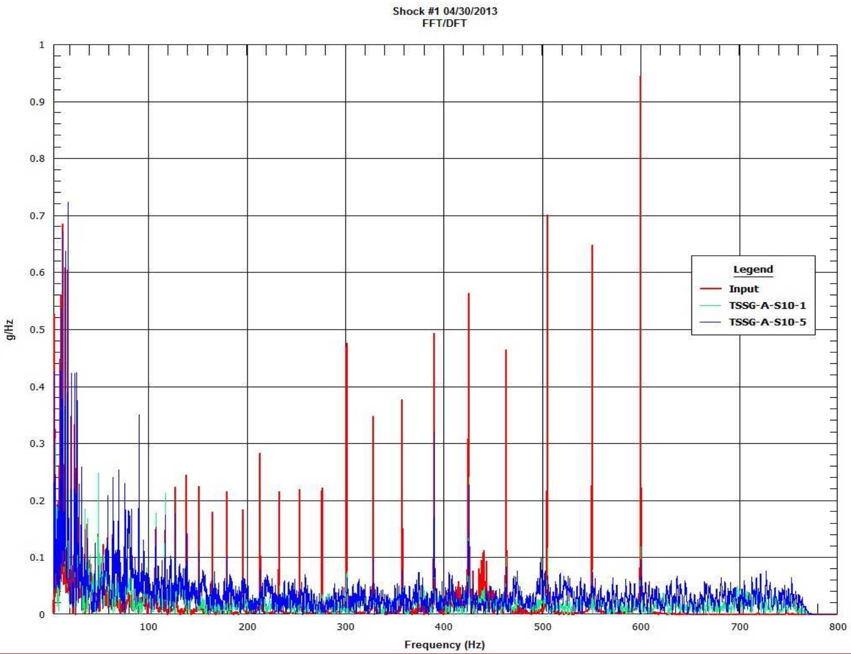




Shock Test Input / Control and Top-side Spacer Grids and Rod Accelerations Fast Fourier Transformation, g/Hz v. Hz.

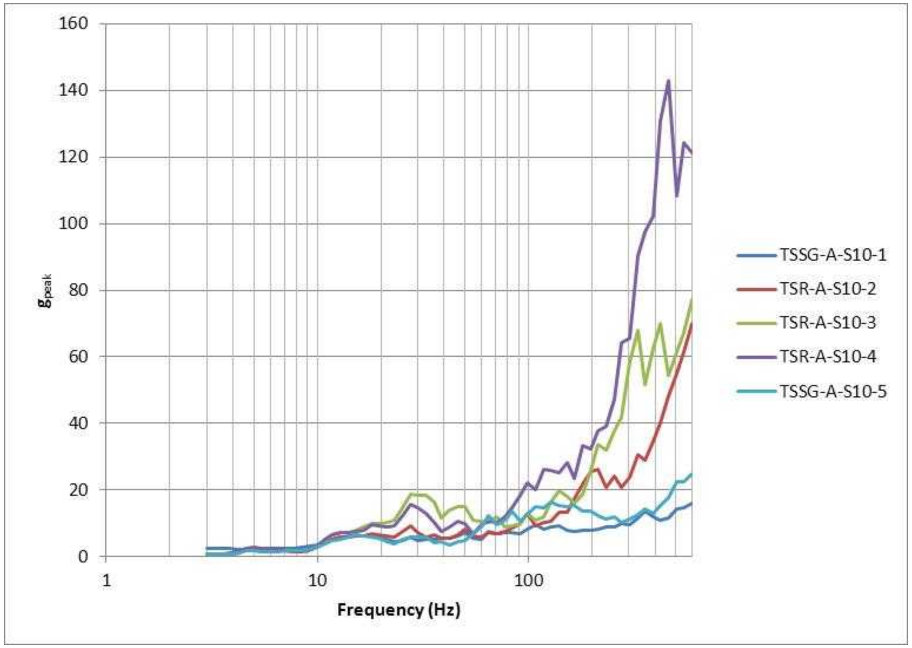


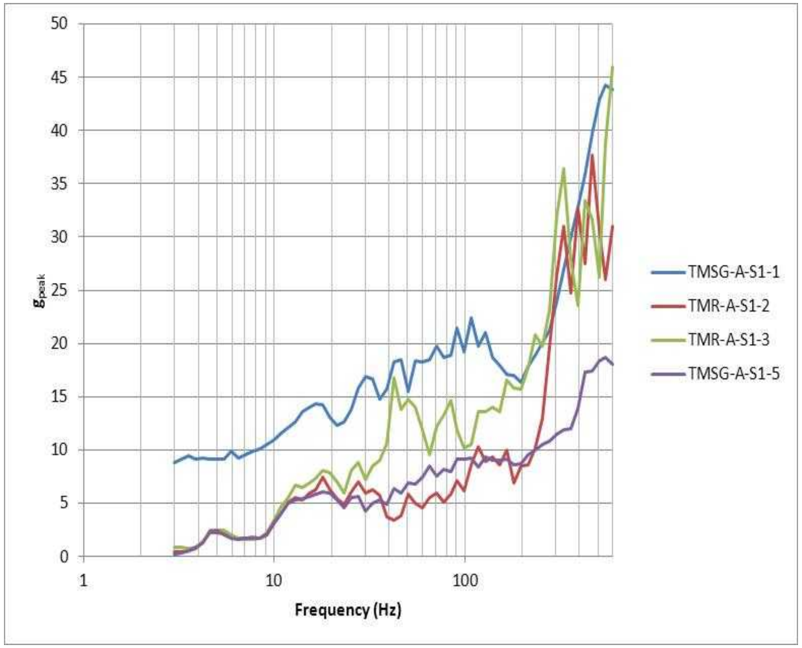
The rods responded to the input accelerations at all frequencies.



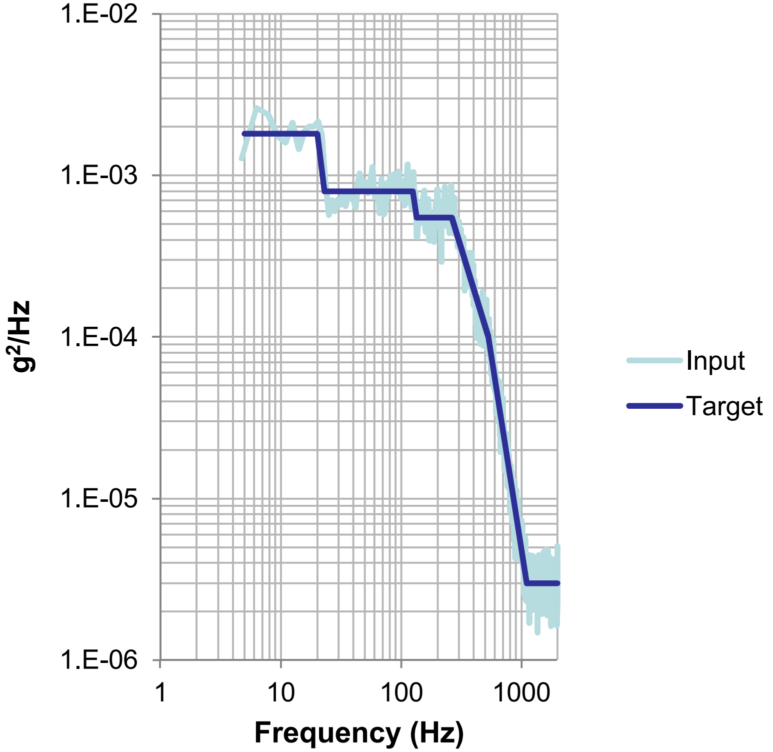
The assembly spacer grids did not respond to the input accelerations beyond approximately 200Hz.

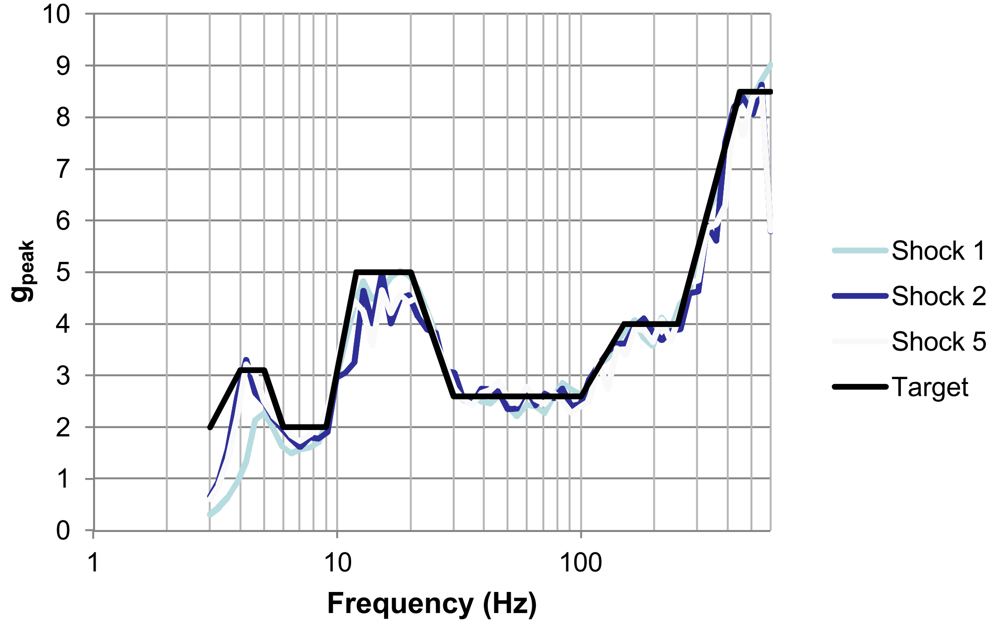
Shock Test Shock Response Spectra, g_{peak} v. Hz





Vibration Test Target Data and Shaker Control System Acceleration Power Spectral Density, g^2/Hz, *v*. Hz and Target Data and Shaker Control System Peak Accelerations for Shock Tests, g_{peak}, *v*. Hz.





Conclusion

- The strains measured in the shaker test program were in the **micro-strain levels** – well below the elastic limit for either unirradiated or irradiated Zircaloy-4.
- Based upon the test results, which simulated normal vibration and shock conditions of truck transport, strain- or stress-based failure of fuel rods during normal transport seems unlikely.
- Additional testing – shaker and high burnup Zircaloy rod – and additional finite elements analyses are recommended.

Future Testing

- Perform tests on the assembly/basket test unit on the Sandia shaker using rail vibration and shock inputs .
- Perform tests on the assembly/basket test unit on a seismic shaker down to 2 Hz using truck and rail vibration and shock inputs .
- Instrument an assembly for actual over-the-road testing.