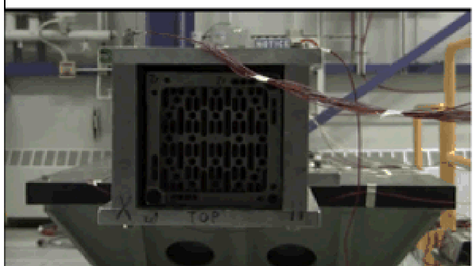
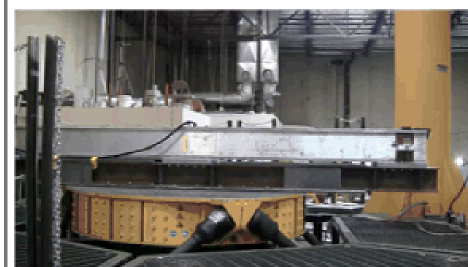
SAND2016-8682C

Exceptional service in the national interest

Sandia National Laboratories

SNL Shaker	Over-the-Road Truck Test	Multi-axis Shaker
		

Fuel Assembly Tests under Normal Conditions of Transport

18th International Symposium on the Packaging and Transportation of Radioactive Materials

Paul McConnell, Sylvia Saltzstein & Ken Sorenson

20 September 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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The Surrogate PWR Assembly Test Series

2013 SNL Shaker

- Truck NCT vibration and shock
- Only Vertical accelerations
- Greater than 3.5 Hz
- Lead Rope only

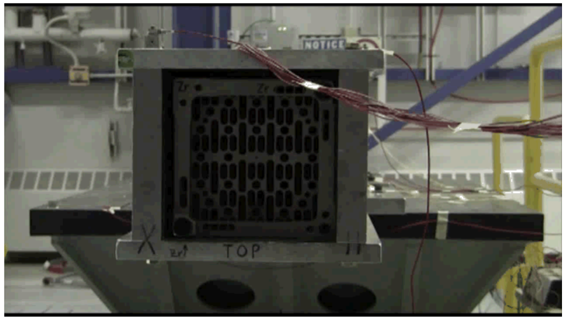
2014 Over-The-Road Truck Test

- Over-the-road truck test
- All acceleration directions
- All Hz
- Lead Rope only

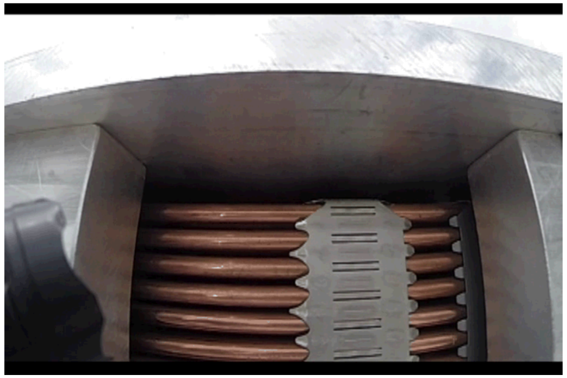
2015 Multi-Axis Shaker for Truck and Rail

- Multi-axis (6)
- Truck NCT vibration and shock
- Rail NCT vibration and shock
- All Hz.
- Lead Rope, Lead Pellets, and Mo Pellets

Sandia Unidirectional Shaker Test



2013 SNL Shaker Truck NCT



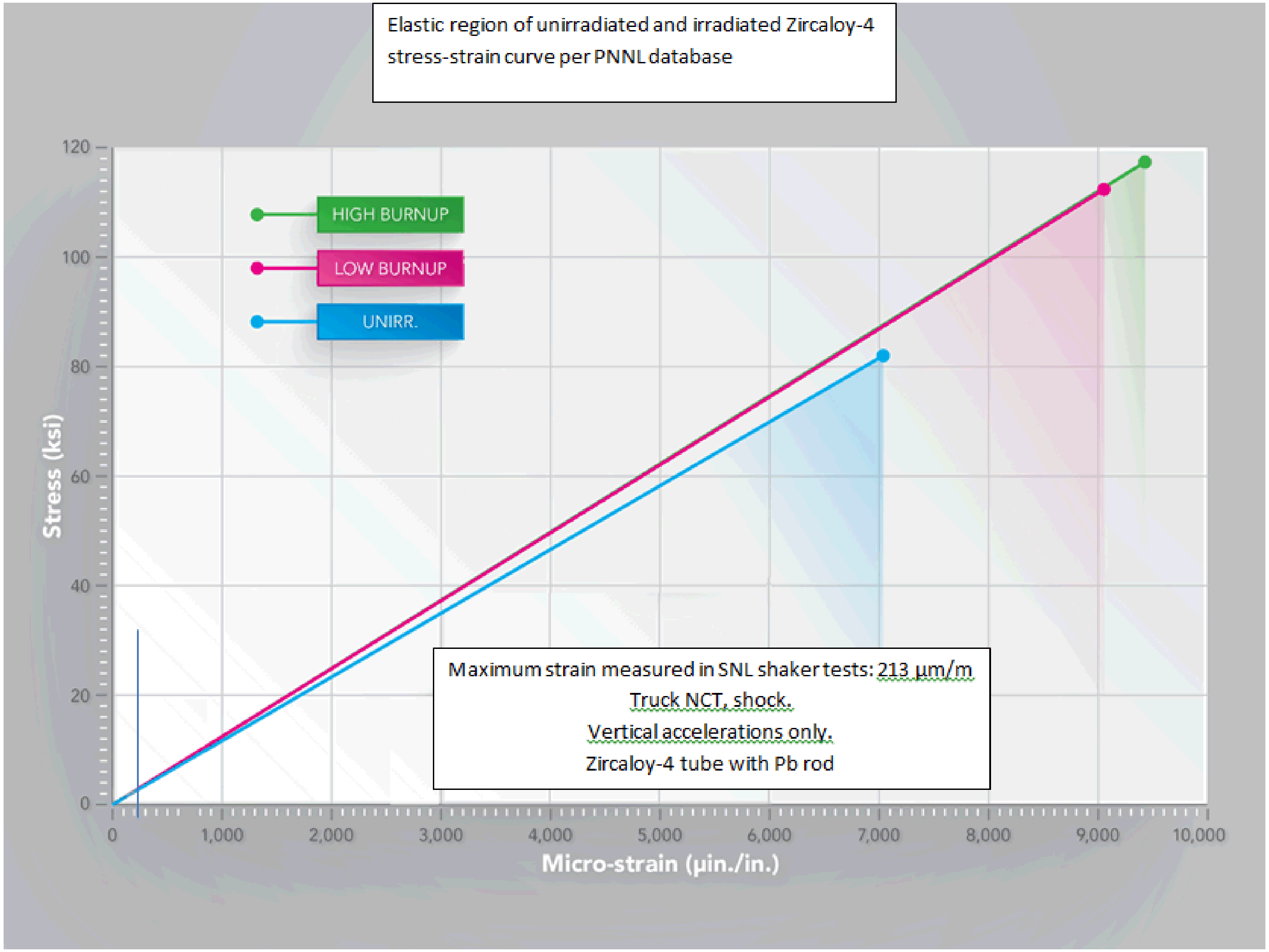
2014 Over-The-Road Truck Test

2015 Multi-Axis Shaker for Truck and Rail NCT

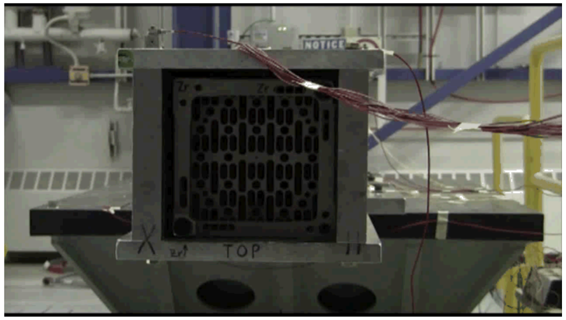
Sandia Truck Shaker Test Results

Sandia National Laboratories

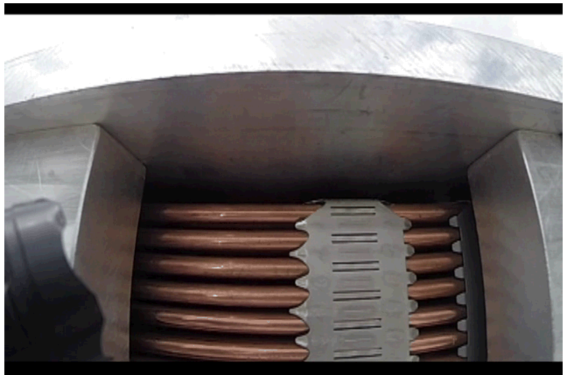
(213 µm/m maximum strain; 16 strain gauges; 6 vibration tests, 5 shock tests)



2014 Over-The-Road Truck Test



2013 SNL Shaker

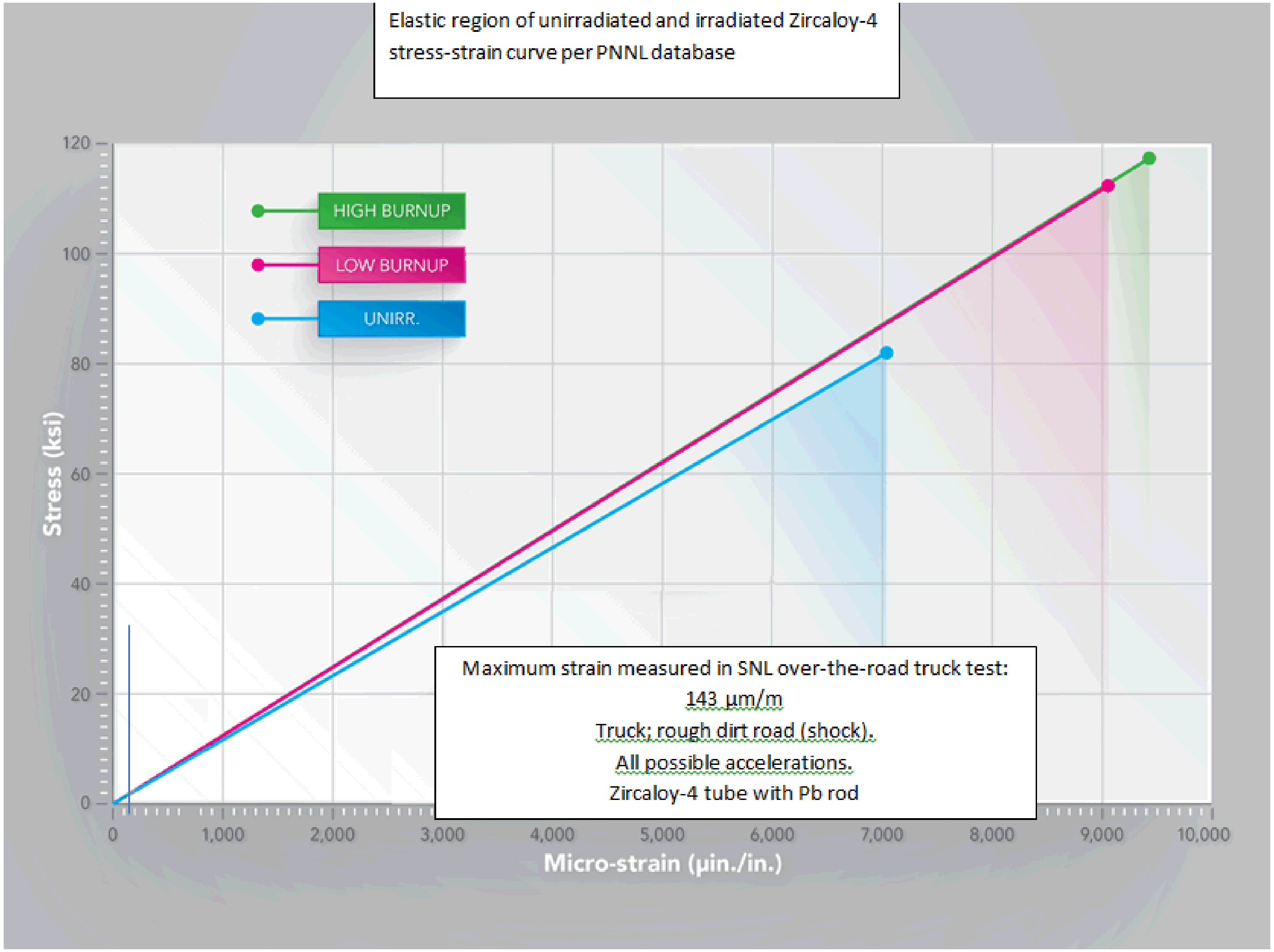


2014 Over-The-Road Truck Test

2015 Multi-Axis Shaker for Truck and Rail

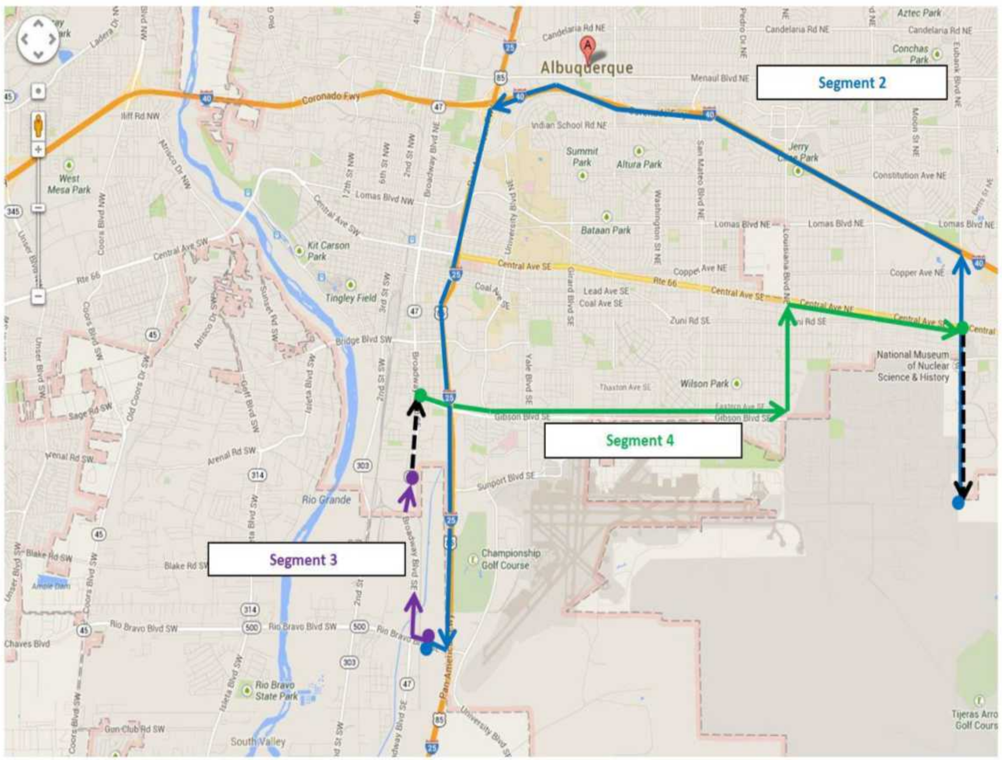
Over-The-Road Truck Test Results

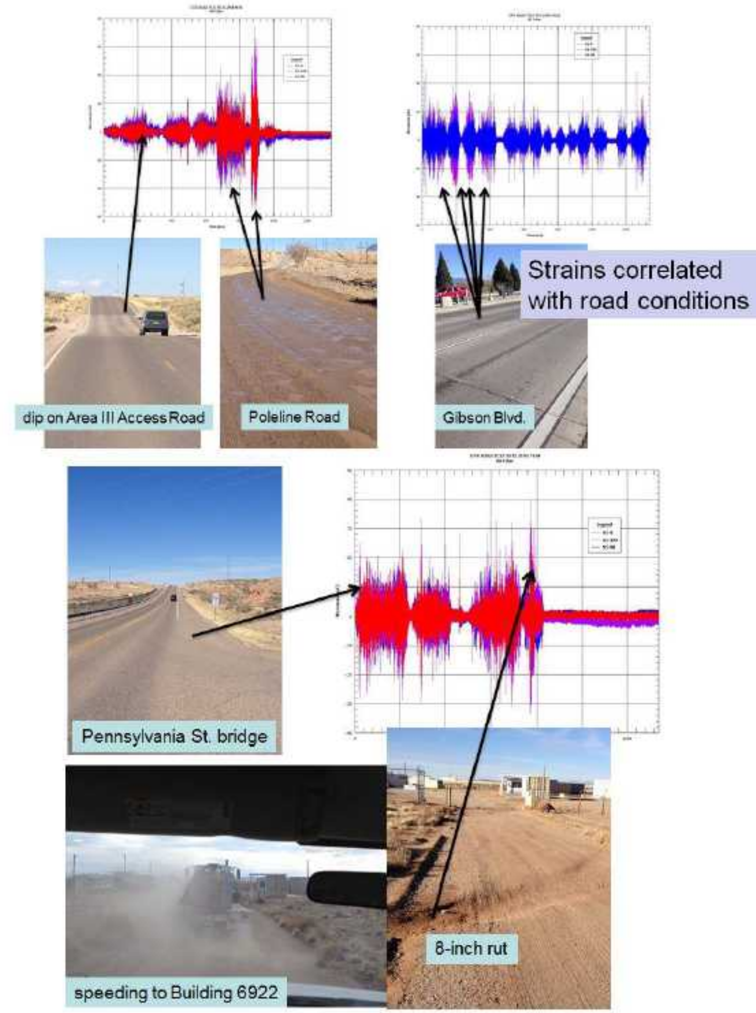
(143 µm/m maximum strain; 12 strain gauges)



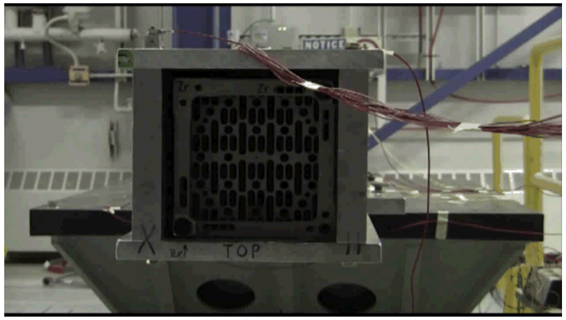
Over-the-Road Truck Tests

The same assembly used in the shaker tests was used for the truck test. Strain gauges and accelerometers were placed on Zircaloy rods within the assembly. Accelerometers were on the assembly basket and the truck trailer. A variety of road surfaces were traversed.

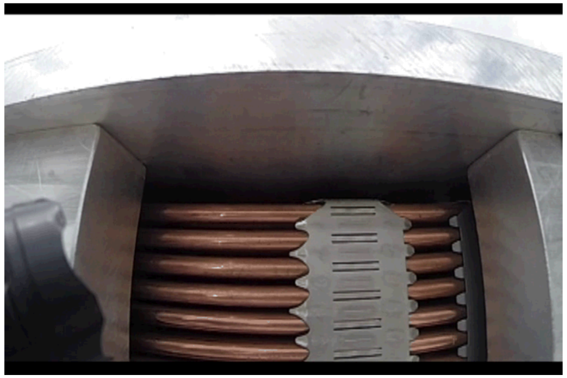




2015 Multi-Axis Shaker for ***Truck*** and ***Rail***



2013 SNL Shaker

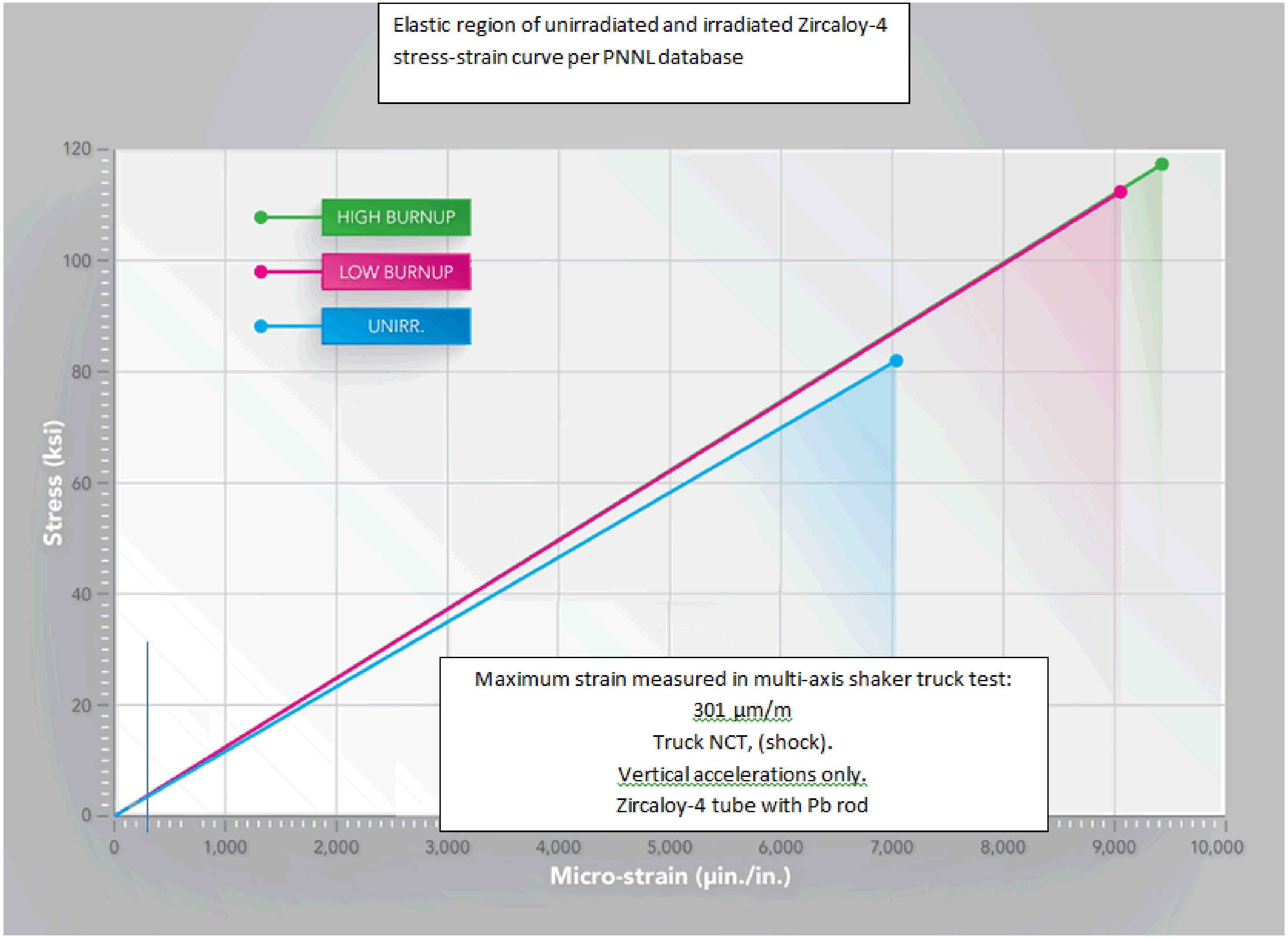


2014 Over-The-Road Truck Test

2015 Multi-Axis Shaker for Truck and Rail

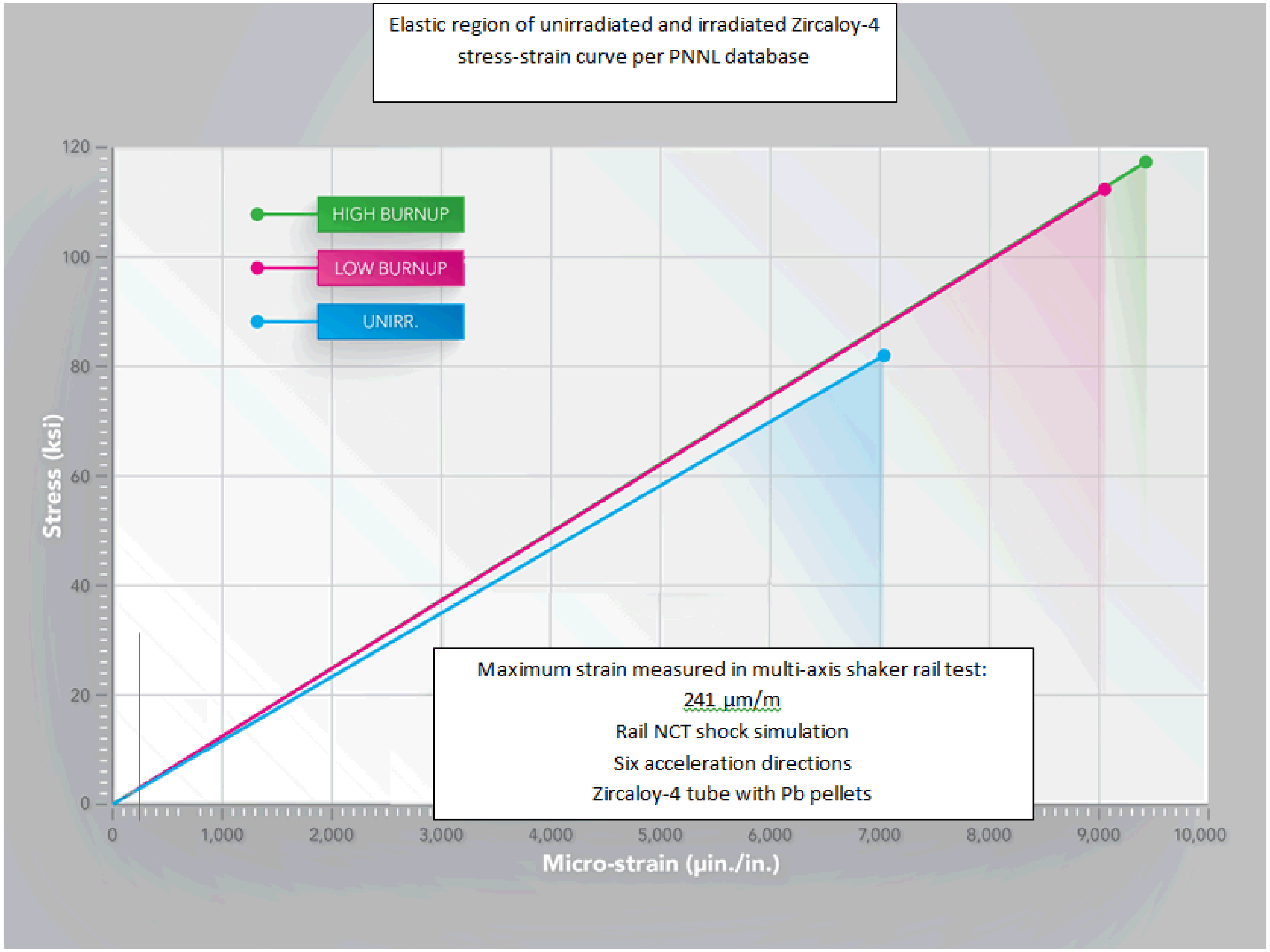
Multi-Axis Shaker ***Truck*** Test Results

(301 µm/m maximum strain; 8 strain gauges; 7 truck tests: 2 vibration, 5 shock)

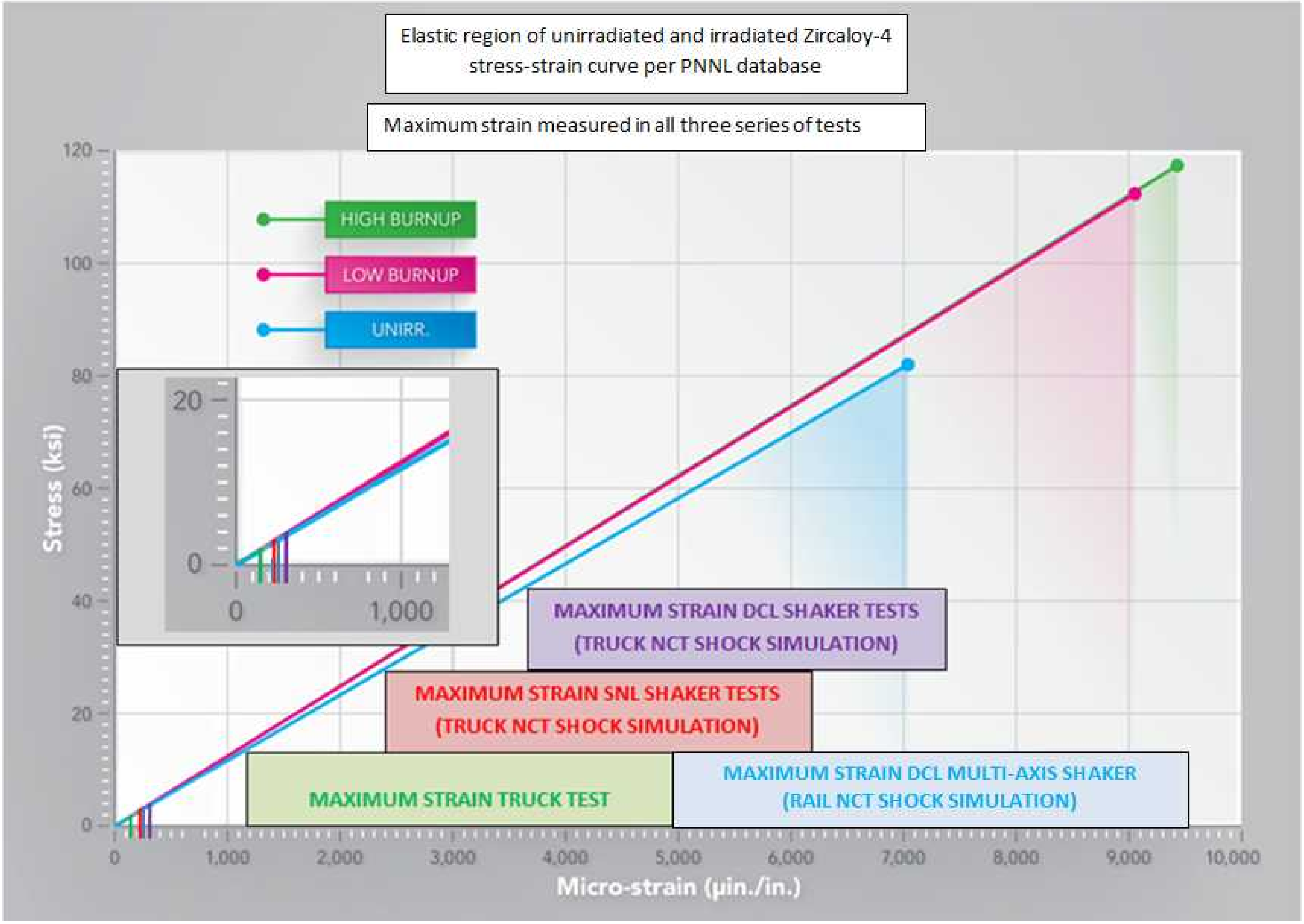


Multi-Axis Shaker ***Rail*** Test Results

(241 µm/m maximum strain; 8 strain gauges; 15 tests: 3 vibration, 12 shock)



Summary: All test results were similar: Strains are very low compared to elastic limit of Zircaloy-4.



Dynamic Certification Laboratories Assembly Shaker Tests

- **Sandia assembly with**
  - **Three instrumented Zircaloy-4 tubes**
    - **One filled with Pb rod**
    - **One filled with Pb pellets**
    - **One filled with Mo pellets**

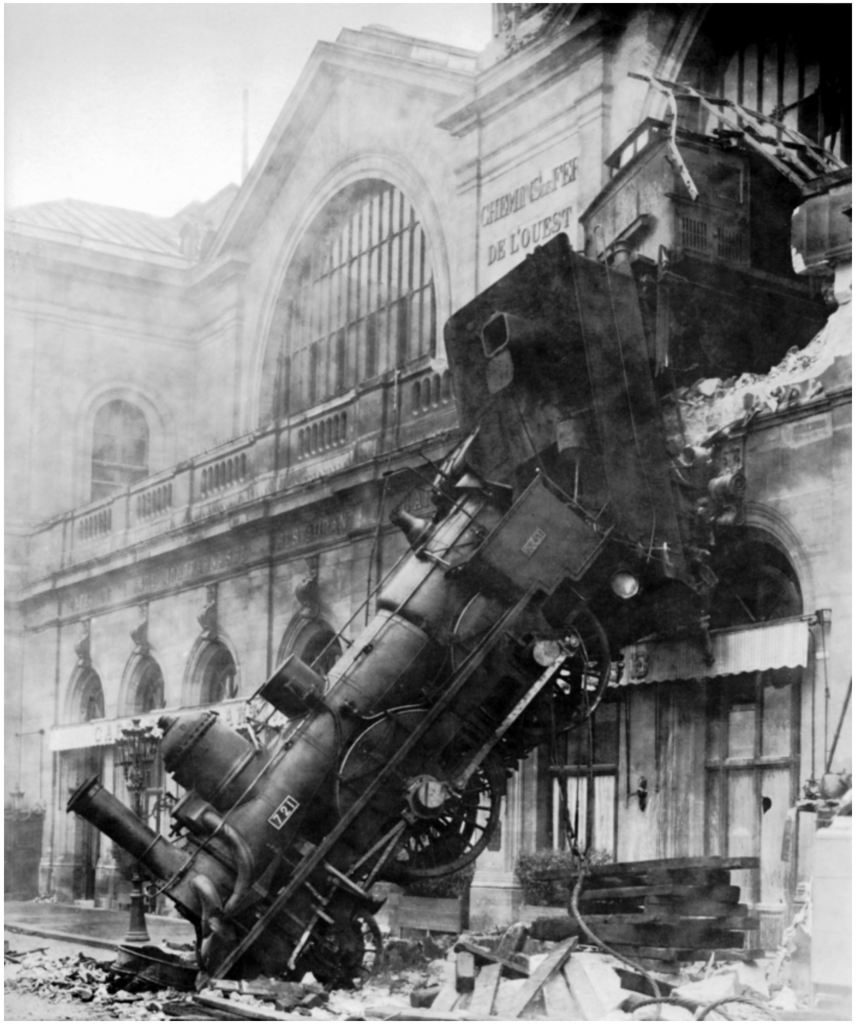
- Rail shock and vibration tests including rail coupling shock
  - Tests based on railcar deck accelerations and basket accelerations
- Truck shock and vibration tests

Maximum strains measured in all three test series were extremely low.

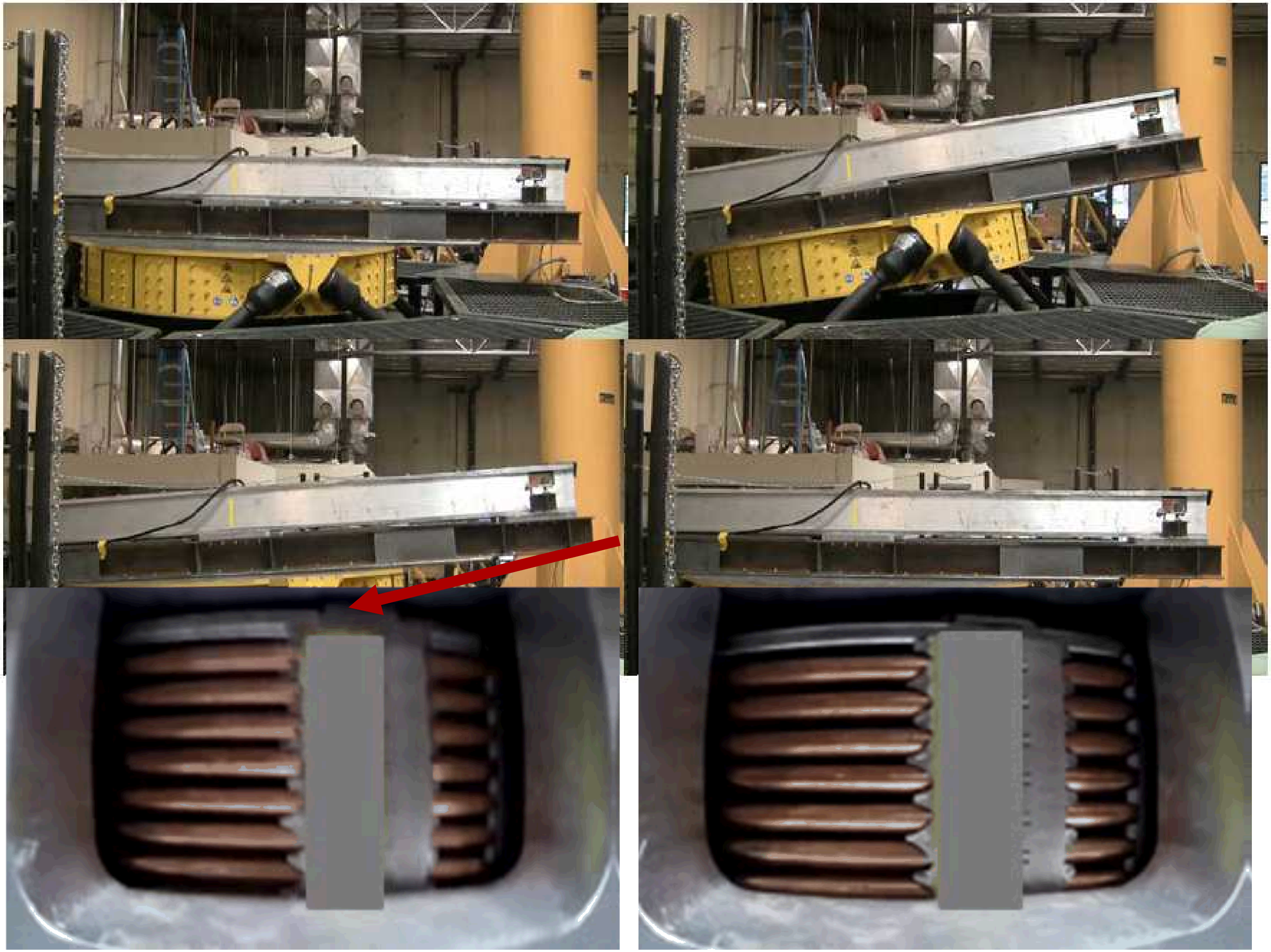
Strain Gauge / Surrogate UO_2 Material within Zircaloy-4 Tube	Rod Location within Assembly (Axial Location on Assembly: Adjacent to First Spacer Grid, Middle Span) Same Axial Location for all Strain Gauges	Sandia Shaker Truck Shock Test Maximum Micro-Strain (µin./in.)	Truck Test Maximum Micro-Strain (µin./in.)	DCL Shaker Truck Shock Test Maximum Micro-Strain (µin./in.)
S3 - 0° Pb "rope"	Middle Rod		143	
TMR-G-S5-0° Pb "rope"	Middle Rod	119		
S3- 0° Pb pellets	Right-edge Rod			160
S7 - 0° Mo pellets	Middle Rod			214
S8 - 0° Pb "rope"	Left-edge Rod			301

Effect of Pb rod, Pb pellets, and Mo pellets in Zircaloy tubes was insignificant.

Not a Normal Condition of Transportation



Video screen-capture photographs of shaker and basket/assembly during an unexpected malfunction of the shaker

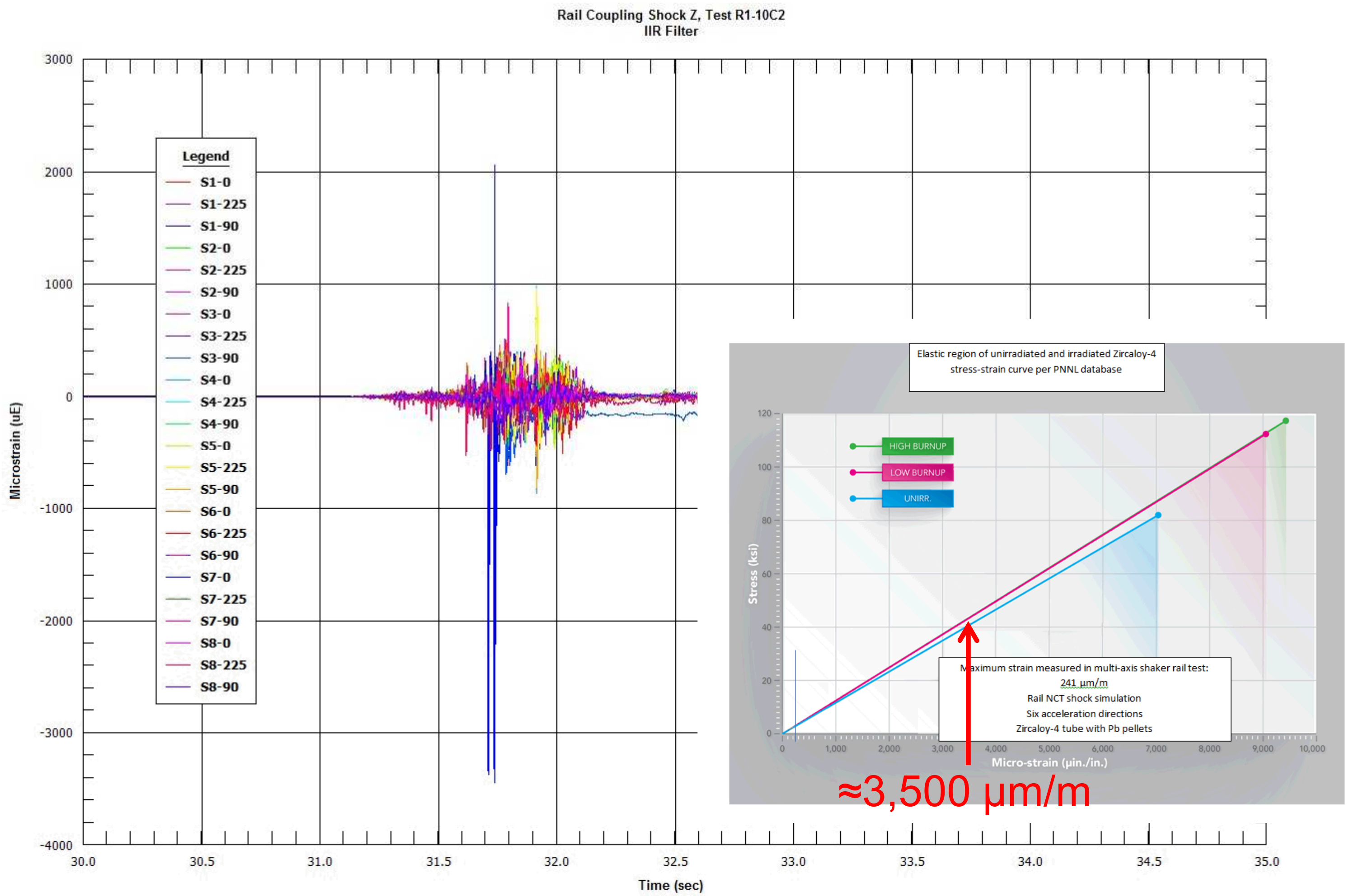


Shaker test video simulating rail coupling shock. NOT a Normal Condition of Transport simulation.

Rail coupling shock shaker test, GoPro® video side of rods (NOT NCT)

Watch the Zircaloy Rod hit the top of the basket.

Strains Measured During the Non-normal Shock Event



Comparison of Sandia Assembly Tests and Oak Ridge National Laboratory Fatigue Tests

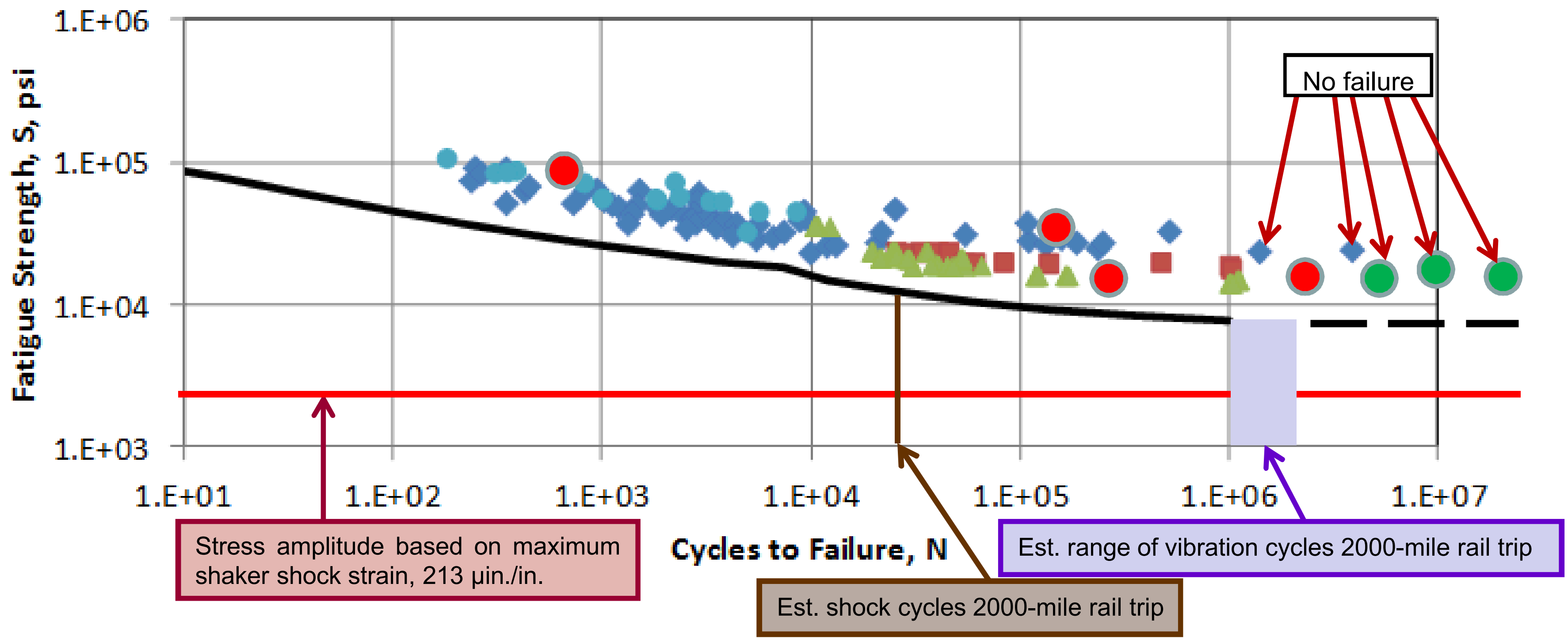
Sandia National Laboratories

Selected ORNL HB Robinson Zircaloy-4 fatigue test data							
Specimen	Burnup (GWd/MTU)	Applied Bending Moment, M (N-m)	Curvature, κ_{max} (m^{-1})	Strain (μm/m)	Stress (lb/in^2)	Cycles $x10^6$	Failure?
D2	63.8	5	0.16	862	1.15E4	6	NO
D4	66.5	7.6	0.23	1239	1.65E4	11	NO
D5	66.5	9	0.22	1185*	1.58E4	2.3	YES
D9	66.5	35	1.2	6464	8.60E4	0.007	YES
D13		13.72	0.44	2370	3.15E4	0.129	YES
D14		8.89	0.27	1454	1.93E4	0.27	YES
D15		7.62	0.22	1185	1.58E4	22.3	NO
Conditions for SNL NCT assembly tests							
		0.7	0.04	≈ 200			

*strain calculated via $r_o(\kappa_{max})$
r_o^{Zirc4} = 5.385 mm (HBR cladding)

Bending moments, curvature, and strain applied in ORNL tests exceed NCT and Non-Normal Shock conditions.
A cross-country trip is expected to experience 1-2 million cycles.

NCT vibrations unlikely to result in fatigue failure



Fatigue design curve (▬▬): O'Donnel and Langer, "Fatigue Design Basis for Zircaloy Components," Nucl. Sci. Eng. 20, 1, 1964. (cited in NUREG-0800, Chapter 4)

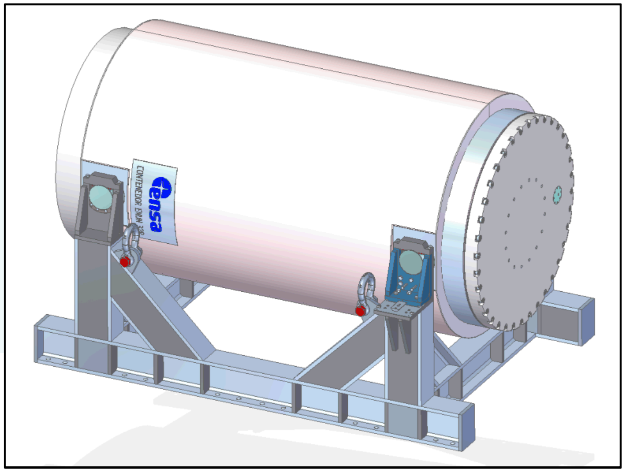
Data plot courtesy of Ken Geelhood, PNNL
The large circles are ORNL HBR data

Plans for completing this work

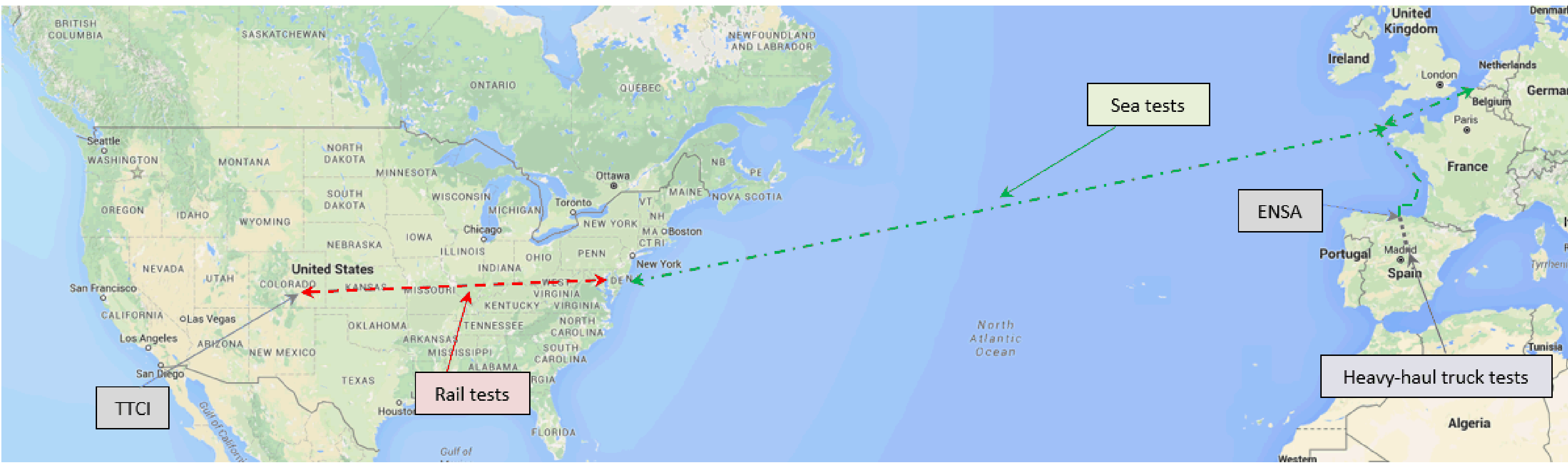
- Tests in 2017 of instrumented PWR assemblies…
  - within a rail-cask basket which is…
  - within an actual rail cask…
  - which will then be…
  - transported on a truck, ships, and railcar

- Rail-cask tests will use an ENSA ENUN 32P cask

These rail tests will:
- eliminate questions regarding the simulated tests
- support future licensing and transport of spent fuel
- support public acceptance of rail transport



ENSA ENUN 32P Cask Testing Routes



BACKUP SLIDES

What We Have Learned

- Rail results are similar to truck results
  - The strains measured on the rods during the NCT test simulations were in the micro-strain levels – well below the elastic limit for either unirradiated or irradiated Zircaloy-4
- Non-Normal Shock Test revealed strains below yield point.
- Fatigue conditions during cross-country transport appear to be less than rod failure conditions.

How were the Shaker Table Tests Conducted?

Two sets of shaker table tests were performed.

These tests are described in:

"FUEL ASSEMBLY SHAKER TEST for Determining Loads on a PWR Assembly under Surrogate Normal Conditions of Truck Transport", SAND2013-5210P, Rev. 0.1, FCRD-UFD-2013-000190, June 30, 2013 (revised December 1, 2013)

"Surrogate Fuel Assembly Multi-Axis Shaker Tests to Simulate Normal Conditions of Rail and Truck Transport", SAND2016-4576 R, FCRD-UFRD-2015-00128, REV. 1, May 12, 2016.

The tests used a 17 X 17 PWR surrogate assembly, and placed within a surrogate truck-cask basket. Zircaloy-4 rods were filled with lead "rope," lead pellets or Molybdenum pellets. They were instrumented with strain gauges and accelerometers. The remainder of the rods were copper tubing filled with lead rope to simulate the real PWR assembly mass and stiffness.

The Sandia shaker tests used a one-degree of freedom (vertical) shaker table. The second set of shaker tests used a multi-axis (six-degrees of freedom) shaker table.

The Sandia shaker tests simulated normal conditions of transport (NCT) truck shock and vibration (NRC NUREG/CR-0128). The multi-axis shaker tests simulated NCT truck and rail shock and vibration. Rail data was obtained from measured shock and vibration data on a 50,000 lb coal car and converted into those expected on a 2043 railcar using TTCI's NUCARS code.

All test inputs and results were provided to PNNL for modeling. PNNL modeled the assembly and rods used in the testing.

The test results were also compared with testing done at ORNL on irradiated rods. The strains measured in the SNL tests were far lower than the strains which caused fatigue failure in the ORNL tests.

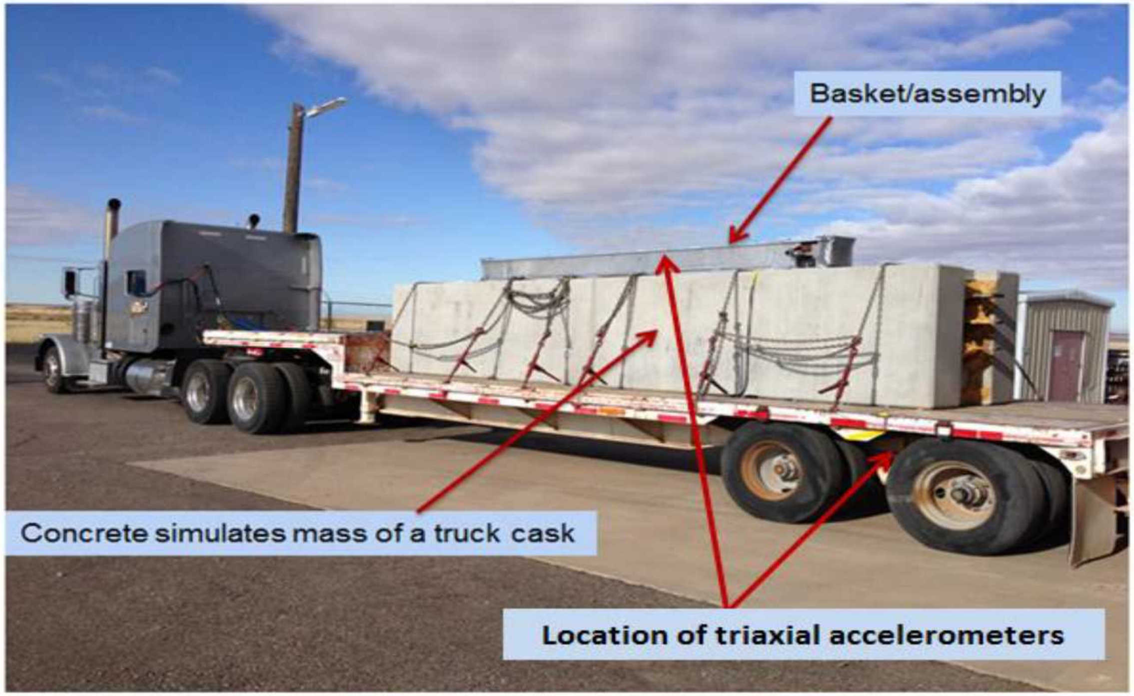
ORNL Zircaloy-4 fatigue test data

Specimen	Burnup (GWd/MTU)	Applied bending moment (N-m)	Curvature of rod (m^{-1})	Strain on rod (μm/m)	Fatigue cycles $x10^6$	Rod Failure?
D2	63.8	5	0.16	862	6	NO
D4	66.5	7.6	0.23	1239	11	NO
D5	66.5	9	0.22	1185	2.3	YES
D9	66.5	35	1.2	6464	0.007	YES
D13		13.72	0.44	2370	0.129	YES
D14		8.89	0.27	1454	0.27	YES
D15		7.62	0.22	1185	22.3	NO
SNL NCT assembly tests						
		0.7	**0.04**	**≈ 200**		

Q: Cycles-to-failure for a rod subjected to NCT?

A: Cycles-to-failure estimated to be ≫ 22 $x10^6$

The truck test is described in "Normal Conditions of Transport Truck Test of a Surrogate Fuel Assembly", SAND2014-20495, FCRD-UFD-2014-000066, Revision 0.1, December 15, 2014.



How were decisions made on the assembly design?

- Sandia had a 17 x 17 PWR assembly skeleton.
- Modeling suggested that using three Zircaloy rods would suffice so the remaining rods were made of copper to fit within the budget and time constraints.
- All rods were filled with Pb or Mo since simulating the mass of uranium oxide was the primary factor for simulating the dynamic response of a real assembly.

3.2.1 Selection of rods for tests

The relative differences between the elastic moduli and the densities lead and molybdenum as compared with UO_2 are shown below.

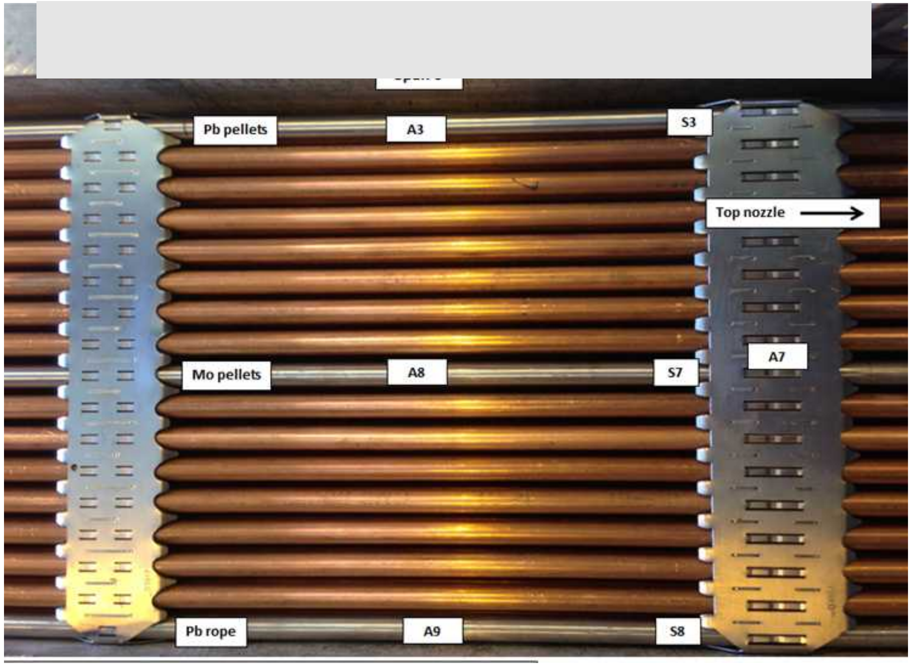
Table 3.1 Comparison of Properties of Materials Used for Rods within the Assembly

	Density (g/cm^3)	Density ratio	Elastic modulus (GPa)	Ratio of Mo/Pb pellet weight
UO_2	10.97	1	192	
Pb	11.34	1.03	16	1.13*
Mo	10.22	0.93	329	1.13*
Zr-4	6.52		99	
Cu	8.94		115	

* 12-foot (3.7 m) tube of Mo pellets = 4.1 lbs (1.9 kg); 12-foot tube of Pb pellets = 3.6 lbs (1.6 kg)

Comparison of micro-strains on different rods: no significant differences in rods with pellets and rod with Pb "rope"

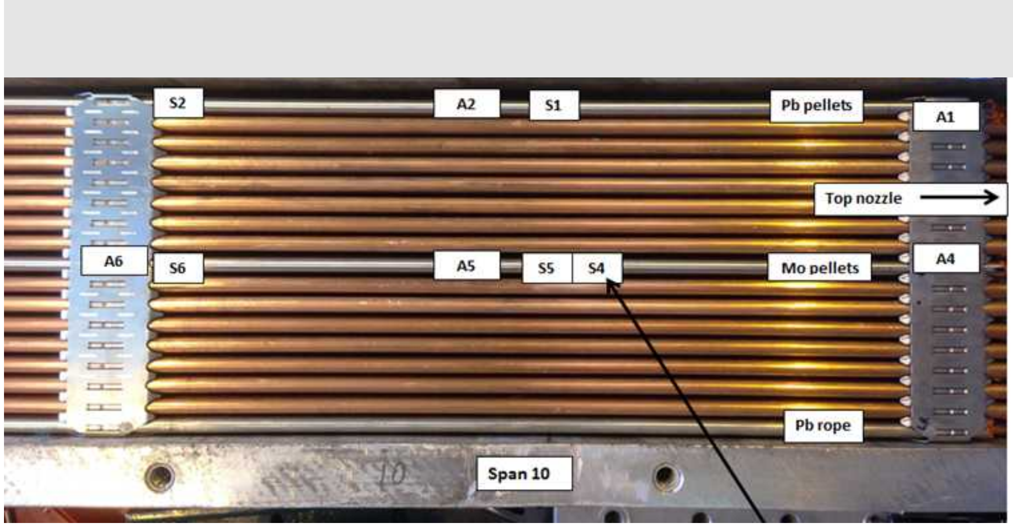
TEST 9 Rail Shock – Basket Loadings	Pb-"rope" rod	Mo-pellet rod	Pb-pellet rod
	S8	**S7**	**S3**
0°	172	44	112
90°	171	225	241
225°	109	182	209
TEST 12 Truck Shock	Pb-"rope" rod	Mo-pellet rod	Pb-pellet rod
	S8	**S7**	**S3**
0°	192	214	160
90°	165	108	95
225°	301	146	135



TEST 10xyz-3 Rail coupling	Pb-"rope" rod	Mo-pellet rod	Pb-pellet rod
	S8	**S7**	**S3**
0°	130	91	104
90°	82	34	30
225°	208	47	77

Comparison of micro-strains at pellet-pellet interface v. strain on single pellet: virtually no difference in strains measured

TEST 9 Rail shock – Basket Loadings	Mo-pellet rod S.G. straddled pellet-pellet gap	Mo-pellet rod S.G. straddled single pellet
	S5	**S4**
0°	67	52
90°	118	108
225°	83	81
TEST 12 Truck Shock	**Mo-pellet rod S.G. straddled pellet-pellet gap**	**Mo-pellet rod S.G. straddled single pellet**
	S5	**S4**
0°	149	158
90°	52	56
225°	104	114



Irradiated rods are stiffer than unirradiated tubes. Strains decrease with stiffness.

1. **Bending stiffness (=*EI*) of HBR high burnup irradiated Zircaloy-4 rod *with pellet-clad interaction* (per ORNL):** **$EI_{Zirc4\text{-}irr} \approx 52$ N-m^2**

Range of irradiated rod EI ≈ 16.5 – 87 N-m^2 (depending upon interfacial bonding condition)

2. **Bending stiffness of unirradiated Zircaloy-4 *tube* (SNL assembly tests):**

$EI_{Zirc4\text{-}unirr} = 17.7$ N-m^2 [includes contribution of Pb]

3. **Bending stiffness ratio: Zircaloy-4 (irradiated/unirradiated) = 52/17.7 = 2.9**

The maximum strain measured in the truck test was 147µm/m so, for the same loading environment, the NCT strain on an irradiated rod would be: ≈ 147(17.7/52) = 50 µm/m

(or ≈ 70 µm/m considering difference in natural frequency of irradiated rod and unirradiated tube)

Range irradiated rod NCT strain: ≈ 157 – 30 µm/m
(depending upon interfacial bonding condition)

Comparison of strains from all three test series at same location on assembly

Strain Gauge ID	Location on Assembly: Adjacent to first spacer grid, Span 5	Sandia Shaker Truck Shock Test Maximum Strain Absolute Value (µin/in)	Truck Test Maximum Strain Absolute Value (µin/in)	DCL Shaker Truck Shock Test Maximum Strain Absolute Value (µin/in)
S3 - 0° Pb "rope"	Middle rod		143	
TMR-G-S5-2 (0°) Pb "rope"	Middle rod	119		
S3 - 0° Pb pellets	Right-edge rod			160
S7 - 0° Mo pellets	Middle rod			214
S8 - 0° Pb "rope"	Left-edge rod			301