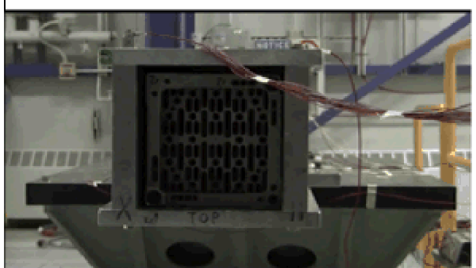
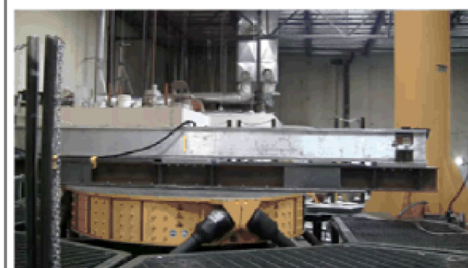
SAND2016-0913PE

Exceptional service in the national interest

Sandia National Laboratories

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

Normal Transport Loads on Fuel in a Surrogate Assembly

EPRI ESCP

Sylvia Saltzstein & Paul McConnell

1 December 2015

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Overview

- Review of the Normal Conditions of Transport Test Series.
- What have we learned since the last EPRI Meeting?
- What are our future plans?

The Test Series

FY13 SNL Shaker

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

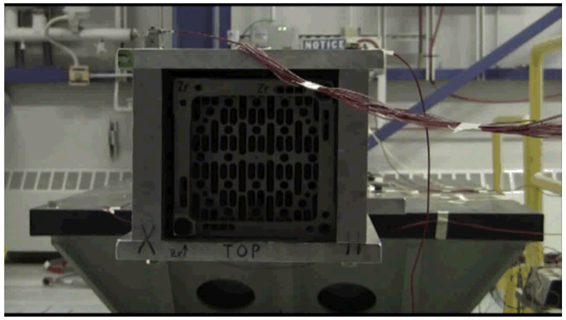
FY14 Over-The-Road Truck Test

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

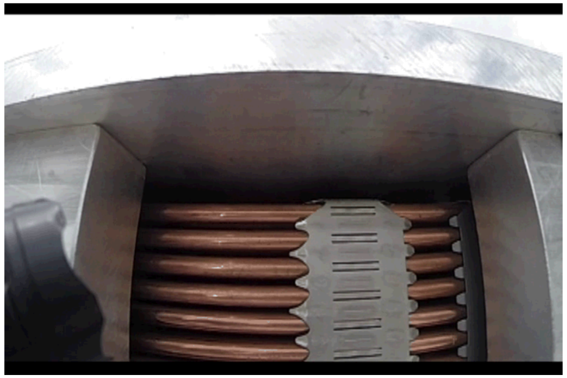
FY15 Multi-Axis Shaker for Truck and Rail

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

FY13 SNL Shaker Test



FY13 SNL Shaker

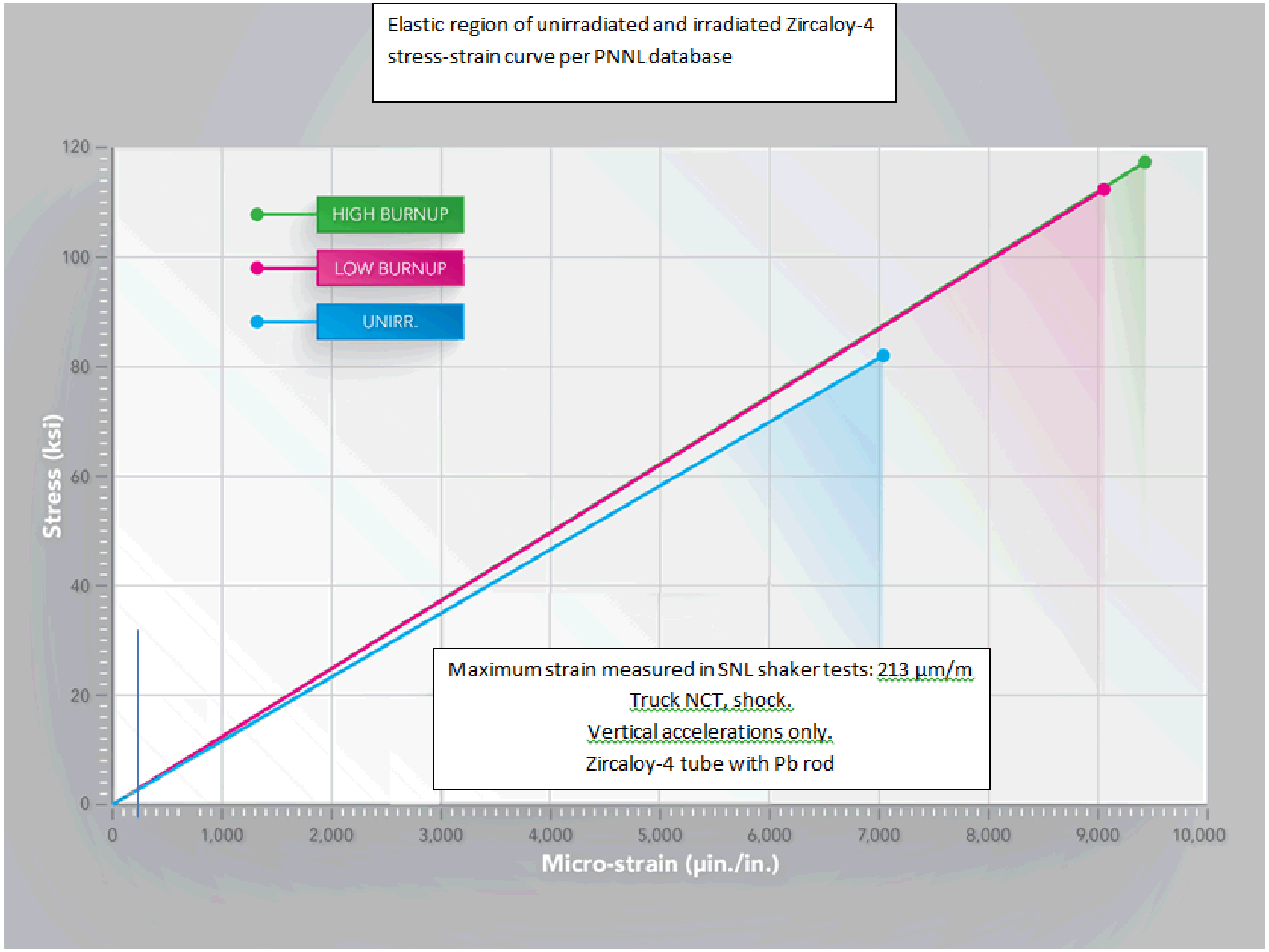


FY14 Over-The-Road Truck Test

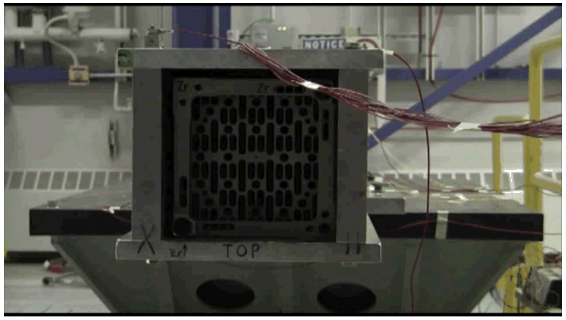
FY15 Multi-Axis Shaker for Truck and Rail

SNL Truck Shaker Test Results

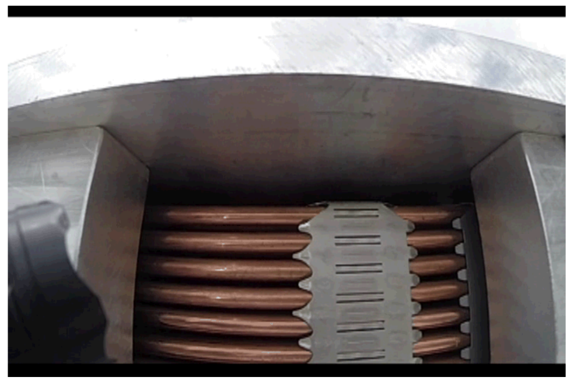
(213 microstrain maximum; 16 strain gauges; 6 vibration tests, 5 shock tests)



FY14 Over-The-Road Truck Test



FY13 SNL Shaker

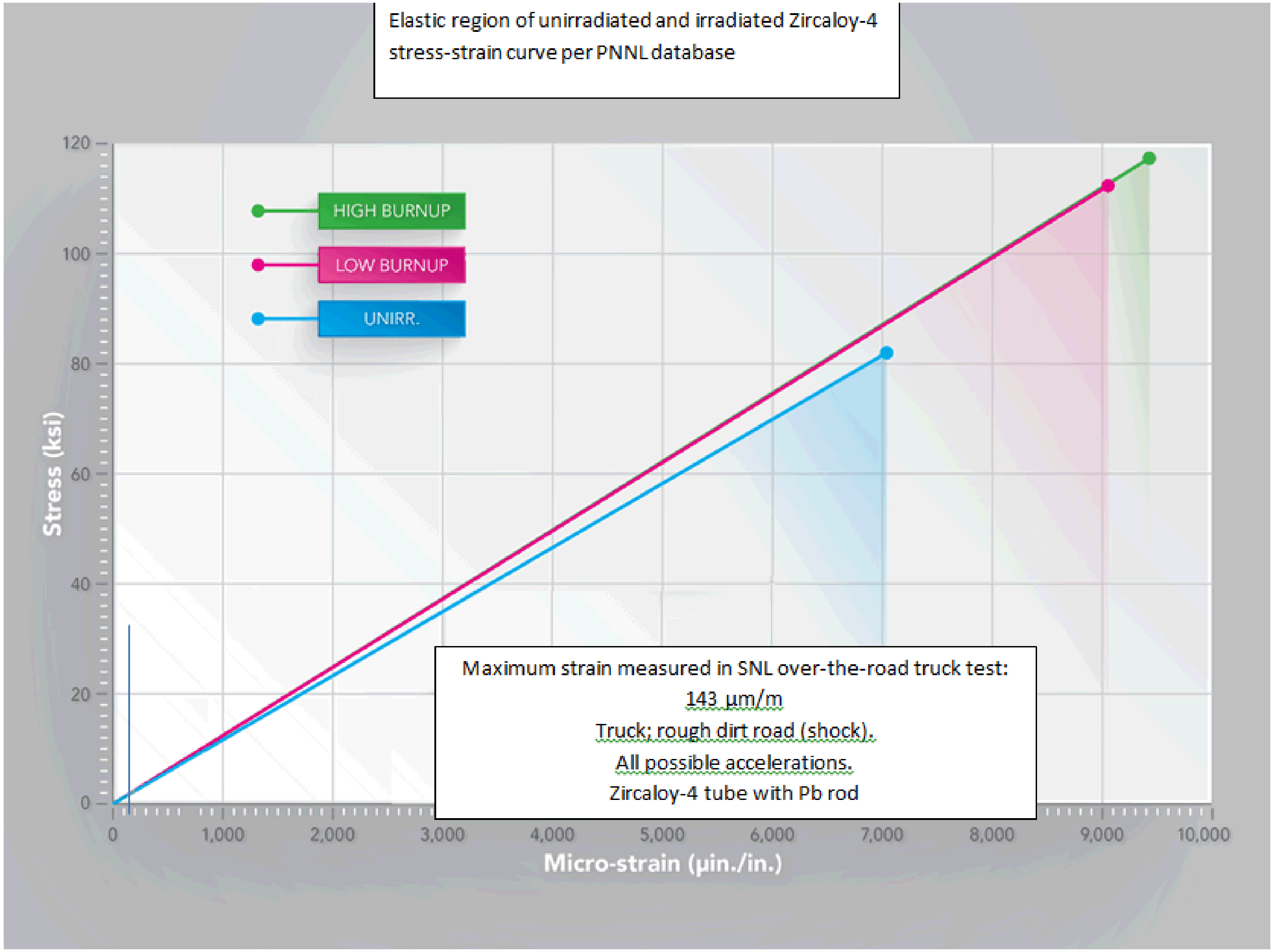


FY14 Over-The-Road Truck Test

FY15 Multi-Axis Shaker for Truck and Rail

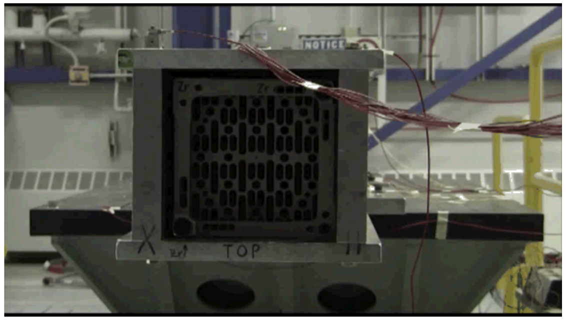
Over-The-Road Truck Test Results

(143 microstrain maximum; 12 strain gauges)

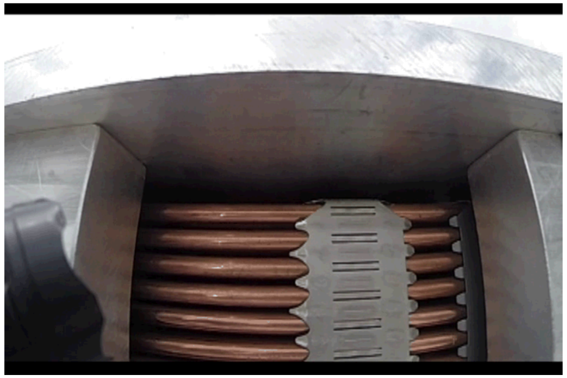


FY15 Multi-Axis Shaker for ***Truck*** and ***Rail***

Sandia National Laboratories



FY13 SNL Shaker

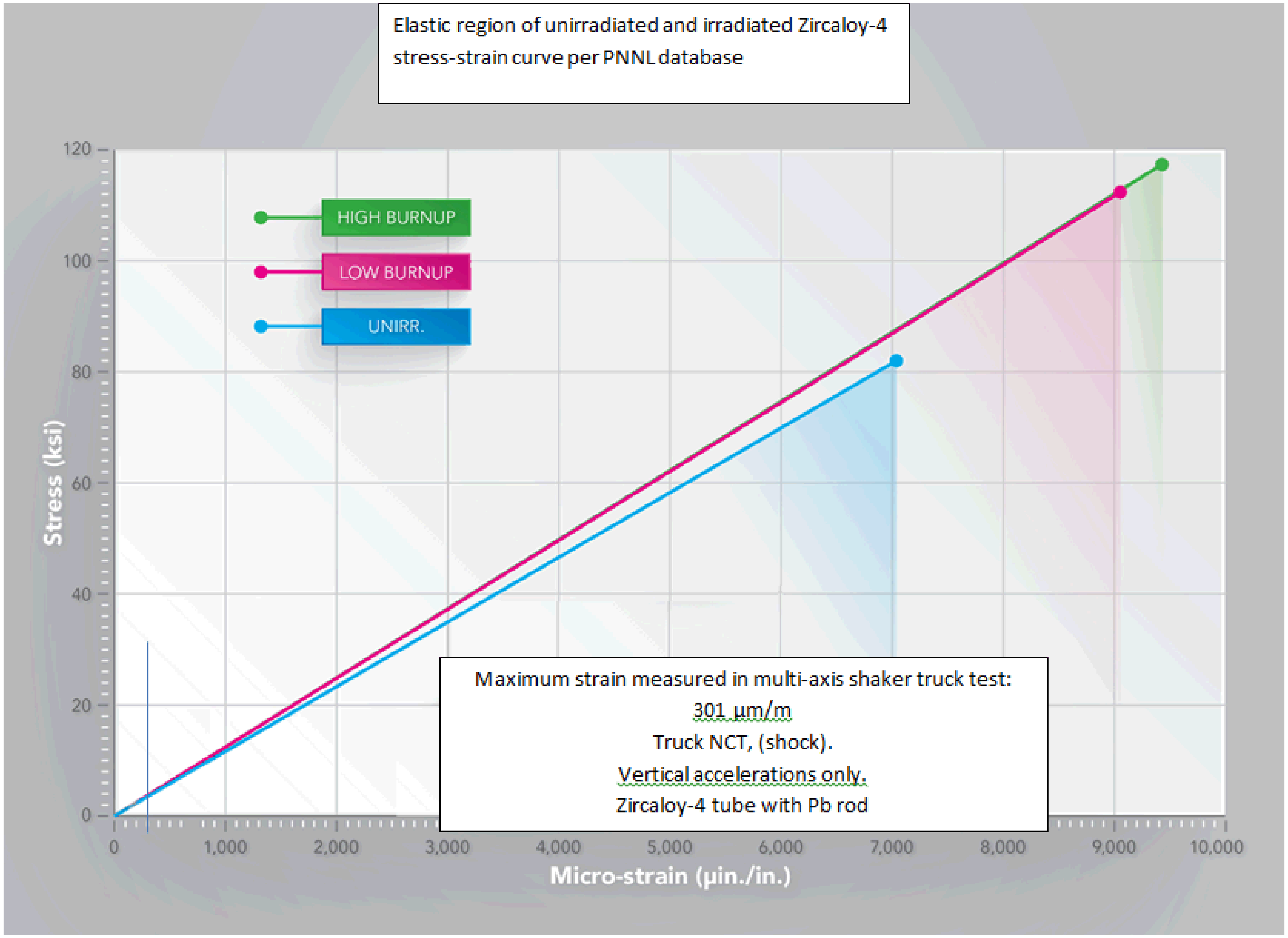


FY14 Over-The-Road Truck Test

FY15 Multi-Axis Shaker for Truck and Rail

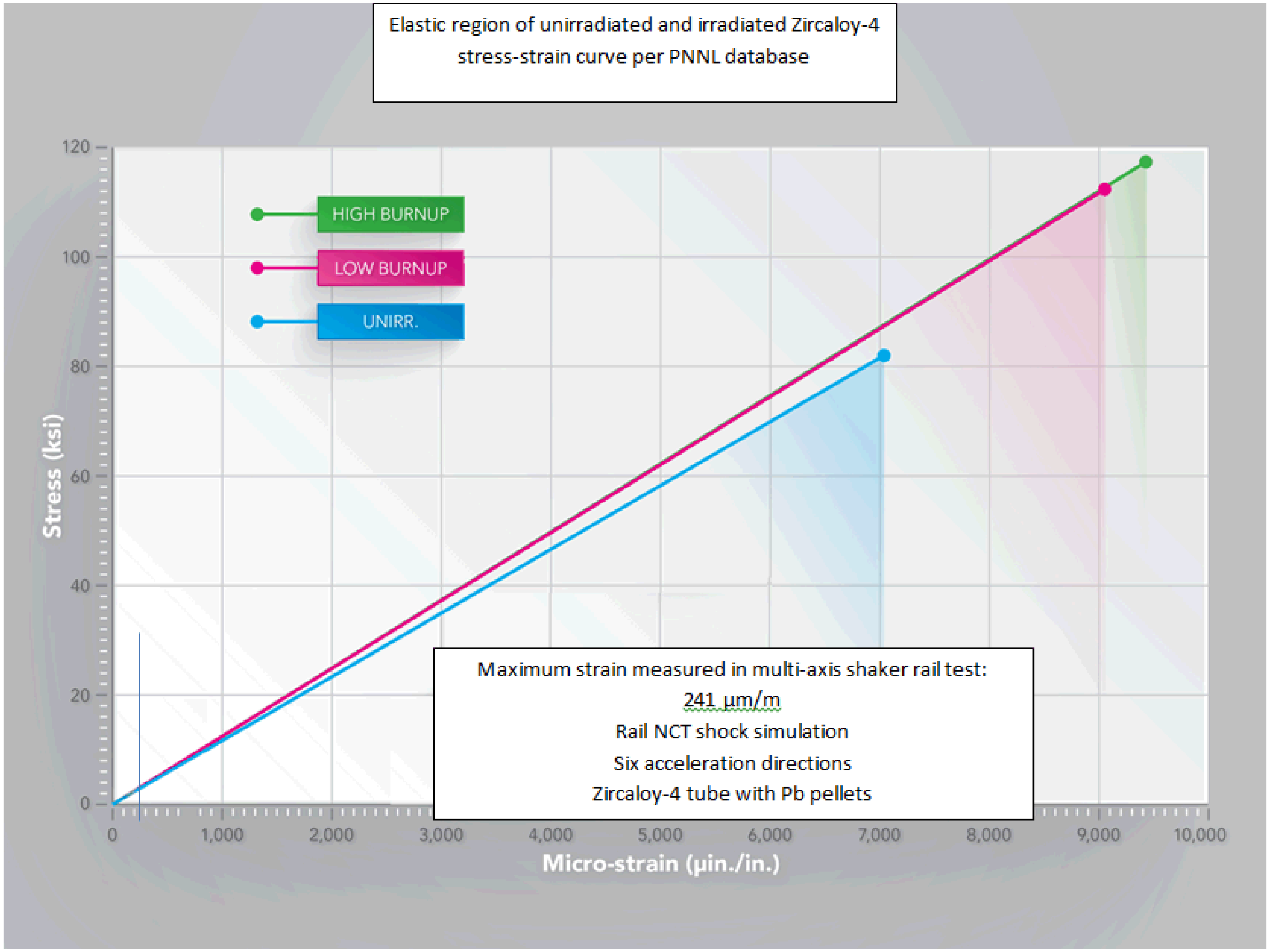
Multi-Axis Shaker ***Truck*** Test Results

(301 microstrain maximum; 8 strain gauges; 7 truck tests, 2 vibration, 5 shock)

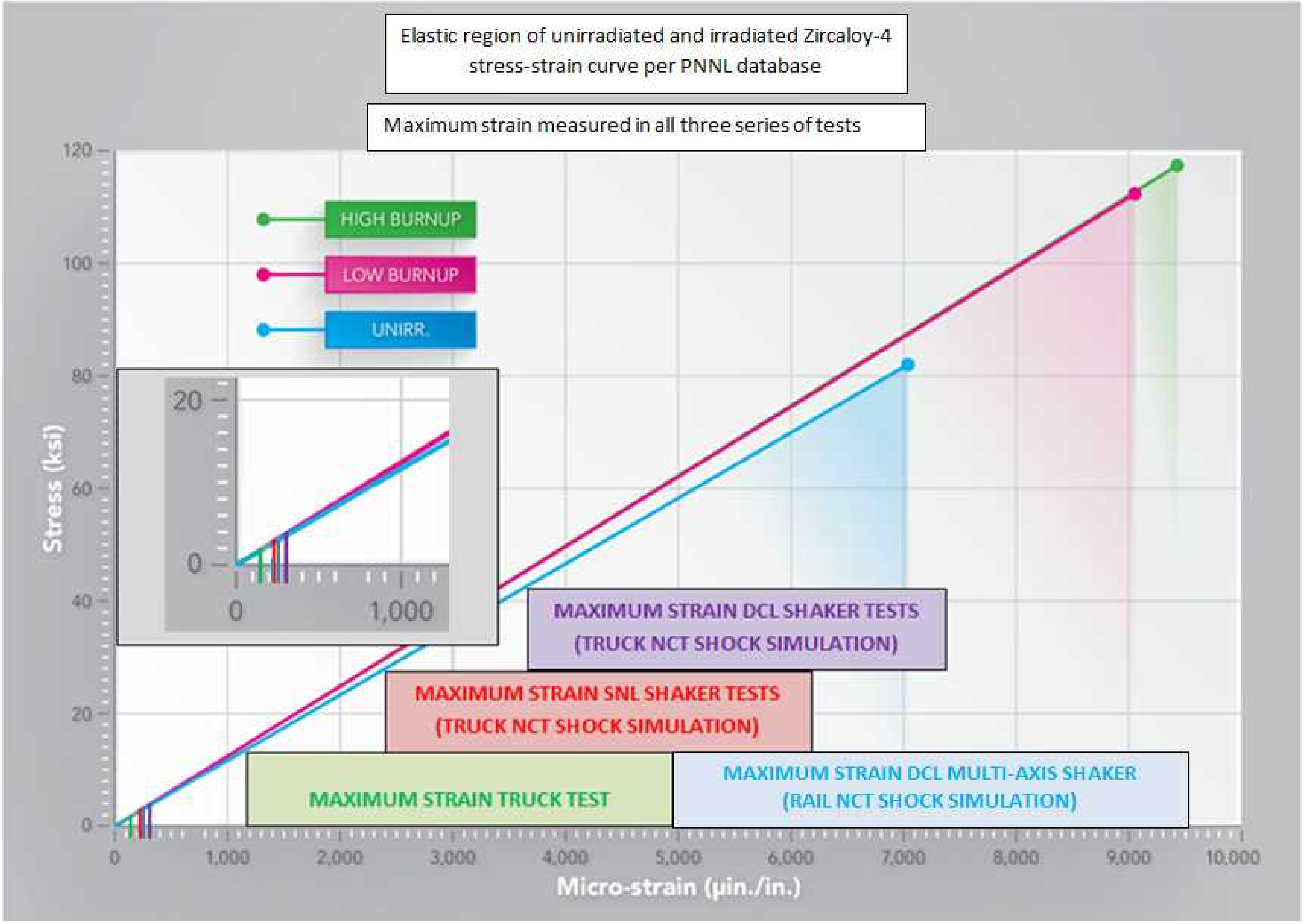


Multi-Axis Shaker ***Rail*** Test Results

(241 microstrain maximum; 8 strain gauges; 15 tests, 3 vibration, 12 shock)

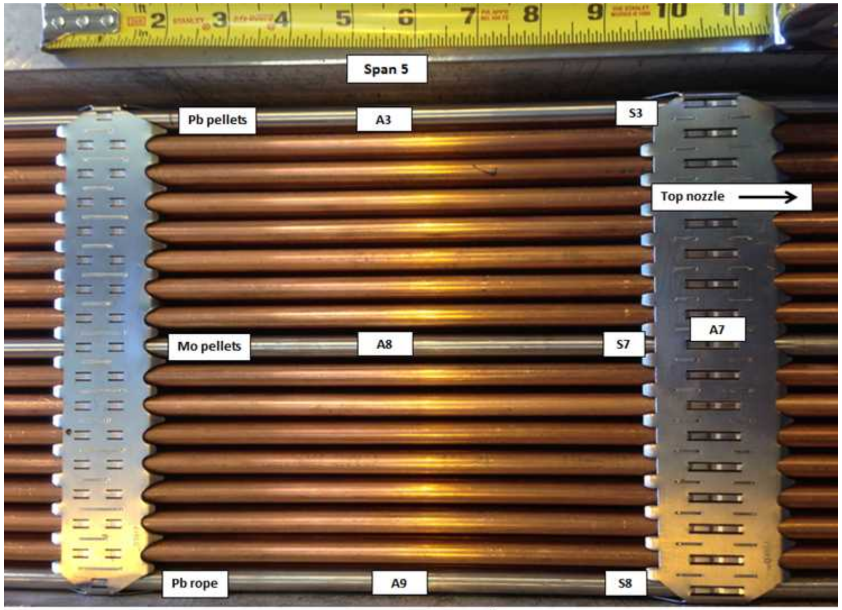


Summary: Multi-Axis Rail and Truck test results were similar to previous test results. Strains are very low compared to yield strength of Zircaloy-4.



Dynamic Certification Laboratories Assembly Shaker Tests

- **Dynamic Certification Laboratories, Sparks, Nevada, May 12-13, 2015**
- **Sandia assembly with**
  - **Three instrumented Zircaloy-4 tubes**
    - **One with Pb rope**
    - **One with Pb pellets**
    - **One with Mo pellets**



- Rail shock and vibration tests including rail coupling shock
  - **Mod/Sim project (Adkins) “P3” (“2043”) rail data inputs**
  - **Tests based on railcar deck accelerations and basket accelerations**
- Truck shock and vibration tests

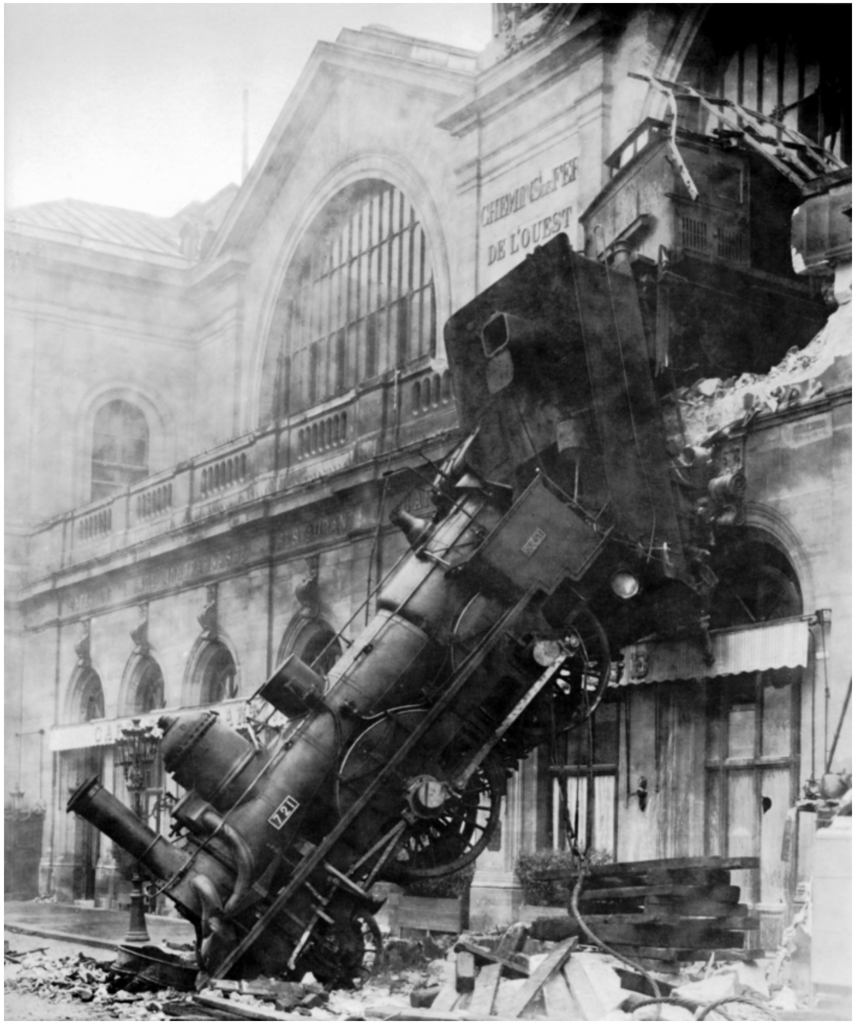
Shaker Tests at Dynamic Certification Laboratories

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

Pb Rope, Pb Pellets, and Mo Pellets did not have substantial differences.
Pb Rope appears to be the most conservative.

Not a Normal Condition of Transportation

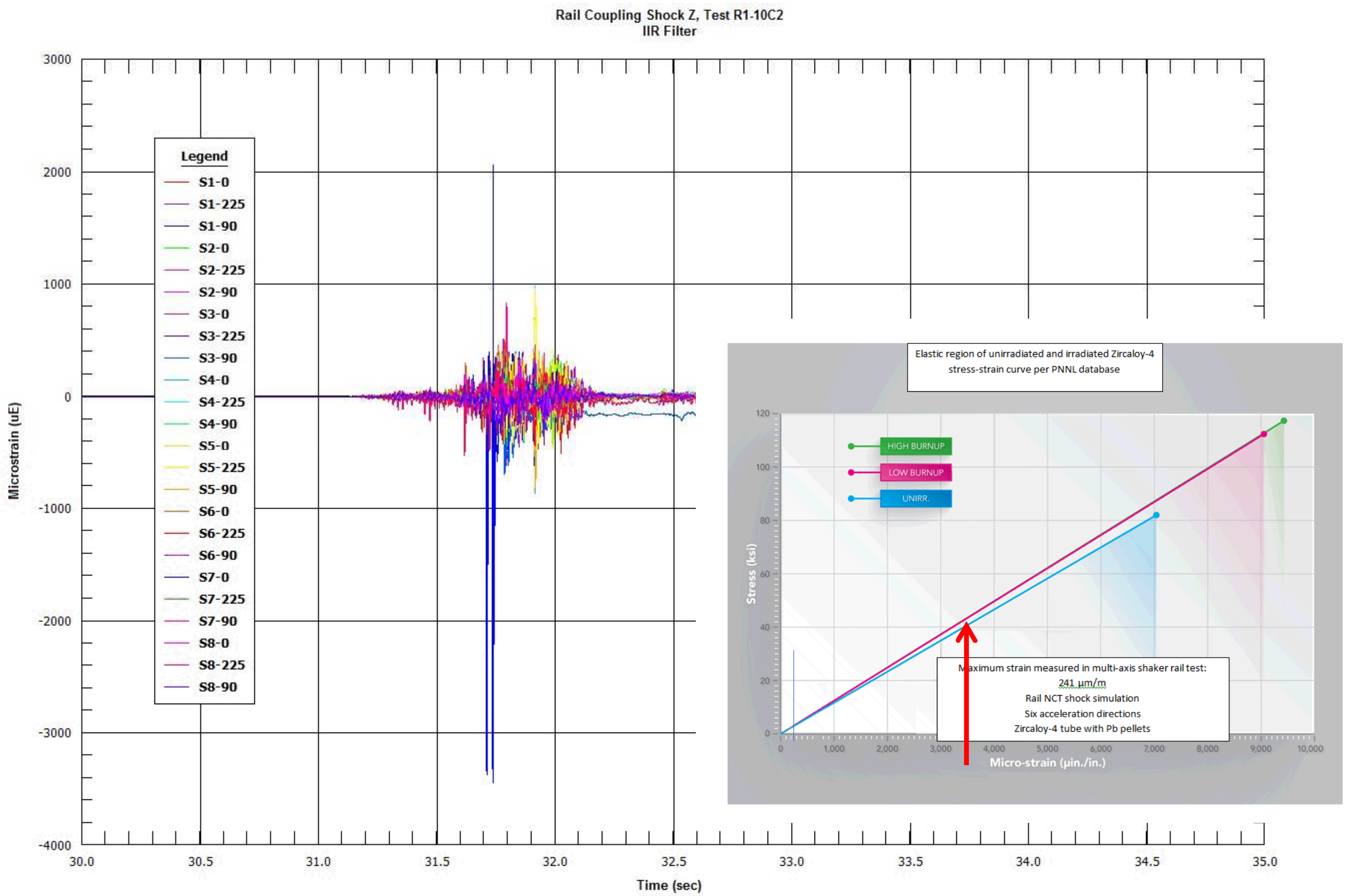


Shaker test video simulating rail coupling shock **NOT** a Normal Condition of Transport simulation

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

Watch the Zircaloy Rod hit the top of the basket.

Strains Measured During the Non-normal Shock Event. (≈3,500 microstrain)



Connection between Loading Tests and CIRFT 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 $r_o(\kappa_{max})$

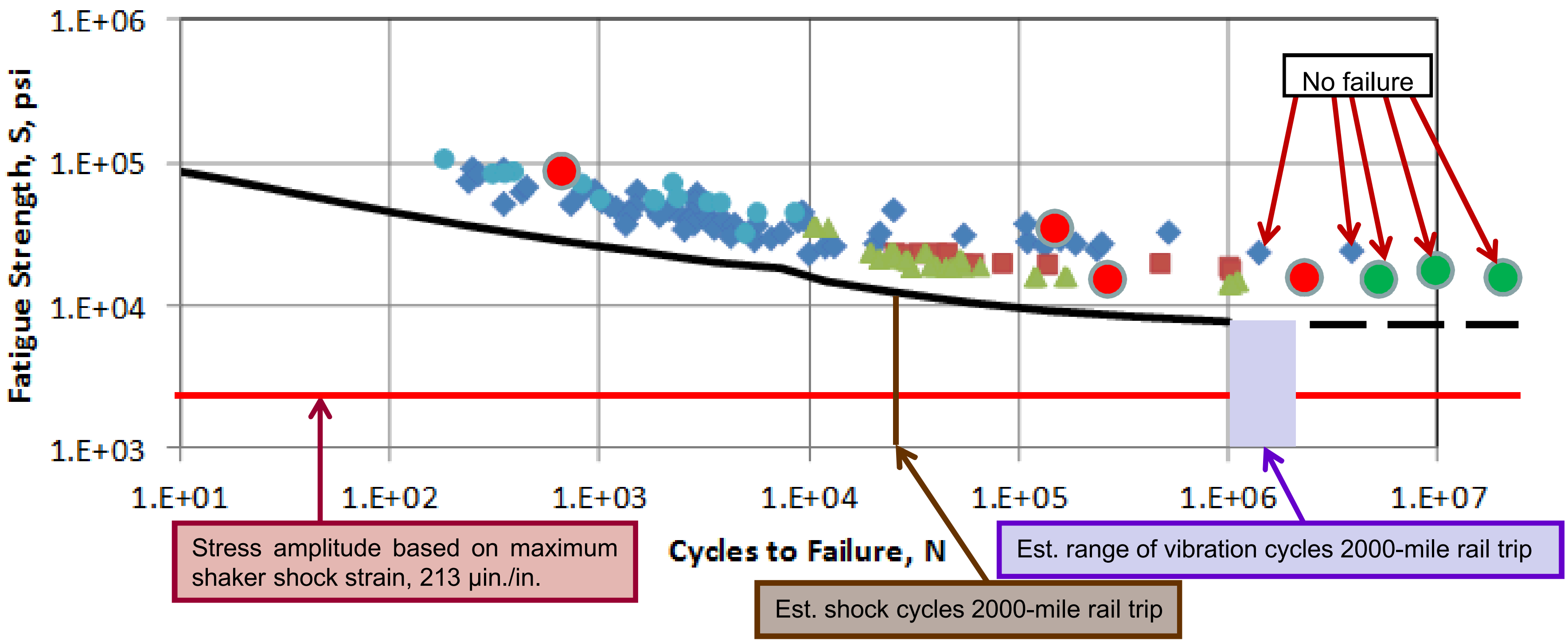
r_o^{Zirc4} = 5.385 mm (HBR cladding)

(other strains based upon ratio of [κ_{max}/.22] x 1185)

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 still 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

What We Have Learned in the Last Year

- 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.
- Lead rope as a surrogate fuel appears to be similar (if not more conservative) than Lead pellets or Mo pellets.

Plans for completing this work

- Prepare Test Plan (FY16) for tests (FY17) of PWR assemblies…
  - within a rail-cask basket which is…
  - within an actual rail cask which is…
  - on a rail car which will then be…
  - transported over commercial rail lines, and

at the AAR Transportation Technology Center, Inc.

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

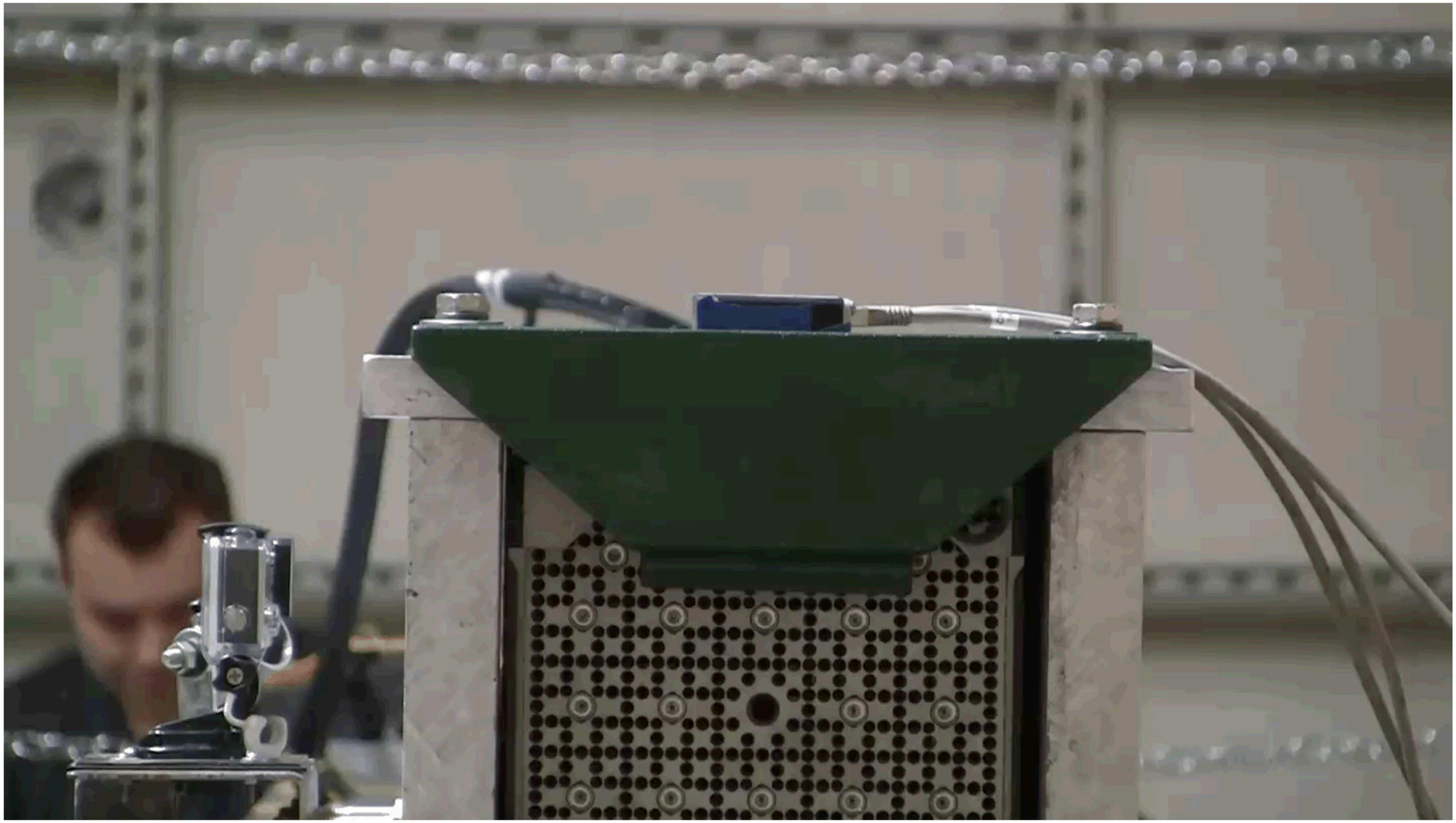
These rail tests will:
- eliminate questions re the simulated tests
- support future licensing and transport of UNF
- support public acceptance of rail transport

Questions?

THANK YOU!

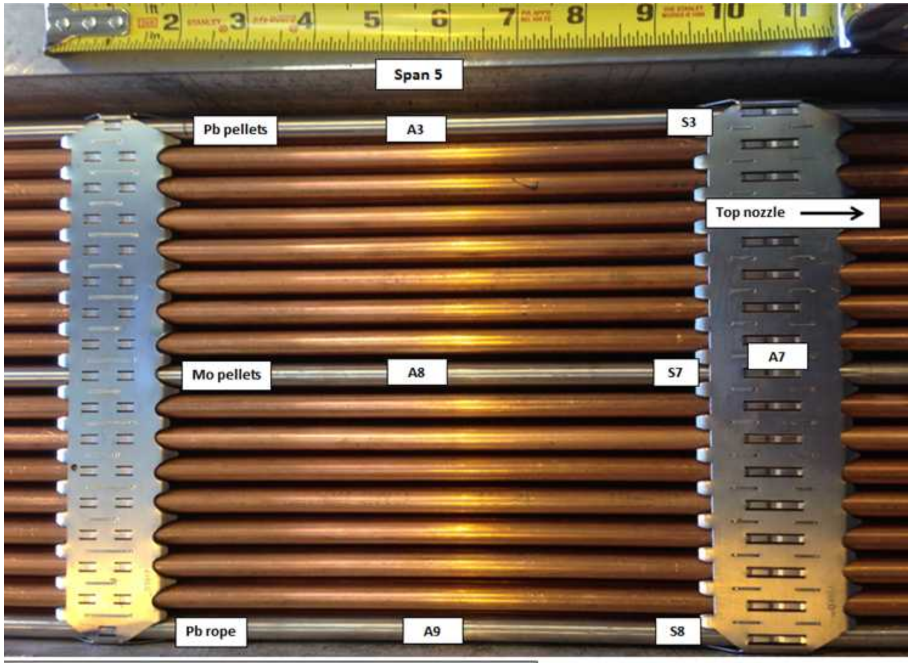
BACKUP SLIDES

Non-normal rail coupling shock event, bottom-nozzle view



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

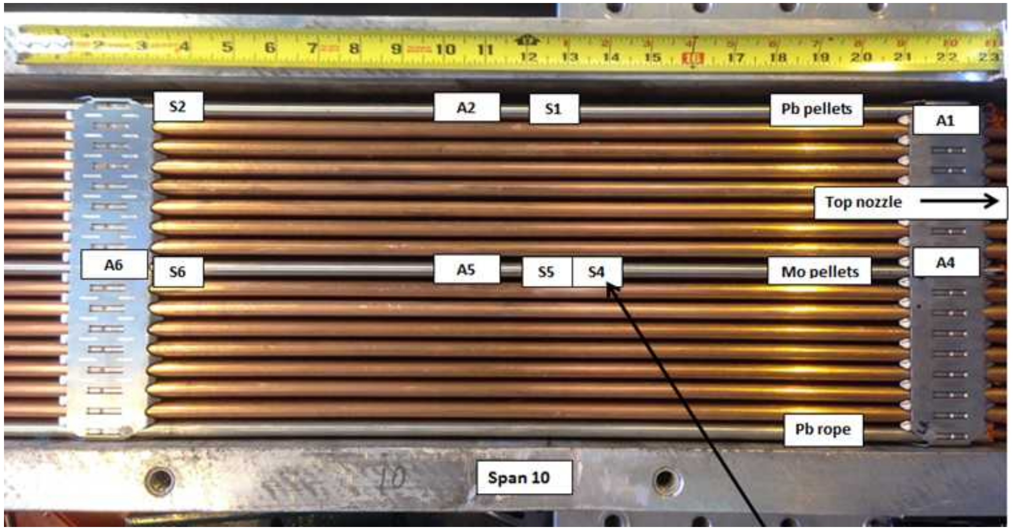


TEST 10xyz-3 Rail coupling	Pb-“rope” rod	Mo-pellet rod	Pb-pellet rod
	S8	**S7**	**S3**
0°	130	91	104
90°	82	34	30
225°	208	47	77

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
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