SAND2015-5337PE

Used Fuel Disposition Campaign

Assembly Tests
and
Possible Future Rail Tests

ST Transportation Work Packages

Paul McConnell: Sandia National Laboratories

UFD Annual Meeting
June 10, 2015
Las Vegas

Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

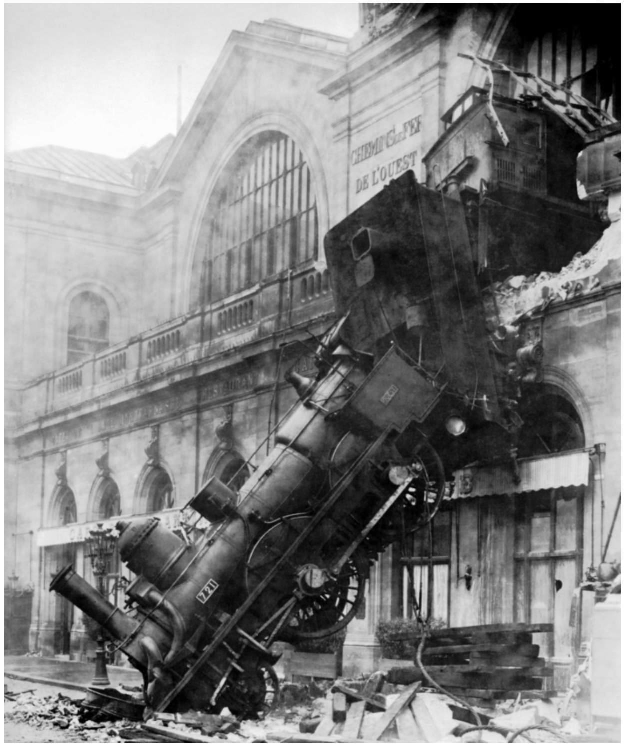
NNSA National Nuclear Security Administration

Shaker Tests at Dynamic Certification Laboratories Sparks, Nevada

Dynamic Certification Laboratories Assembly Shaker Tests

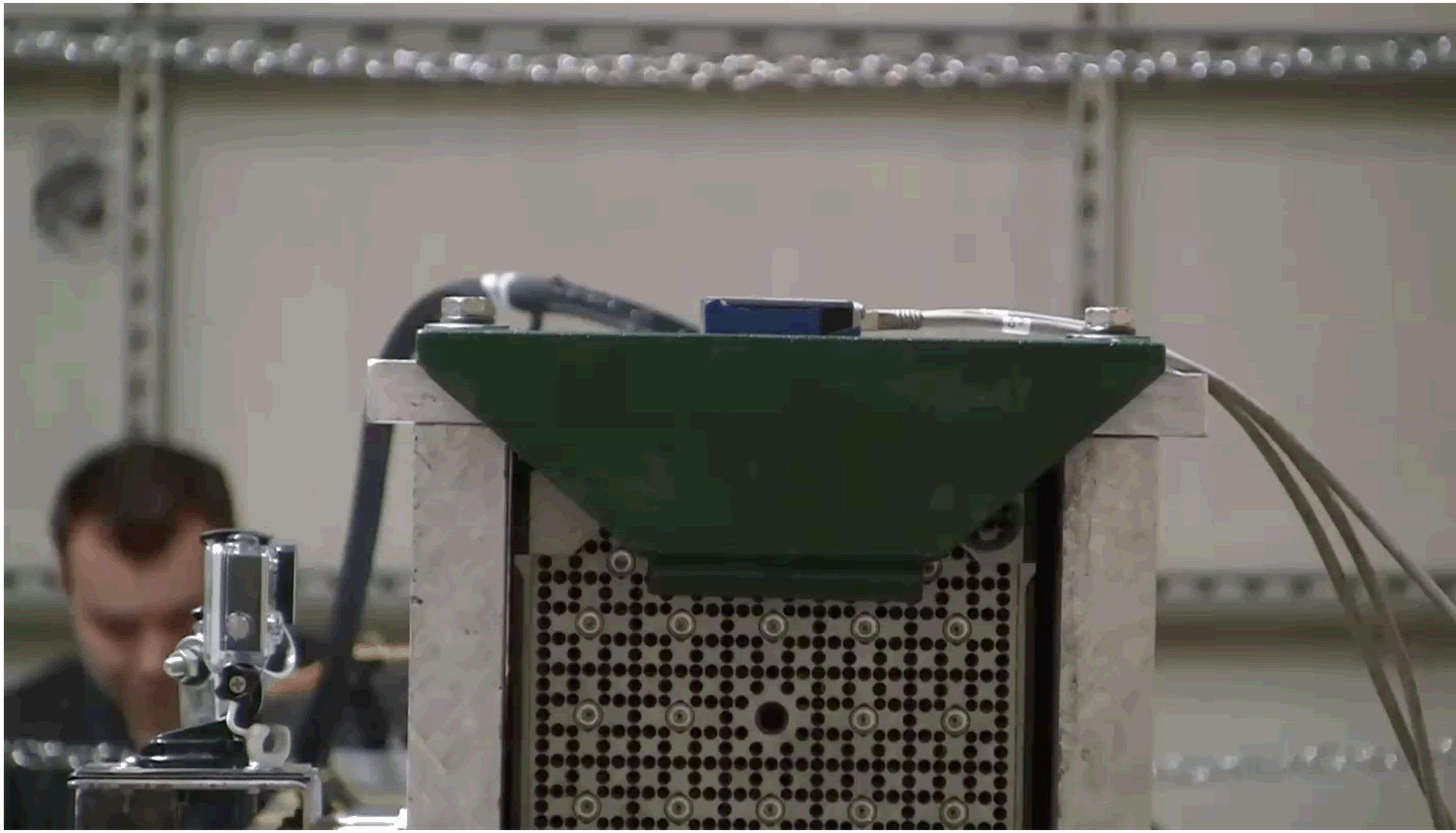
- Dynamic Certification Laboratories, Sparks, Nevada, May 12-13, 2015
- Sandia assembly with
  - Three instrumented Zircaloy-4 tubes
    - *One with Pb rope*
    - *One with Pb pellets*
    - *One with Mo pellets*
- Rail shock and vibration tests including rail coupling shock
  - Mod/Sim project (Adkins) “P3” (“2043”) rail data inputs
  - Tests based on railcar deck accelerations and basket accelerations
- Truck shock and vibration tests

A Non-Normal Condition of Transport



Test 10z-2: Rail coupling shock, side view

Test 10z-2: Rail coupling shock, bottom-nozzle view

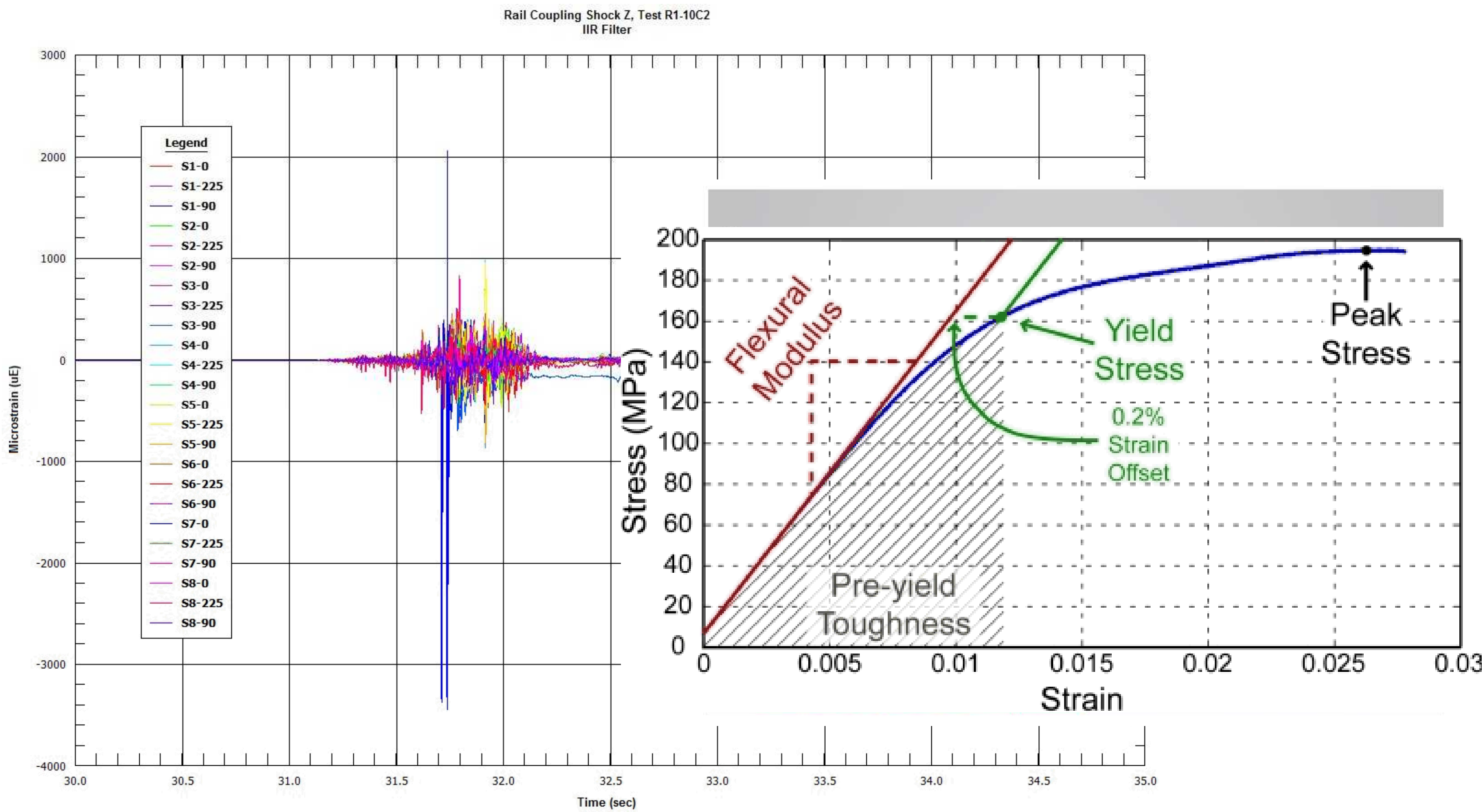


Shaker actuators

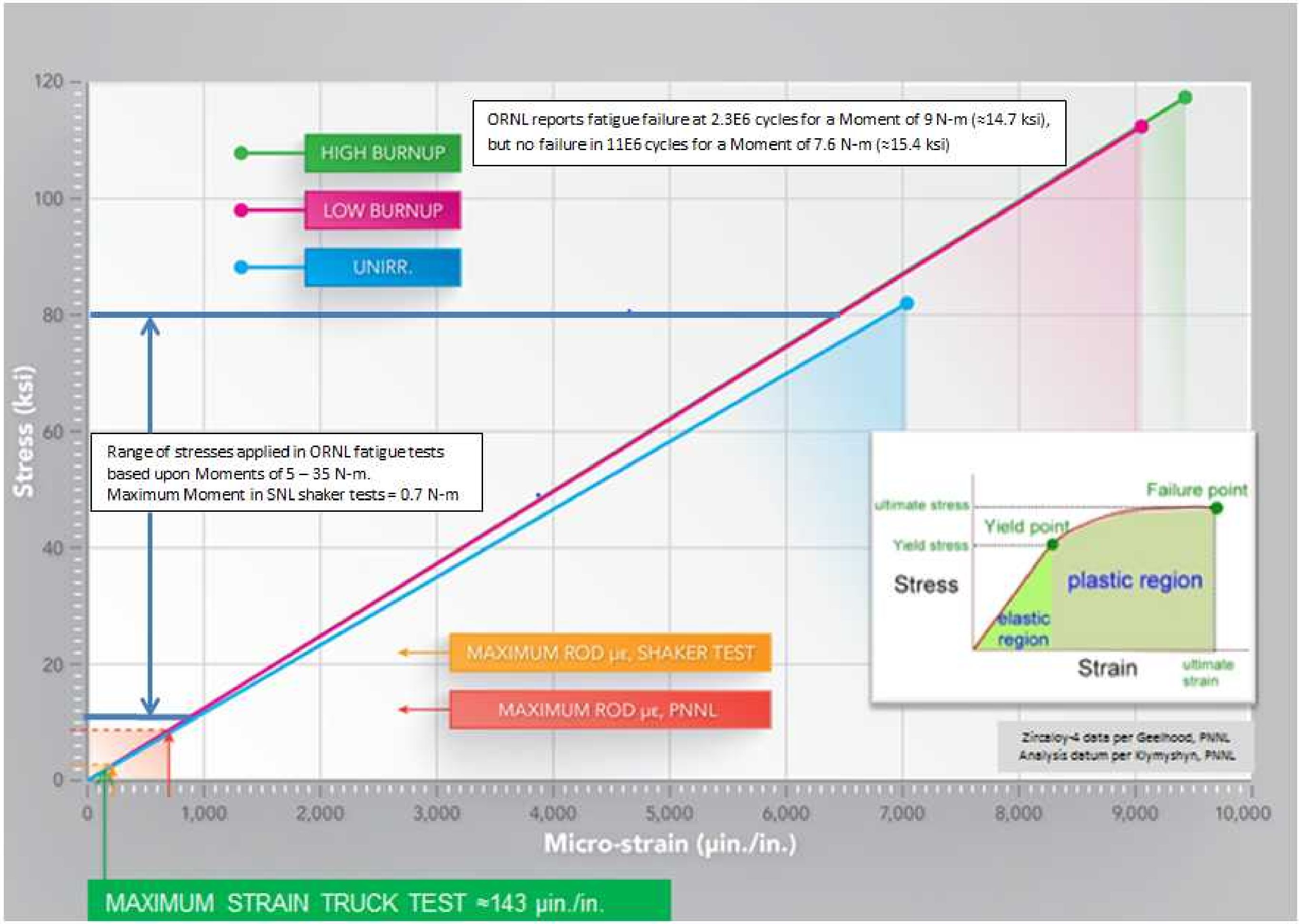
Test 10z-2: Rail coupling shock, GoPro view, 11 frames/second

Used Fuel Disposition

Test 10z-2: Rail coupling shock strains

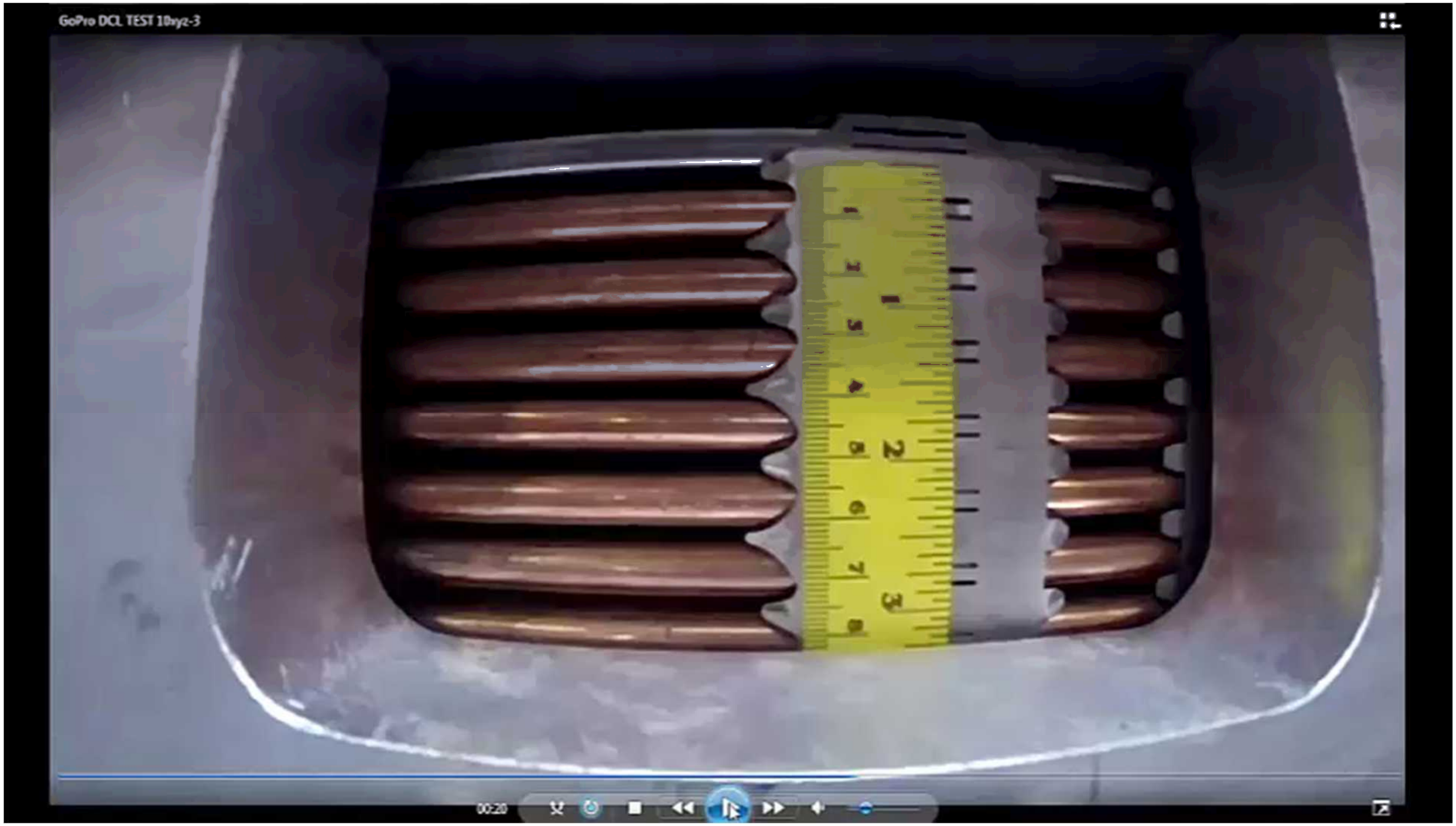


Measured strains very low relative to elastic limit of Zircaloy



Test 9: rail shock
max x, y, z basket accelerations

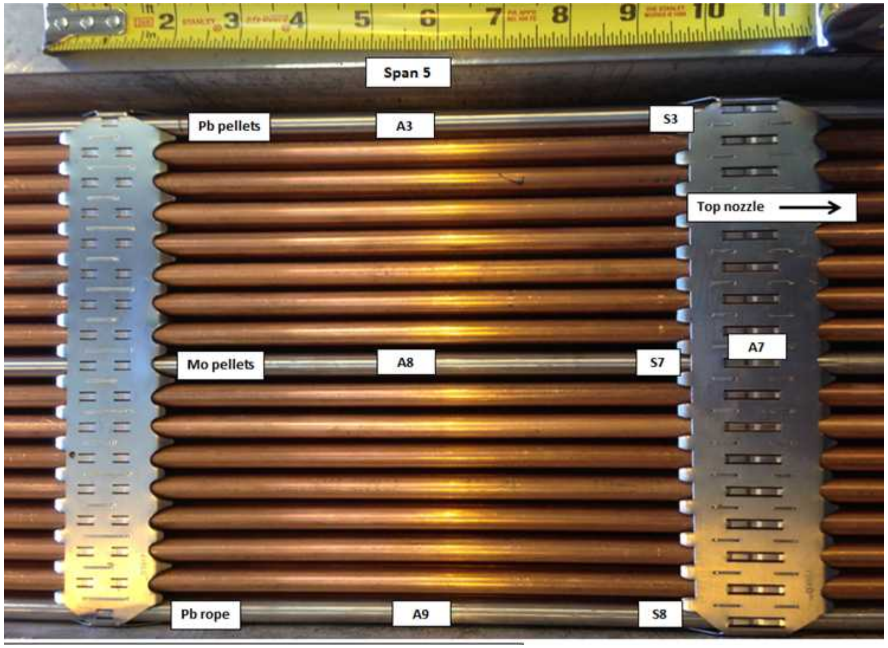
Test 10xyz: Rail coupling shock GoPro view, 11 frames/second



Used Fuel Disposition

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

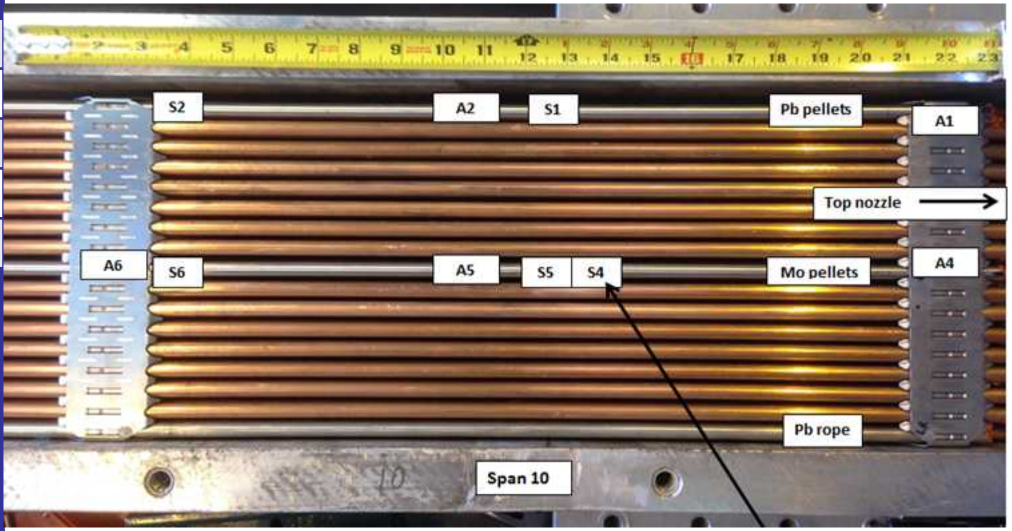


TEST 10xyz-3 Rail coupling	Pb-“rope” rod	Mo-pellet rod	Pb-pellet rod
	S8	**S7**	**S3**
0°	130	91	104
90°	82	34	30
225°	208	47	77

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



Maximum micro-strains DCL rail tests

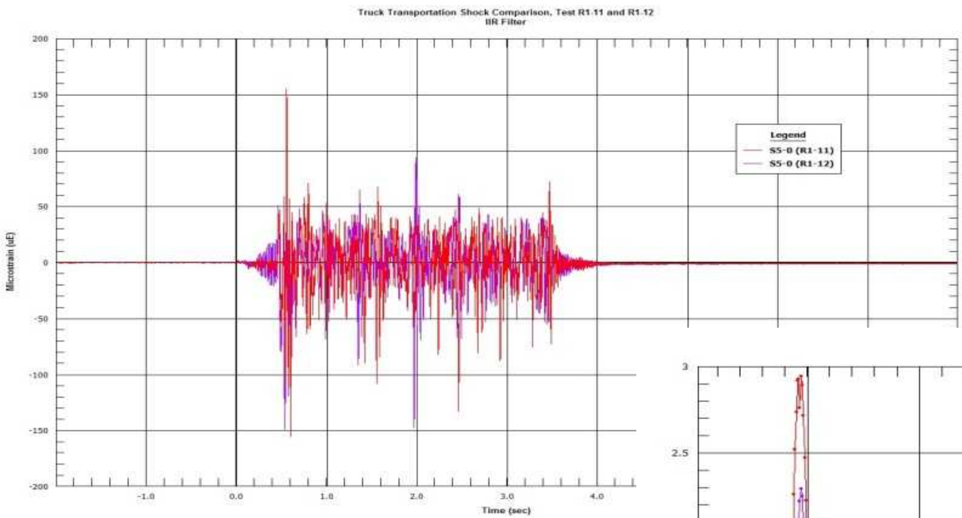
Test	Maximum micro-strain	Strain gauge
4: rail vibration, max x (railcar deck g)	7	S3-90
5: rail vibration, max y (railcar deck g)	9	S3-90
6: rail vibration, max z (railcar deck g)	8	S3-90
7: rail shock, max x and z (railcar deck g)	19	S1-0
8: rail shock, max y (railcar deck g)	34	S3-90
9: rail shock, max x, y, z (basket g)	241	S3-90
10xyz-3: rail coupling	208	S8-225

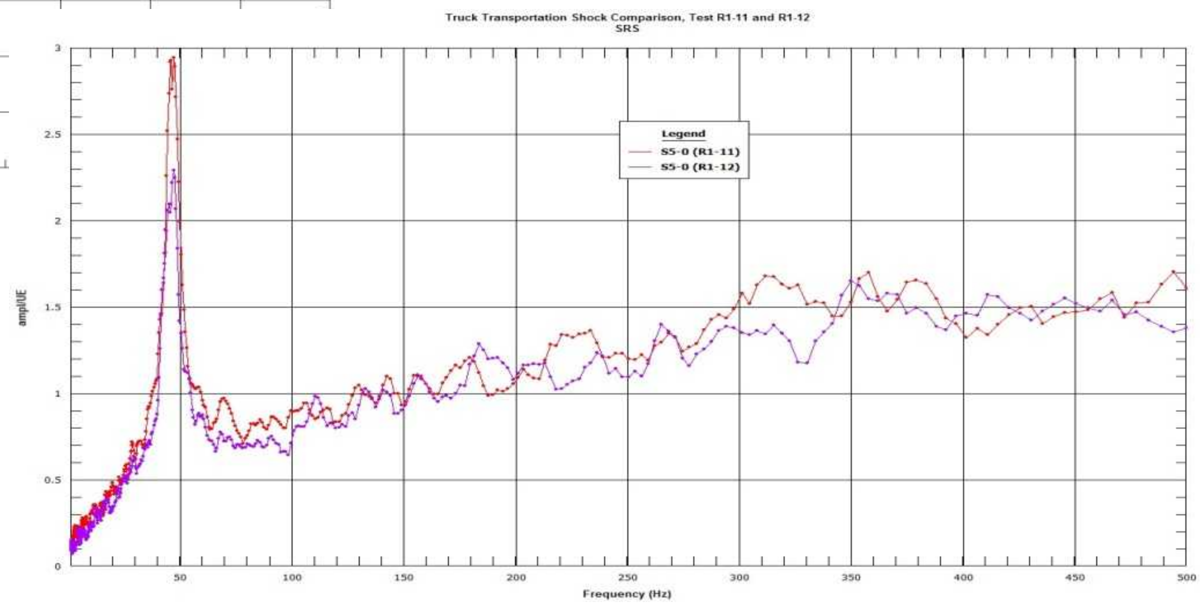
Maximum micro-strains DCL truck tests

Test	Maximum micro-strain	Strain gauge
13: truck vibration, 1 – 100 Hz	198	S8-225
14: truck vibration, 5 – 100 Hz	270	S8-225
11: truck shock, 1 – 100 Hz	246	S8-225
12: truck shock, 5 – 100 Hz	301	S8-225
15-3: truck shock, 2.9 g half-sine 59 ms pulse	130	S8-225

Used Fuel Disposition

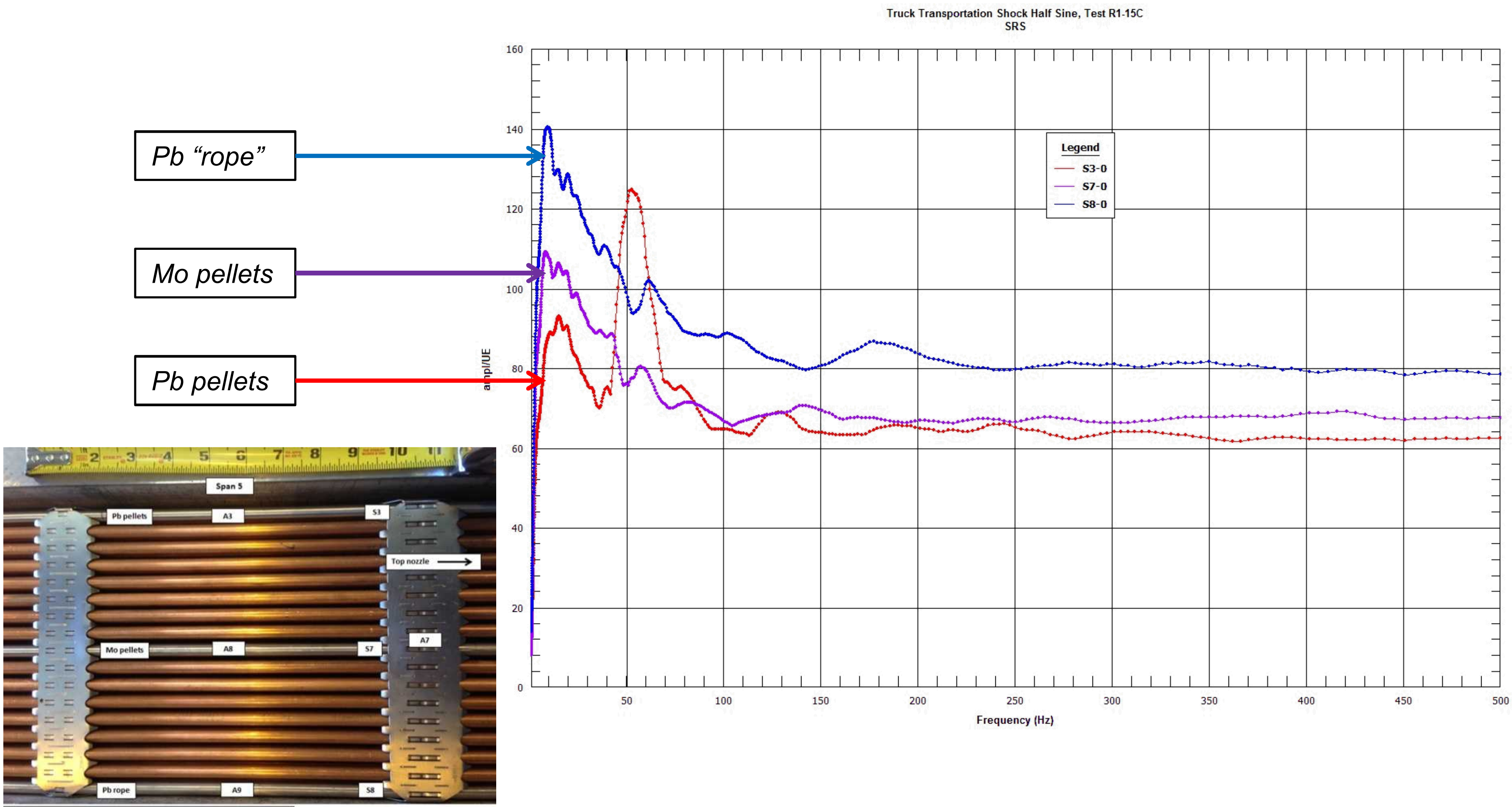
Truck shock, 1-100 Hz v. 5-100 Hz



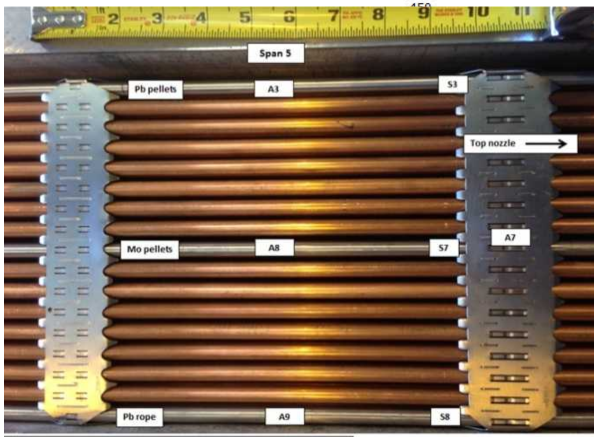


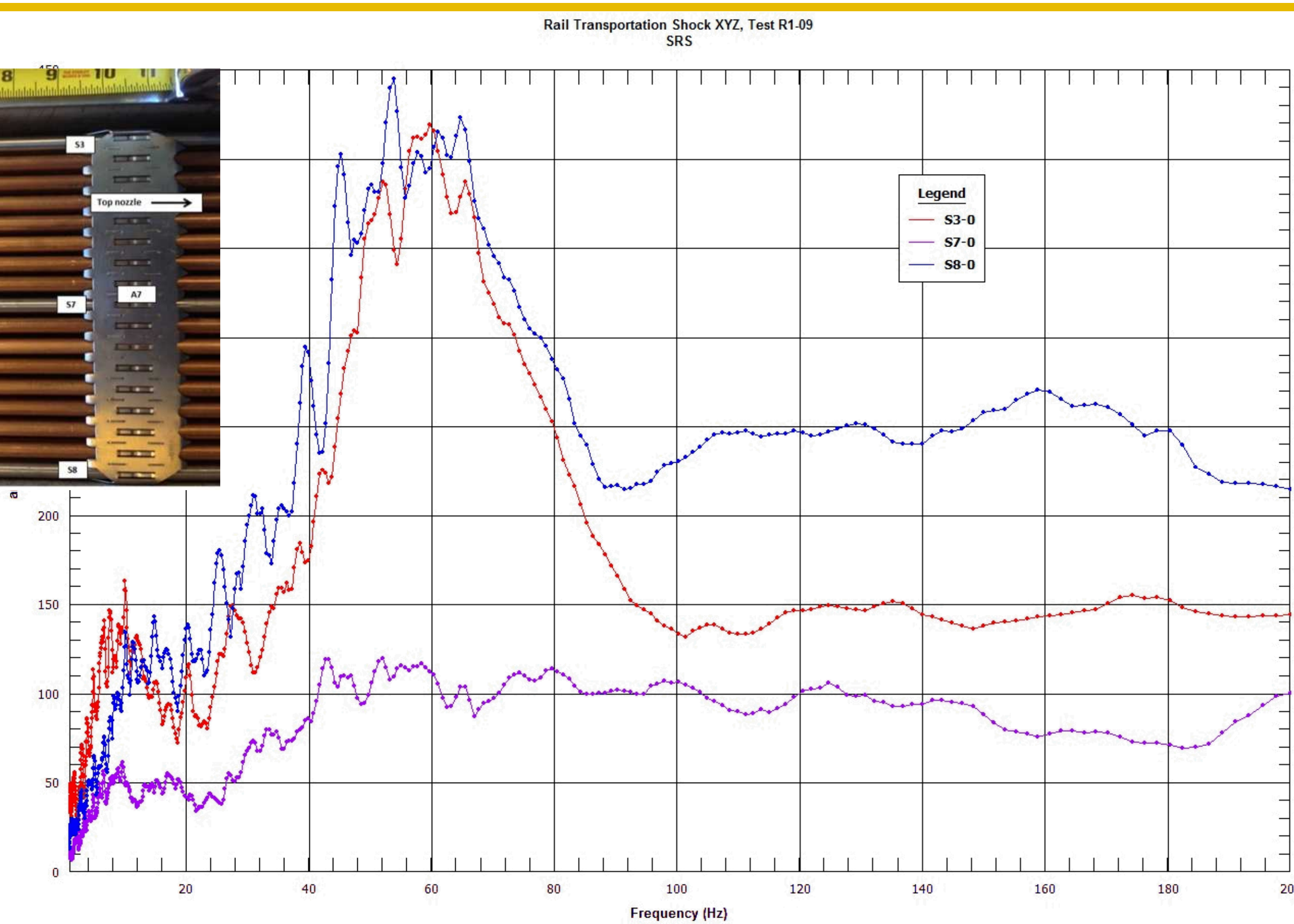
Used Fuel Disposition

Comparison of rod strains for a truck shock test



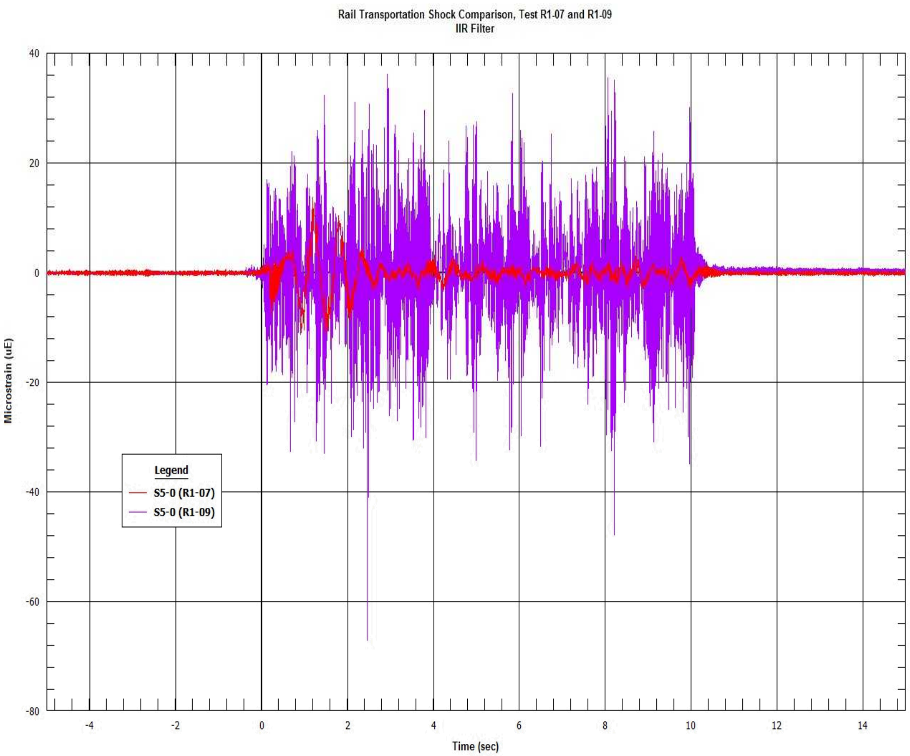
Comparison of rod strains for a rail shock test

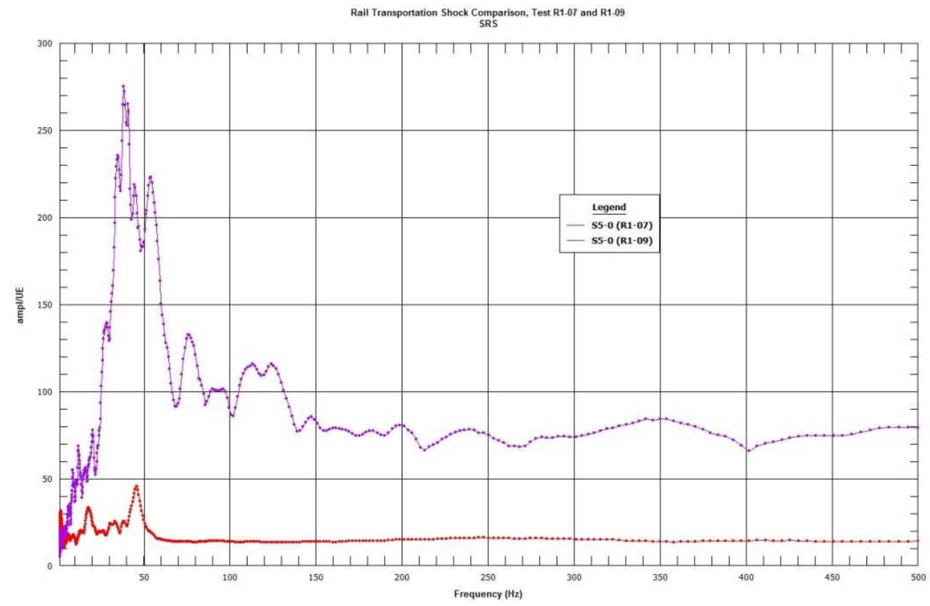




Used Fuel Disposition

Rail shock railcar loadings v. basket loadings, comparison of micro-strains

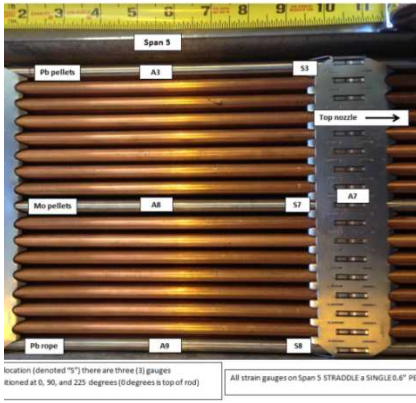




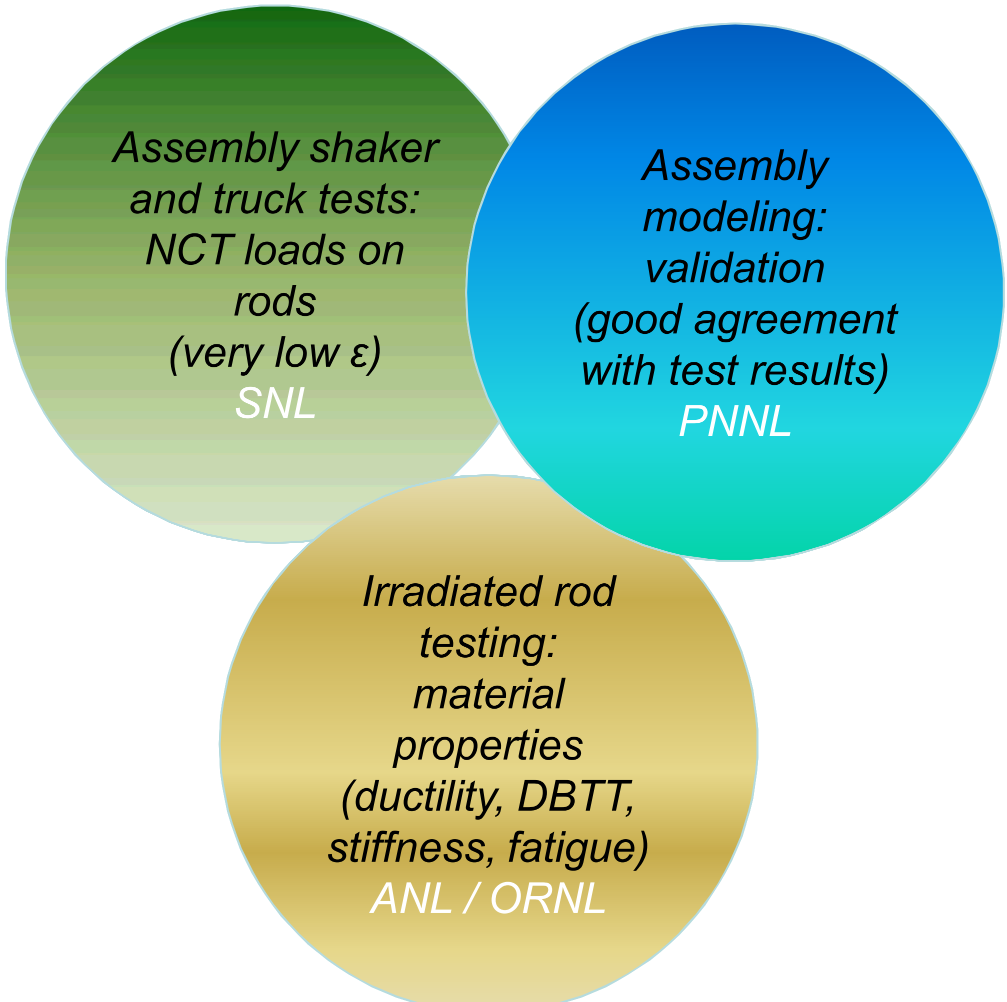
RAIL SHOCK	
	maximum µstrain
TEST 7 – railcar loadings	19
TEST 9 – basket loadings	172

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



The UFDC has a story to tell: Can irradiated rods withstand NCT



What’s next?

Possible Rail Test Option

NLI 10/24 casks and railcars in Augusta, Georgia

Used Fuel Disposition

TCRC Railyard
Richland, Washington

- *Controlled test environment*
- *Variety of track conditions*
- *Repeatability*

Rail Cask/Railcar Quotes

	TCRC	Areva	Holtec	NovaTech
Cask	NLI 10/24	TN-32B	HI-STAR 60 (12 15x15 PWRs)	Square "cask mockup"
Railcar	custom NLI railcar	leased	leased	to be purchased
Basket	tbd	yes	yes	yes (square 4x4-array)
Cradle	yes	transport skid	yes	saddle mounting structure
Surrogate assemblies	no	no	no	yes
Relative cost	low	high	high	medium

Backup slides

Where the UFDC R&D is leading us…

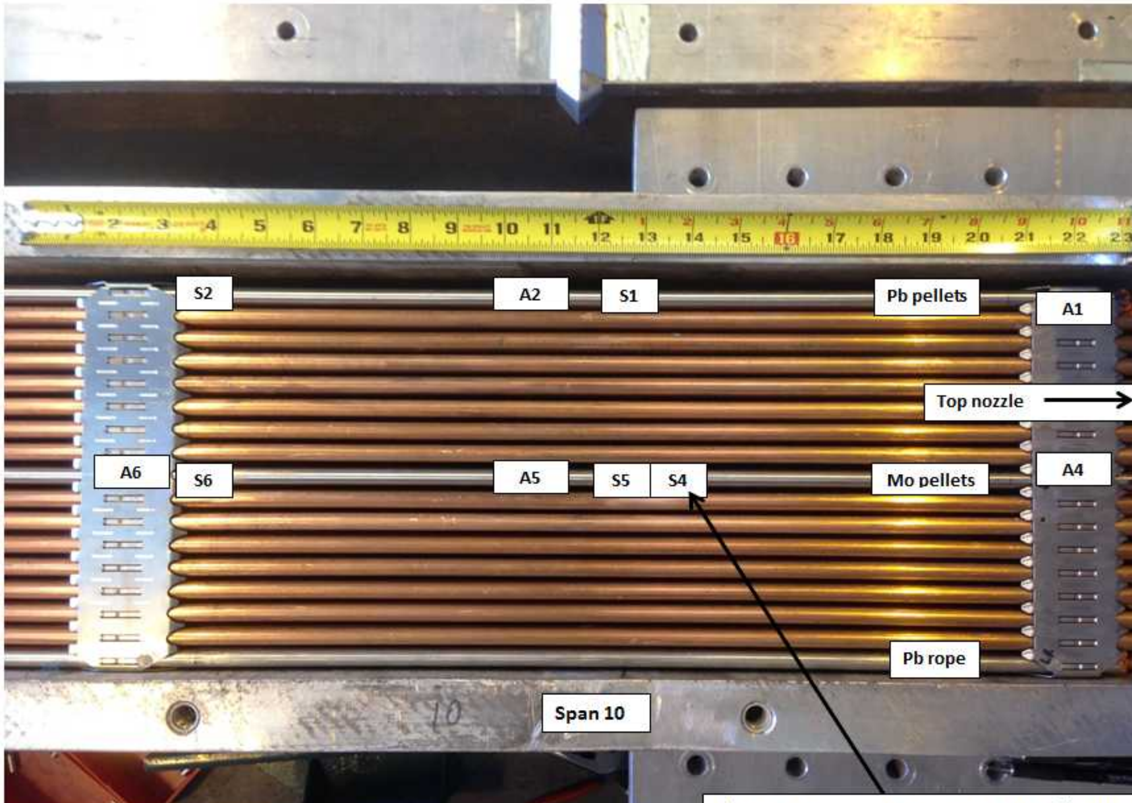
- The strains measured in the assembly NCT test program were in the micro-strain levels – well below the elastic limit for either unirradiated or irradiated Zircaloy-4

- 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

- Strains on irradiated rods with fuel during NCT may be less than the strains measured on unirradiated tubes due to increased stiffness

- Fatigue during transport does not appear to be an issue

Span 10 instrumentation for DCL tests

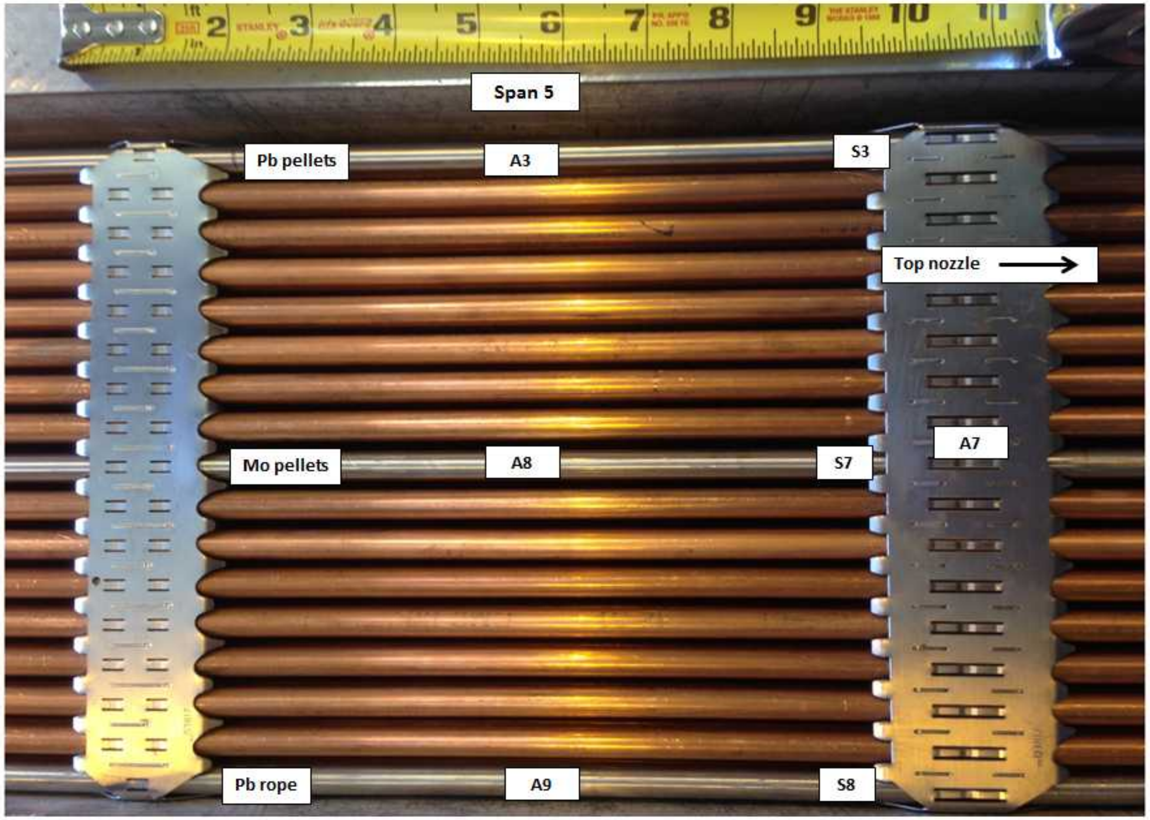


At each strain gauge location (denoted "S") there are three (3) gauges circumferentially positioned at 0, 90, and 225 degrees (0 degrees is top of rod)

These strain gauges STRADDLE a SINGLE 0.6" PELLET

ALL OTHER STRAIN GAUGES STRADDLE THE GAP BETWEEN TWO 0.6" PELLETS

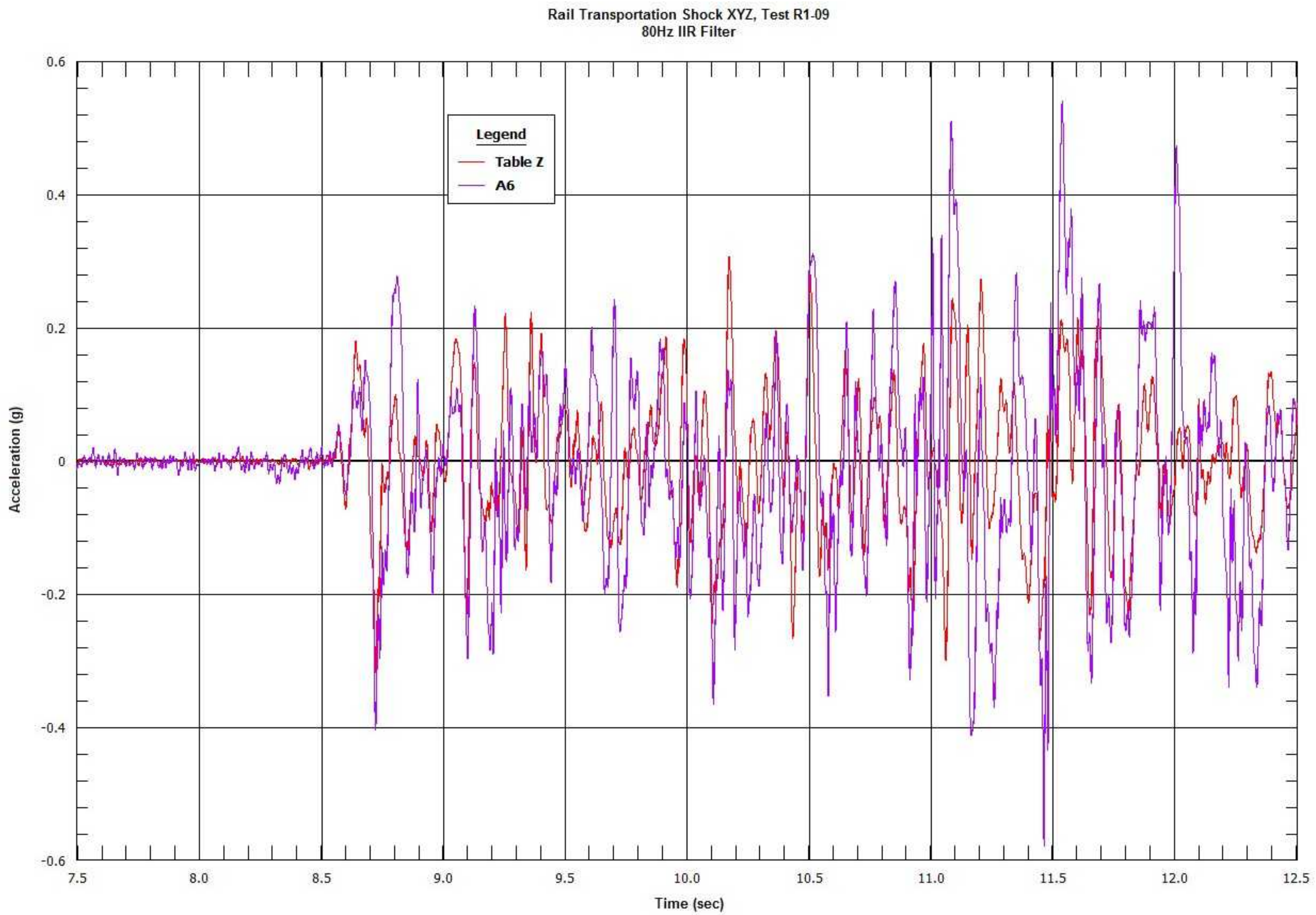
Span 5 instrumentation for DCL tests



At each strain gauge location (denoted "S") there are three (3) gauges circumferentially positioned at 0, 90, and 225 degrees (0 degrees is top of rod)

All strain gauges on Span 5 STRADDLE a SINGLE 0.6" PELLET

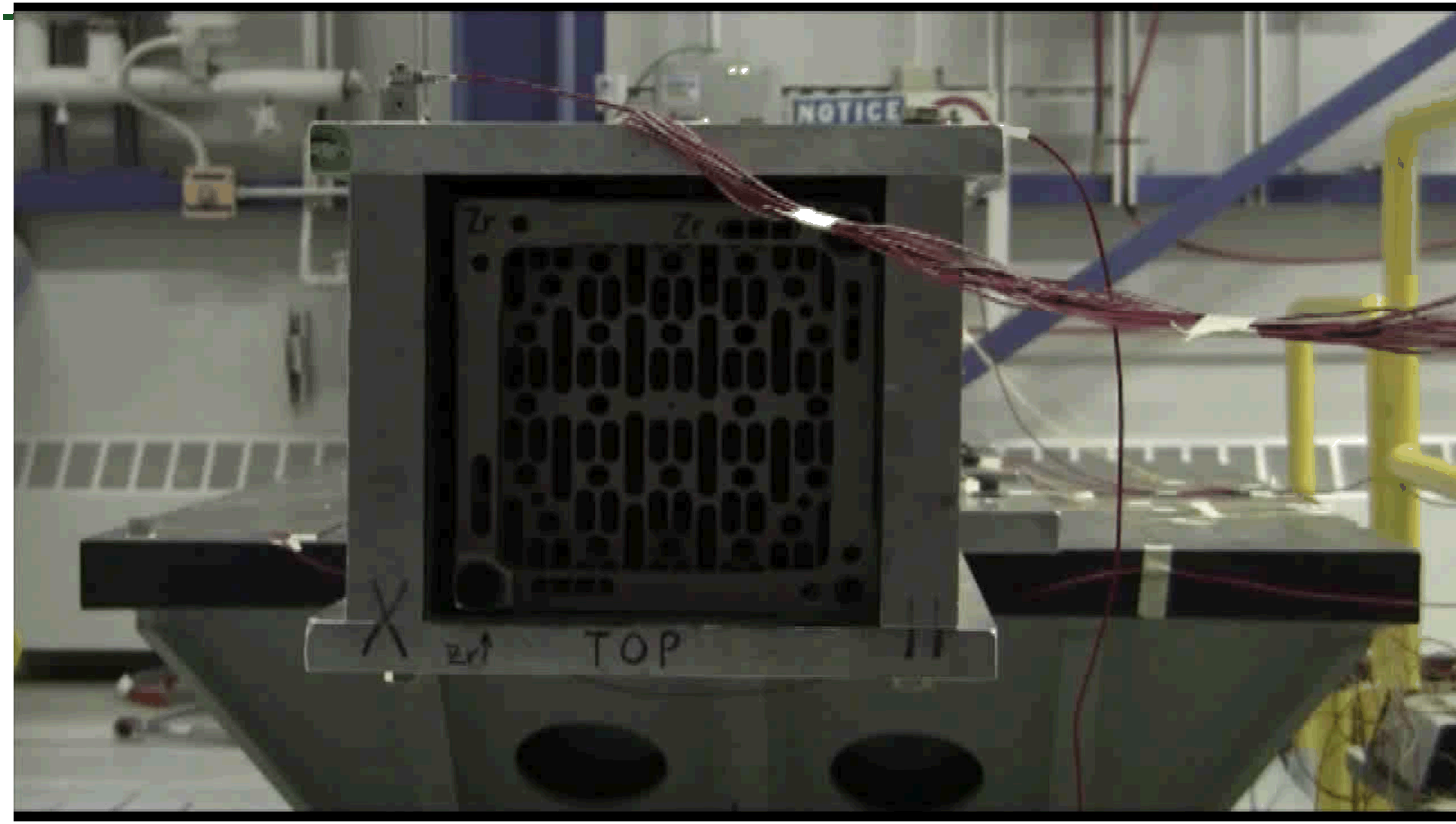
Spacer grid acceleration v. table vertical acceleration for rail shock test



Used Fuel Disposition

SNL Shaker Shock Test Video

Top-end view of assembly in basket



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)

Bending moments applied in ORNL tests exceed NCT bending moments

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 $r_o(\kappa_{max})$*

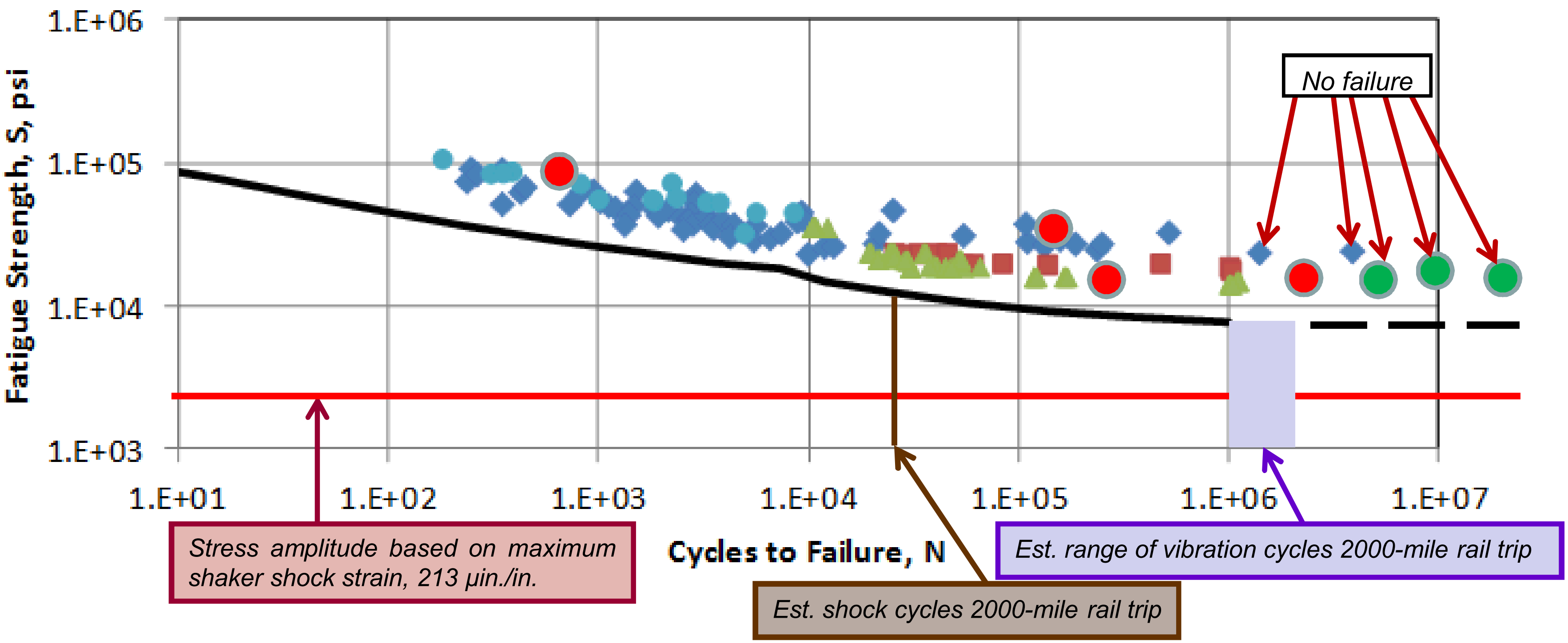
r_o^{Zirc4} = 5.385 mm (HBR cladding)

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

Q: How many cycles to failure for a bending moment of 0.7 N-m?

Answer: cycles to failure should be ≫ 22.3 $x10^6$

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

Conclusion

- The strains measured on the rods in the assembly NCT test program were in the micro-strain levels
- Strains on irradiated fuel rods during NCT may be less than strains measured on the unirradiated Zircaloy-4
- Strain- or stress-based failure of fuel rods during NCT unlikely
- Fatigue during NCT does not appear to be an issue

Empirical evidence for these conclusions:

↓

Transport experience France

More than 75,000 LWR used fuel assemblies transported
(from France, Japan, Germany, Belgium, Switzerland, the Netherlands, Italy)

About 7,500 loaded casks with LWR assemblies

La Hague reprocessing plant has received 15,156 assemblies … with burn-up greater than 45GWd/tU (from EDF)

No assemblies have ever been damaged during transport

No damage to or leaks of the casks has ever occurred

"The information is associated to ***AREVA TN packages, transport means and operational experience."***

AREVA

AREVA TN information EDF website:
http://www.edf.com/fichiers/fckeditor/Commun/En_Direct_Centrales/Nucleaire/General/Notes_Info/Note_info_transport_comb._dechets_nucl_082010.pdf

Comparison of maximum strains measured on Zircaloy-4 rods in truck and shaker tests

Strain Gauge ID (Truck/Shaker)	Location on Assembly (Top-middle Rod)	Truck Test Maximum Strain Absolute Value (µin./in.)	Shaker Vibration Test Maximum Strain Absolute Value (µin./in.)	Shaker Shock Test Maximum Strain Absolute Value (µin./in.)
S1 - 0°	Adjacent to first spacer grid, Span 10	55		
TMR-G-S10-3			89	80
S2 - 0°	Mid-span, Span 10	94		
TMR-G-S10-2			207	213
S3 - 0°	Adjacent to first spacer grid, Span 5	143		
TMR-G-S5-2			97	119
S4 - 0°	Mid-span, Span 5	69		
TMR-G-S5-1			156	114

Used Fuel Disposition

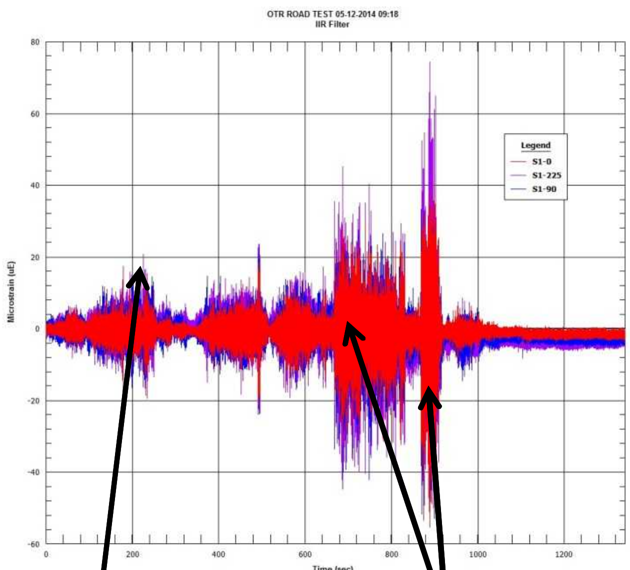
Test Unit on Concrete Blocks on Trailer for Over-the-Road Test

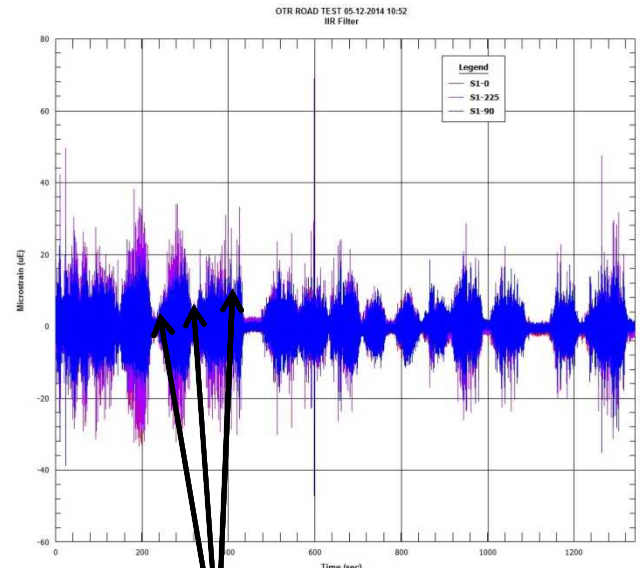
Basket/assembly
Basket based on NAC-LWT PWR design

Concrete simulates mass of a truck cask
≈44000 lbs v. ≈51200 lbs for a NAC-LWT cask

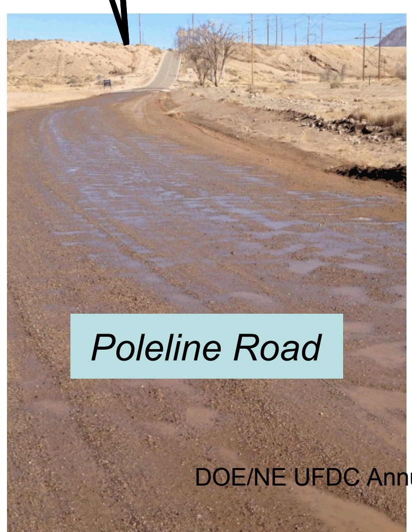
Used
Fuel
Disposition

Low strains measured on instrumented rod during over-the-road test





dip on Area III Access Road



Poleline Road

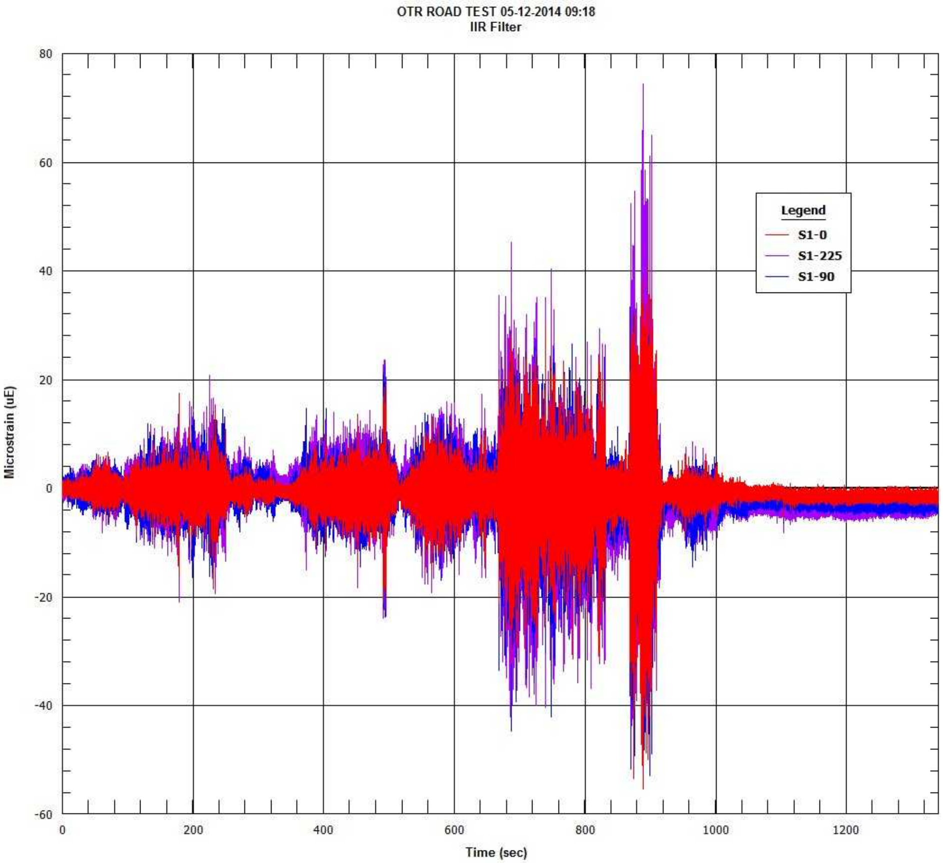
Gibson Blvd.

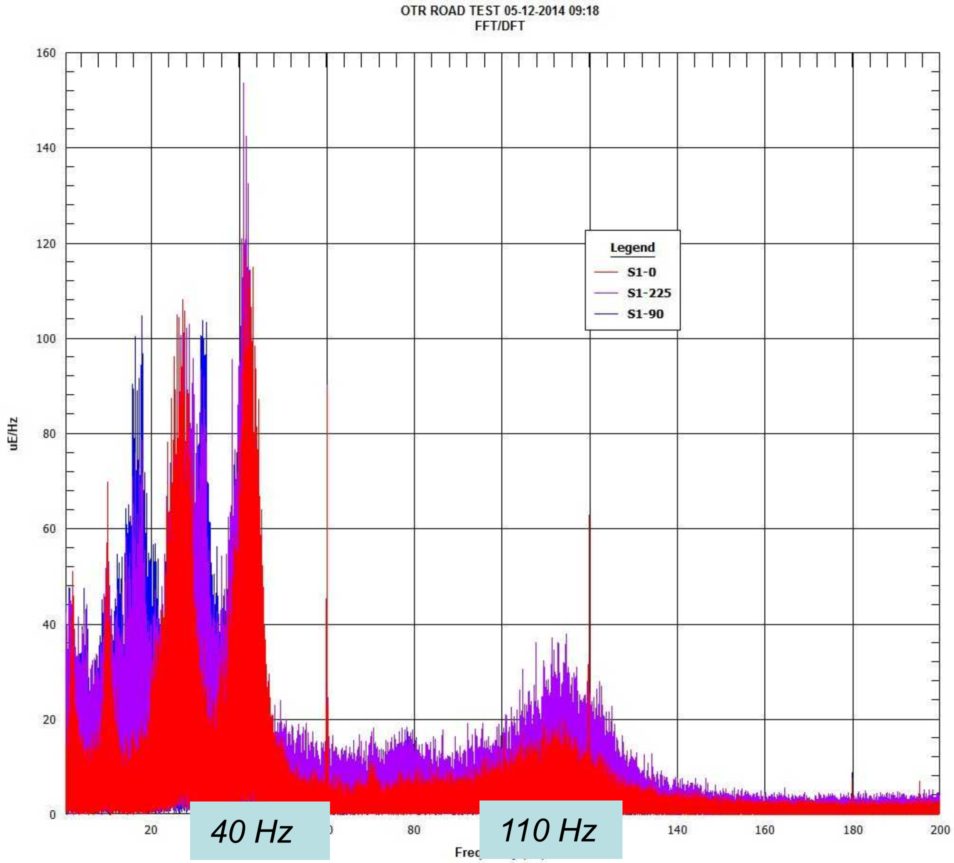
Strains correlated with road conditions

Used Fuel Disposition

Rod strains (με *v.* time) and FFT (με/Hz *v.* Hz) for over-the-road test

maximum strains occurred at low Hz





Gaps

	I.D. (inch)	O.D. (inch)	Gap (inch)
Zr-4 tube	0.334		
Cu rod	0.312		
Pb rod and pellets		0.280	
Mo pellets		0.3125	
Pb in Zr-4			0.054
Mo in Zr-4			0.0215

	Density (g/cm^3)	Density ratio	Elastic modulus (GPa)	Ratio of Mo/Pb pellet weight
UO_2	10.97	1	192	
W	19.25	1.75	411	
WC	15.63	1.42	550	
Pb	11.34	1.03	16	1.13*
Mo	10.22	0.93	329	
Zr-4	6.52		99	
* 12-foot Mo pellets = 4.1 lbs; 12-foot Pb pellets = 3.6 lbs				

Rail Cask / Railcar RFI

- **Sandia issued a RFI for a rail cask and transportation system on Business Opportunities Webpage**
- **Responses from**
  - **Areva,**
  - **Holtec, and**
  - **Tri-Cities Railroad Company/NAC**
  - **NovaTech**
- **Formal RFQ may be issued pending future funding**
- **Testing could be performed at TCRC or TTCI**

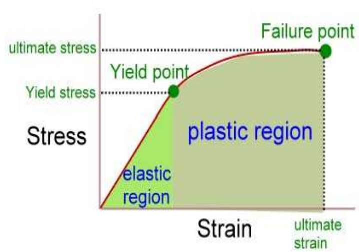
Application of Fuel Assembly Test Results (1)

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

The SNL assembly tests provide data – the applied stresses on the rods - related to the issue of the margin of safety:

***applied rod stress**$_{normal\ transport}$*

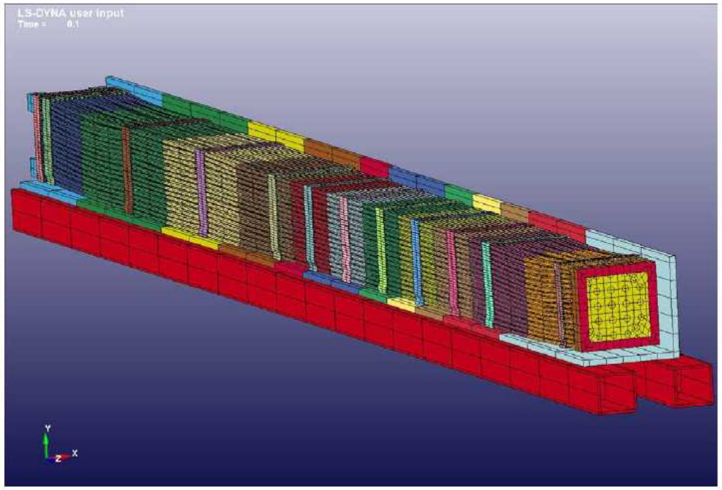
Material property test programs at other national laboratories shall measure properties of high burnup cladding:



***yield strength**$_{cladding}$*
***stiffness**$_{cladding}$*
***fatigue strength**$_{cladding}$*

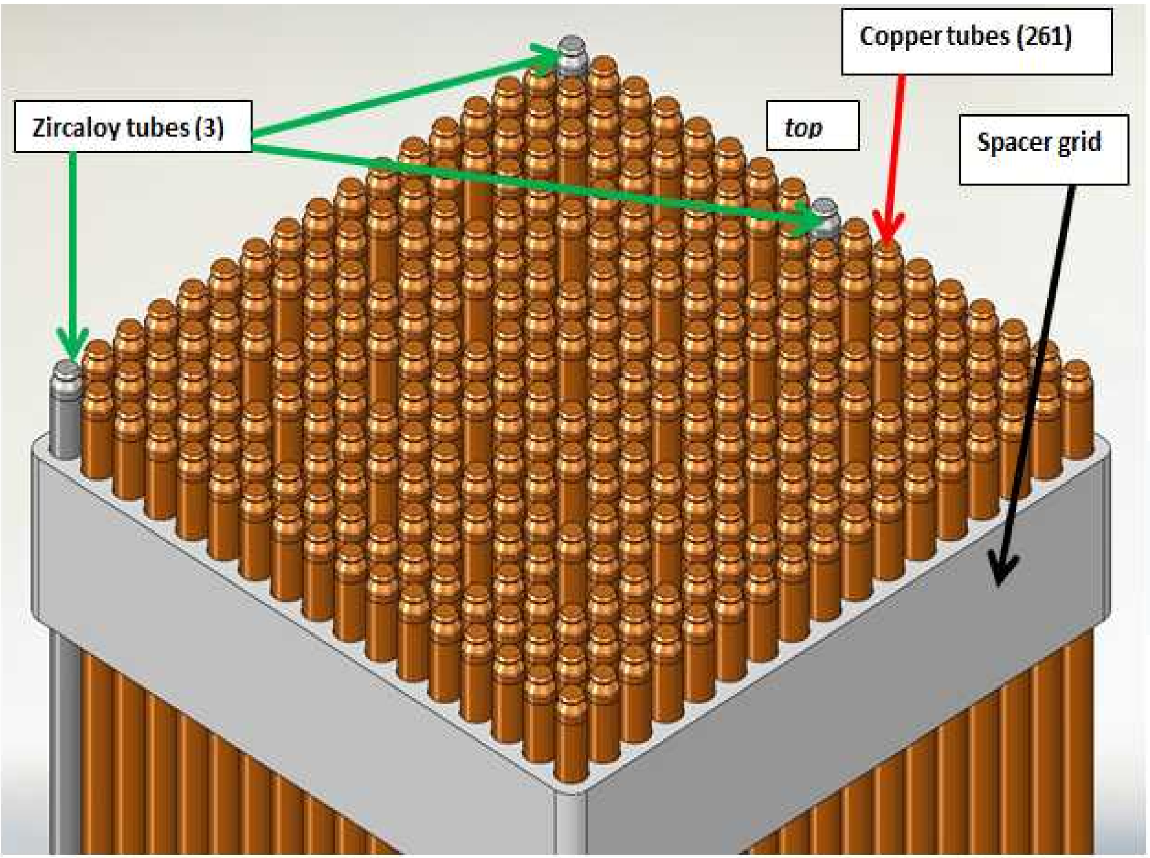
Application of Fuel Assembly Test Results (2)

- The data from the assembly tests *will* 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.



FUEL ASSEMBLY SHAKER TEST SIMULATION, Klymyshyn, et al., PNNL, FCRD-UFD-2013-000168, May 2013

SNL Experimental 17x17 PWR Assembly



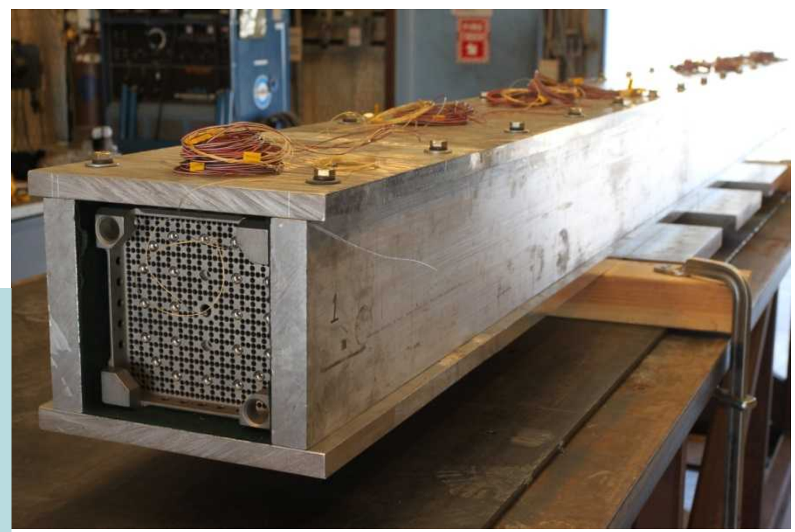
Only Zircaloy rods were instrumented with strain gauges and accelerometers

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

Basket/Assembly Test Unit

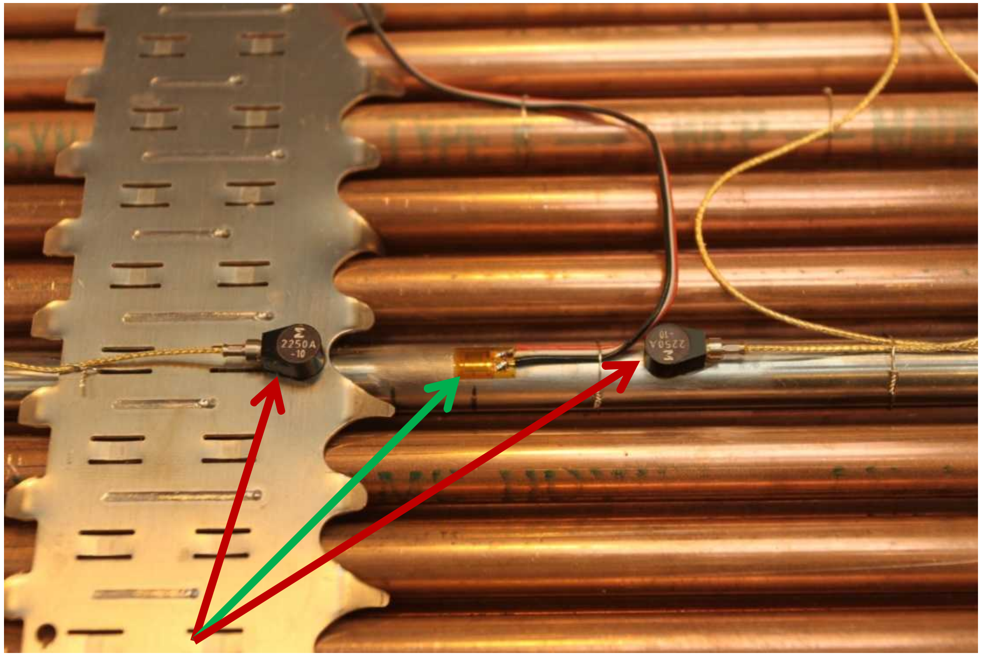
- *The test unit included an assembly and a basket.*
- The basket *is* based upon the geometry of the NAC-LWT truck cask PWR basket.
- The assembly was placed in *a* basket which was placed on 1) a shaker and *subsequently 2) a* truck trailer.
- *The assembly had the same freedom of motion within the basket as it would have in an actual cask.*

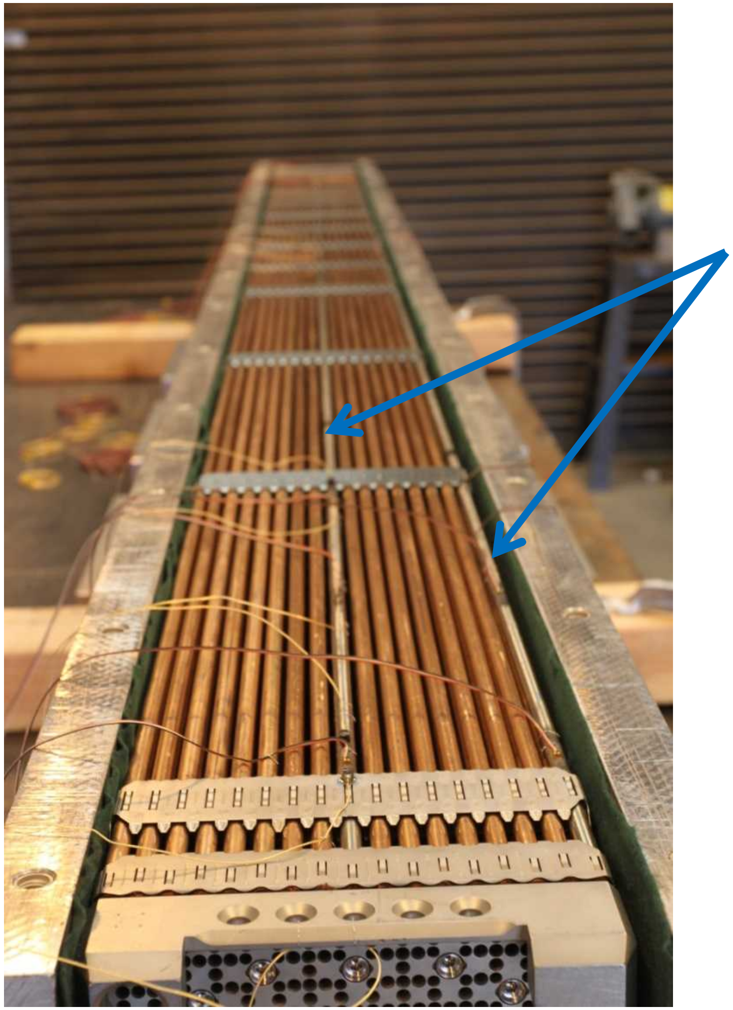
- *6061 Aluminum Basket*
- *Sides 1.5 inches thick*
- *Top/bottom 1 inch thick*
- *Length 161.5 inches*
- *Weight 837 pounds*



Used Fuel Disposition

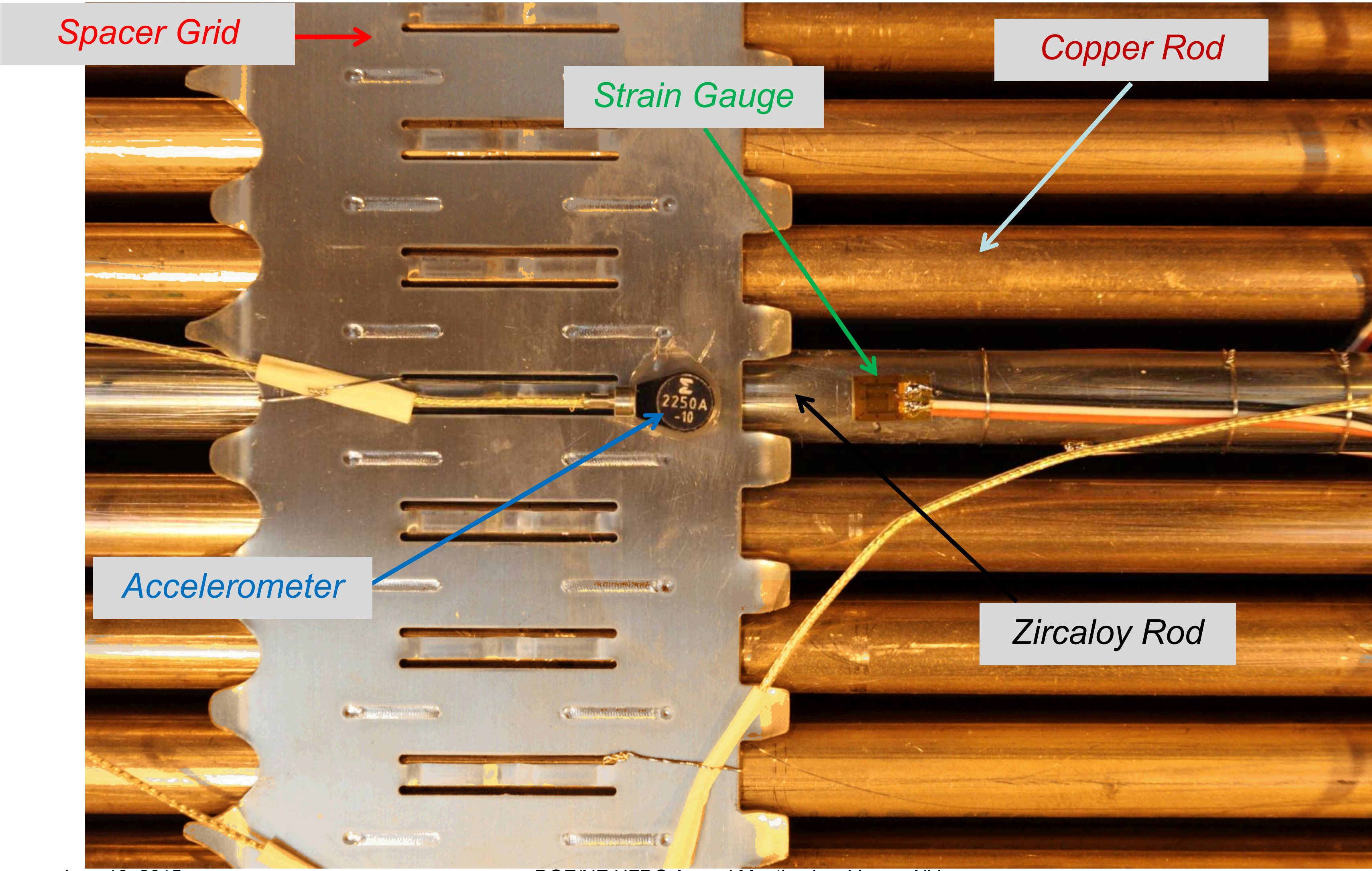
Left: Accelerometers and Strain Gauge on Top-Center Zircaloy Tube and Spacer Grid
Right: Assembly within Open Basket. Note the two Zircaloy-4 rods with instrumentation attached





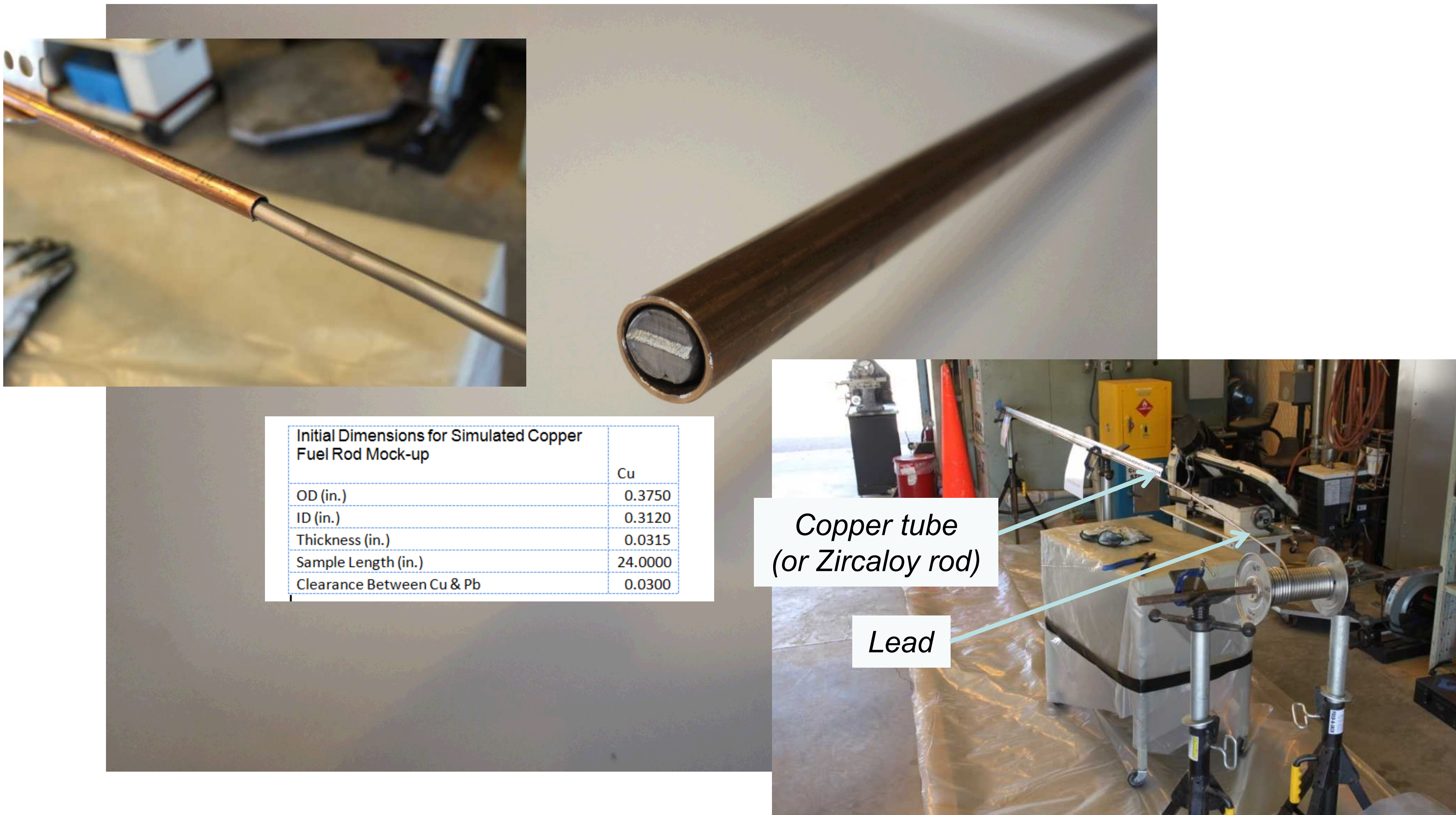
Used Fuel Disposition

Uniaxial Accelerometer and Strain Gauge on Test Assembly



Used Fuel Disposition

Lead Rod within Tube to Simulate Mass of UO_2

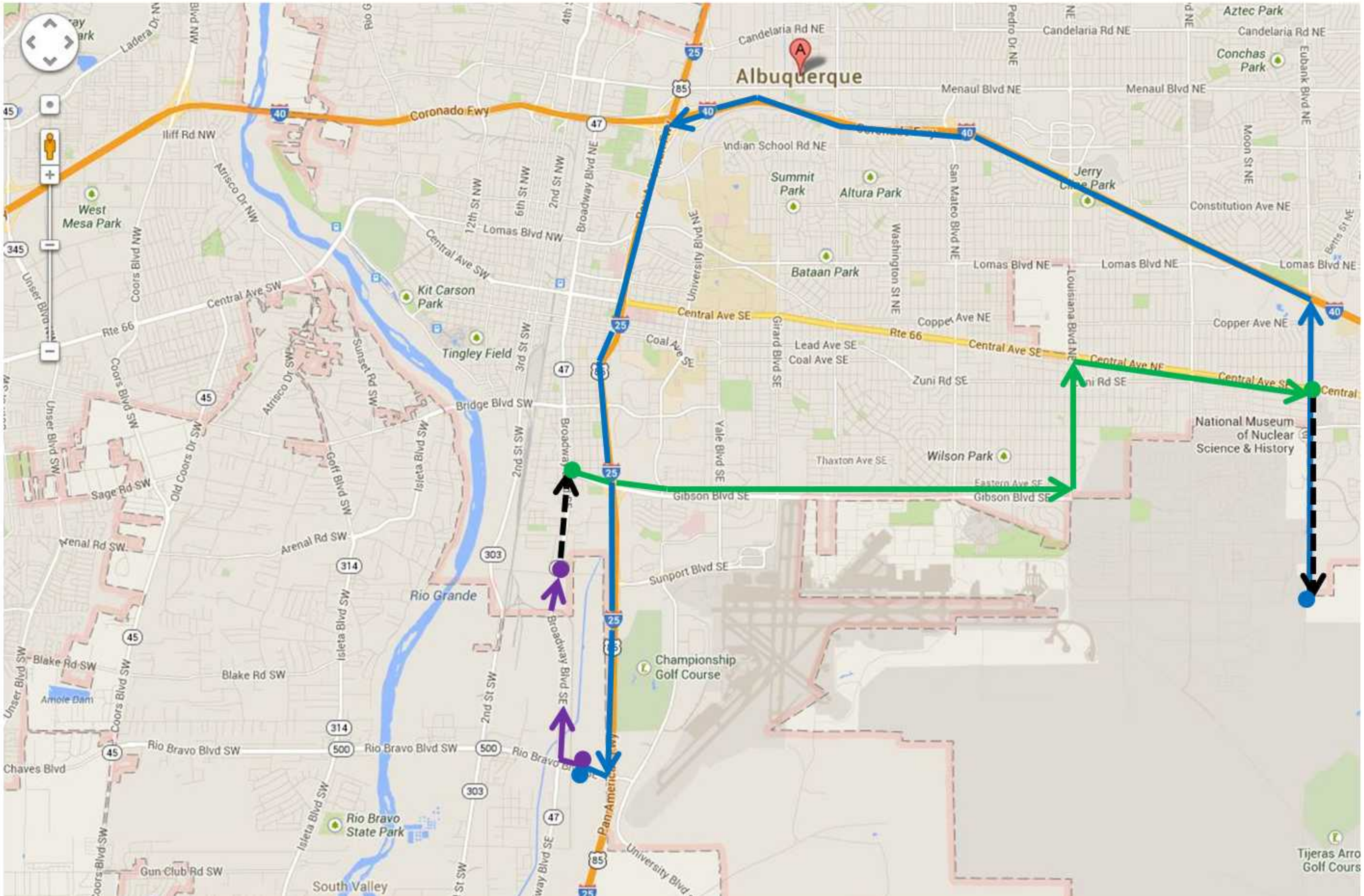


Initial Dimensions for Simulated Copper Fuel Rod Mock-up	Cu
OD (in.)	0.3750
ID (in.)	0.3120
Thickness (in.)	0.0315
Sample Length (in.)	24.0000
Clearance Between Cu & Pb	0.0300

Used Fuel Disposition

Truck Test Route

40 miles in Albuquerque area



Range of Road Conditions

Route included railroad crossings…

…and rough dirt roads

Maximum Strains Measured during Truck Test *essentially identical to shaker results*

Strain Gauge	Location on Assembly	Maximum Micro-strain Absolute Value (µin./in.)	Road Segment
S1 - 0°	Adjacent to first spacer grid, Span 10	55	
S1 - 90°		53	
S1 - 225°		74	
S2 - 0°	Mid-span, Span 10	94	
S2 - 90°		99	
S2 - 225°		86	
S3 - 0°	Adjacent to first spacer grid, Span 5	143	
S3 - 90°		84	
S3 - 225°		108	
S4 - 0°	Mid-span, Span 5	69	
S4 - 90°		101	
S4 - 225°		93	
Average 0°		90	
Average 90°		83	1
Average 225°		90	

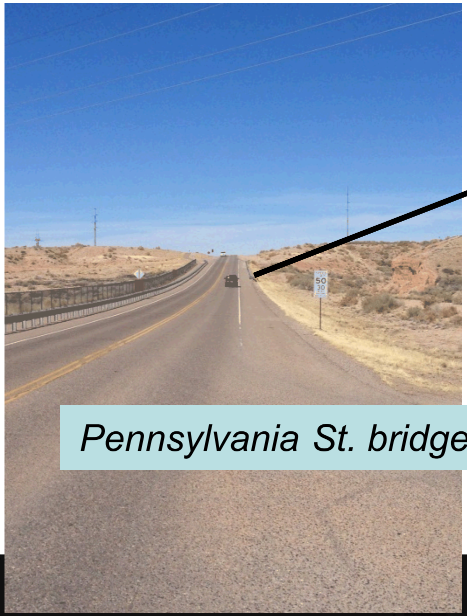
All maximum strains during road Segment #1 at 872.4 – 902.3 seconds into the trip. This corresponds to travel on Poleline Road (dirt).

Truck Test Maximum Accelerations

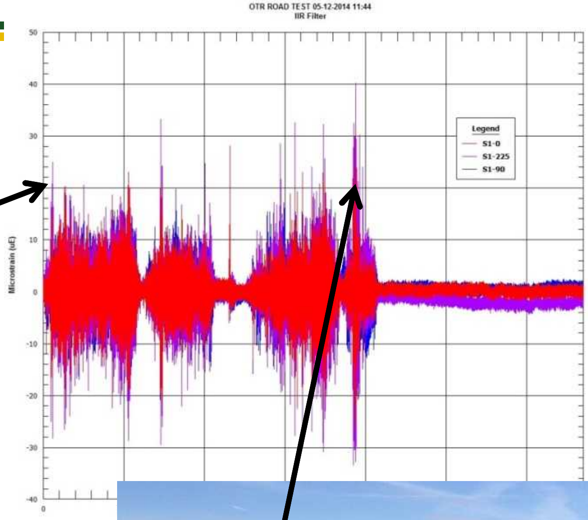
All Segments			
Uniaxial Accelerometer	Location	Maximum Acceleration, g	Road Segment
A1	On first spacer grid, Span 10	9.5	1
A2	Mid-span, Span 10	16.7	
A3	Adjacent to second spacer grid, Span 10	14.6	
A7	Adjacent to second spacer grid, Span 5	22.0	
A8	On second spacer grid, Span 5	11.3	

All Segments		
Triaxial Accelerometer	Location	Maximum Acceleration, g
TA2 – X (longitudinal)	On top of basket above mid-span of assembly (Span 5)	2.1
TA2 – Y (lateral)		3.6
TA2 – Z (vertical)		5.6
TA5 – X (longitudinal)	Below trailer bed above rear axle	13.7
TA5 – Y (lateral)		10.0
TA5 – Z (vertical)		11.8

Strains correlated to road surfaces



Pennsylvania St. bridge



8-inch rut

speeding to Building 6922

Side Basket Showing Cutout for Filming Assembly during Truck Test

Maximum Micro-strains on Zircaloy Fuel Rods during Shaker Shock Test – *Strains are very low*

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*

← *average maximum*

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

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

(dependent upon interfacial bonding conditions)

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

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

Bending stiffness Zircaloy-4 (irradiated/unirradiated) = 52/17.7 = 2.9

Range of bending stiffness Zircaloy-4 (irradiated/unirradiated) ratio: ≈ 1 – 5

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 strain: ≈ 157 – 30 µm/m

(dependent upon interfacial bonding conditions)

Thoughts on the free drop issue

- **Measuring the effects of a free drop on rods in an assembly within an actual package (cask) would be experimentally difficult and expensive.**
  - The cask test would require sacrificial impact limiters.
  - Analysis is far more viable.
    - *A model validated via the assembly NCT tests would be useful.*
- **The peak acceleration would be approximately 20 g.**
  - That acceleration may be low enough that the assembly and rods would probably remain elastic.
- **Should a cask ever experience a free drop in-service (e.g., handling accident) , it is unlikely that the cask would be transported.**
  - It is likely that the assemblies would be removed from the cask, inspected, and possibly repackaged.
- **Sandia performed an actual 0ne-foot drop test of a 1/3-scale ENSA 32 cask. Data supplied to PNNL for analysis of strains on an assembly**

The 1-Foot Free Drop is NOT a test of an assembly – it is a test of a Package

§ 71.55 General requirements for fissile material packages.

(d) A package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in § 71.71 ("Normal conditions of transport"):

(1) The contents would be subcritical;

(2) The geometric form of the package contents would not be substantially altered;

The Free Drop is NOT a test of an assembly – it is a test of a Package

- § 71.71 (a) *Evaluation*. Evaluation of each package design under normal conditions of transport must include a determination of the effect on that design of the conditions and tests specified in this section.
- (c) (7) *Free drop*. … a free drop through the distance specified below onto a flat, essentially unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected.

Package weight		Free drop distance	
Kilograms	**(Pounds)**	**Meters**	**(Feet)**
More than 15,000	**(More than 33,100)**	**0.3**	**(1)**

§ 71.4 Definitions

"*Package* means the packaging together with its radioactive contents as presented for transport."

"*Packaging* means the assembly of components necessary to ensure compliance with the packaging requirements of this part. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The vehicle, tie-down system, and auxiliary equipment may be designated as part of the packaging."

Interface bonding efficiency can significantly affect HBU SNF flexural rigidity and bending moment distribution among fuel pellets and clad

Interfacial Bonding Conditions	Curvature (1/m)	Flexural rigidity, EI ($N \cdot m^2$)	Cladding moment (N*m)	Pellet moment (N*m)
Perfectly bonded	0.072	87	**2.06**	**4.19**
De-bonded pellet–pellet interfaces with gaps	0.118	53	4.90	1.35
De-bonded pellet–pellet and pellet–clad interfaces with gaps	0.209	30	5.96	0.29
De-bonded pellet–pellet interfaces without gaps	0.097	65	**3.52**	**2.73**
De-bonded pellet–pellet and pellet–clad interfaces w/o gaps	0.140	45	3.98	2.27

Jy-An Wang, ORNL
2014 ASTM C26 Committee Meeting
June 10-12, 2014

HBU SNF rod for CIRFT testing reveals good contact at fuel-clad interface

Jy-An Wang, ORNL
2014 ASTM C26 Committee Meeting
June 10-12, 2014

Interface Bonding (IB) can significantly dictate SNF composite system mechanical properties

- IB affects "Flexural Rigidity: $EI = \Delta M/\Delta k$"

  $EI_{System} = E_{Fuel}\, I_{Fuel} + E_{Clad}\, I_{clad}$ (Perfect bonding condition)

  $EI_{System} = E_{Fuel}\, I_{Fuel} + E_{Clad}\, I_{Clad} - IBE$ (loading, frequency, temperature)

- IB can affect significantly on the distribution of bending moment resistance capacity among fuel pellets and clad
- The chemical cohesion bond at interface between UO_2 (fuel) and ZrO_2 (clad ID) is expected to be fairly weak
- The majority IB is coming from the shear resistance capacity, induced by clad radial compressive residual stress inherited from a HBU SNF system

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Environmental effects on Zircaloy

- **Increase Temperature,**
  - Decrease elastic modulus, yield strength, and stiffness
  - Decrease fatigue strength
- **Increase irradiation,**
  - Increase yield strength, modulus (slightly)
  - Decrease fatigue strength (slightly)
- **Increase stiffness,**
  - Decrease strain for a given applied bending moment

Property relationships

- **Flexural rigidity = stiffness = EI** **($N\text{-}m^2$; $lb\text{-}in^2$)**
- **I = moment of inertia** **(m^4; in^4)**
  $= \pi/4(r^4)$ for a rod
  $= \pi/4(r_o^4 - r_i^4)$ for a tube
- **Elastic modulus = E = σ/ε** **(N/m^2; lb/in^2)**
- **Strain = $\varepsilon = r_o\kappa = r_o(M/EI)$** **(m/m; in/in)**
- **Curvature = $\kappa = \varepsilon/r_o\kappa$** **($m^{-1}$; in^{-1})**
- **Bending moment = M = σS** **(N-m; in-lb)**
- **Stress = $\sigma = M/S = M/(I/r_o)$** **(GPa; N/m^2; lb/in^2)**
- **Section modulus = $S = I/r_o = (EI/E)\ r_o$** **(m^3; in^3)**

$r_o^{unirr\text{-}tube} = r_o^{irr\text{-}rod}$
so, for the same applied moment, M:
$\varepsilon_{irr}/\varepsilon_{unirr} = (r_o(M/EI_{irr}))/(r_o(M/EI_{unirr})) = EI_{unirr}/EI_{irr}$
So, $\varepsilon_{irr} = \varepsilon_{unirr}(EI_{unirr}/EI_{irr})$

ORNL reports that for a 6.25 N-m "bending loading" the "maximum clad Von Mises stress is 13.36 ksi for "HBU Zr-4 clad inserted with a single UO_2 rod, rod and clad interface de-bond". So, for a 0.7 N-m "bending load" (applied moment) the stress would be:
$\sigma_{high\ burnup\ irradiated\ Zircaloy\text{-}4} = (13.36)(0.70/6.25) \approx 1.5$ ksi

Used Fuel Disposition

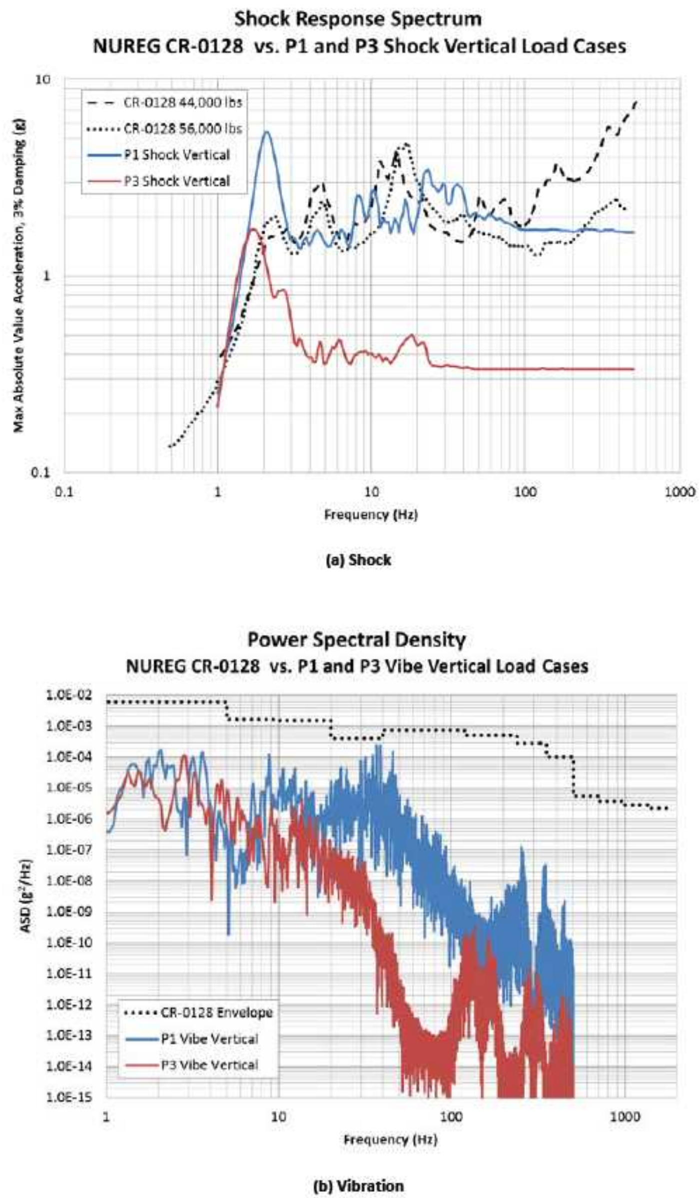

Figure 5.15 Comparison of the P1 and P3 Load Cases with the NUREG/CR-0128 Shock and Vibration Load Environments

Rail loadings less severe than truck loads