SAND2014-18948PE

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Sandia National Laboratories


# Truck Transport Results / Progress on Rail Test

SNL-BAM Workshop
7 October 2014
Paul McConnell

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# What we think we know

- The strains measured in the 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 may be less than strains measured on unirradiated tubes.
- Normal conditions of truck transport are more severe than rail.

# ISFSI Locations

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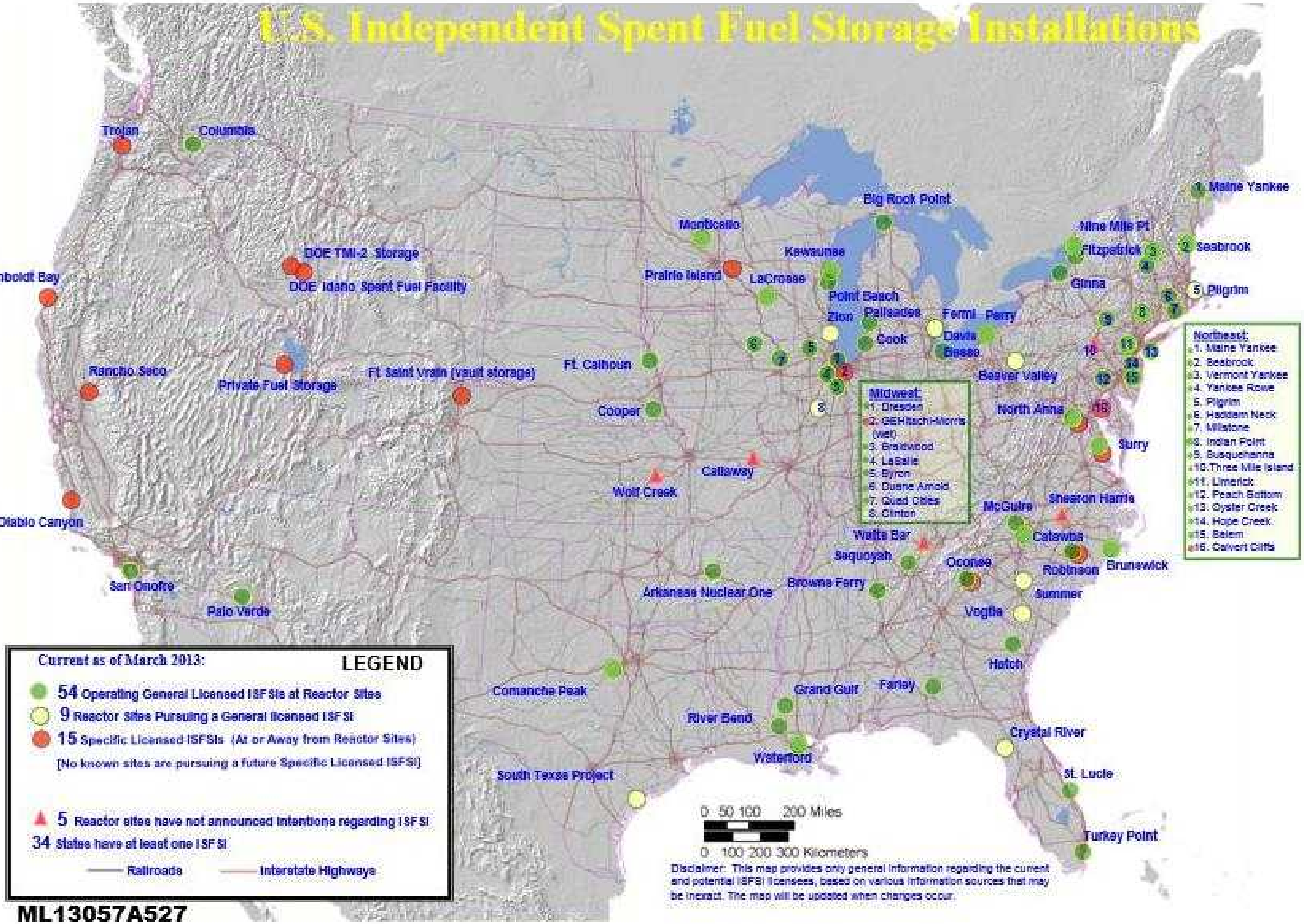



http://www.enviroreporter.com/wp-content/uploads/2013/10/NRC-map-of-Independent-Spent-Fuel-Storage-Installations.jpg

# Lots of Assemblies to be Stored & Transported



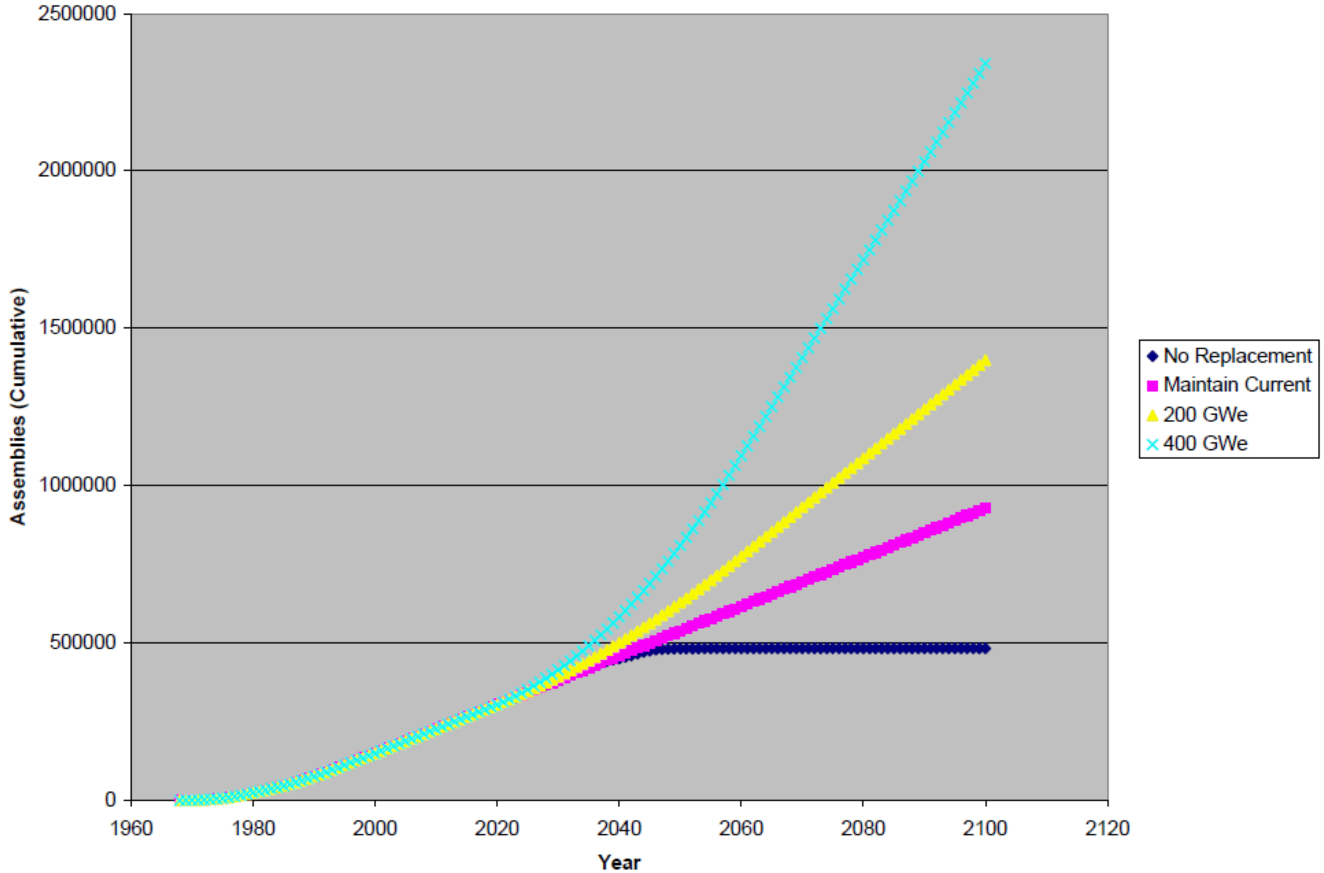
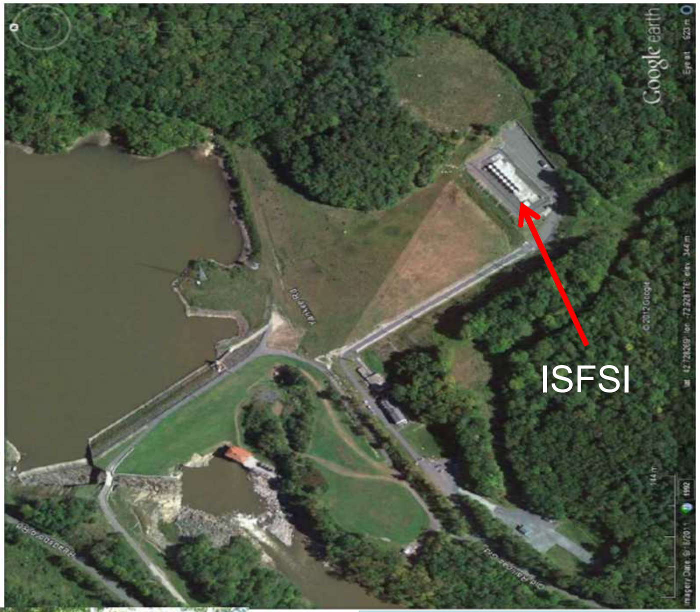



Figure 3-3 Cumulative UNF Assemblies Discharged for the No Replacement, Maintain Current, 200 GWe/yr, and 400 GWe/yr.

# Transportation

NAC-MPCs (MPC-36 canisters)

NAC-STC rail cask
Courtesy Yankee Rowe




Yankee Rowe

Heavy-haul truck required to get to railhead
Courtesy Yankee Rowe

Hoosac Tunnel
See: http://en.wikipedia.org/wiki/Hoosac_Tunnel

# Transportation

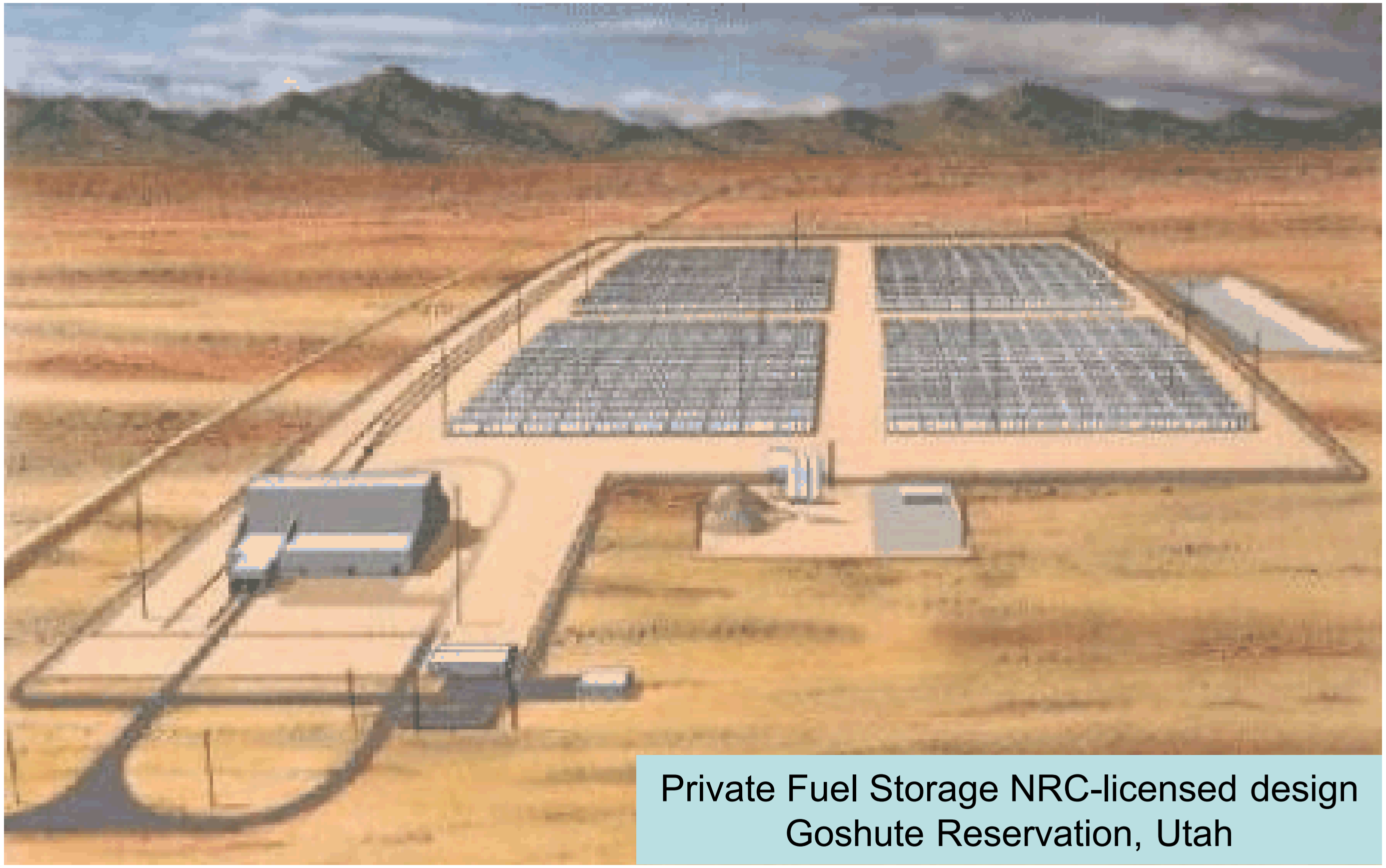

Parking lot for heavy-haul truck access to railhead!

Railhead, Portland, Conn. near Connecticut Yankee

Barge transport, Connecticut River (Connecticut Yankee pressure vessel)
Courtesy Connecticut Yankee

Connecticut Yankee barge slip site

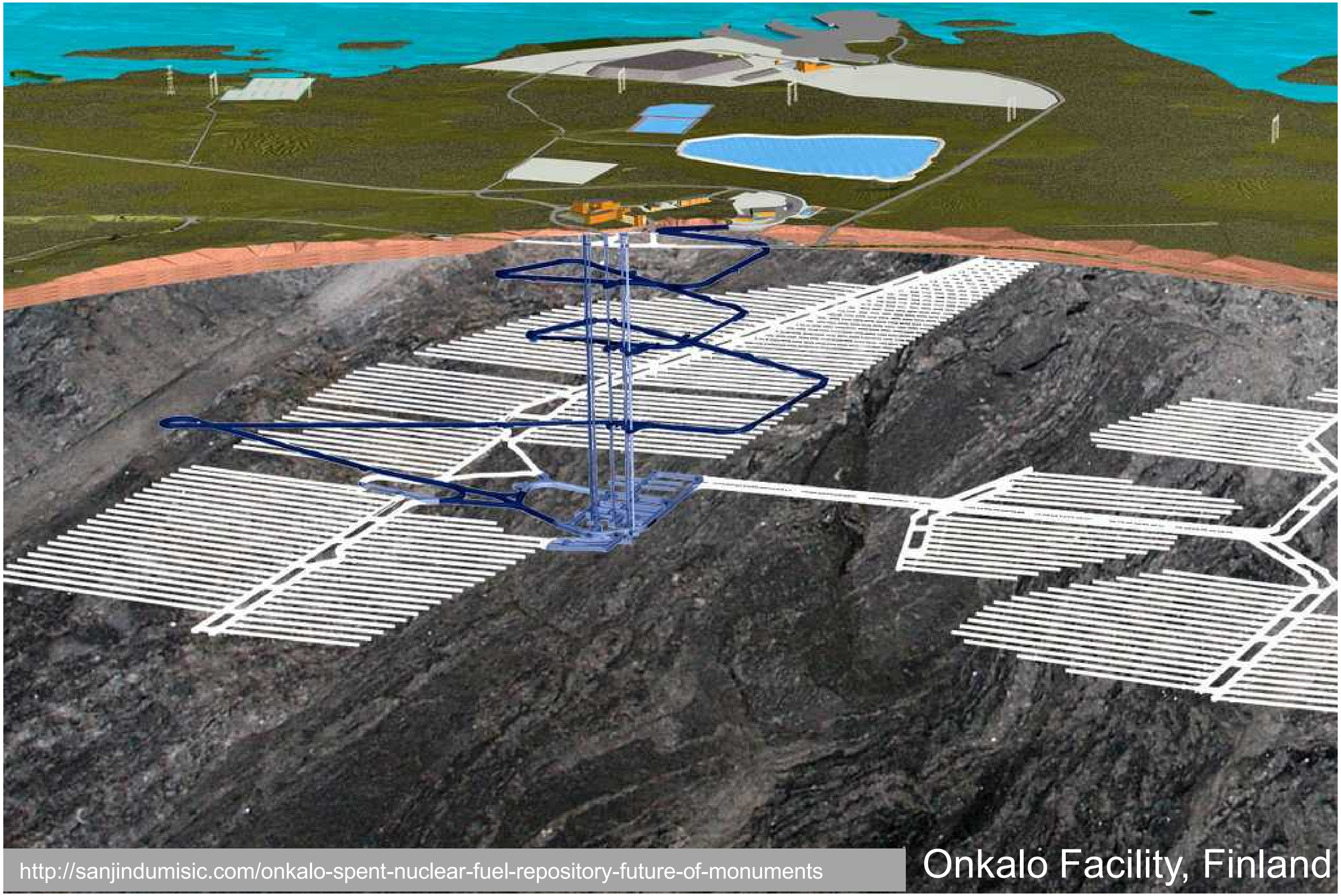
# Central Storage Facility



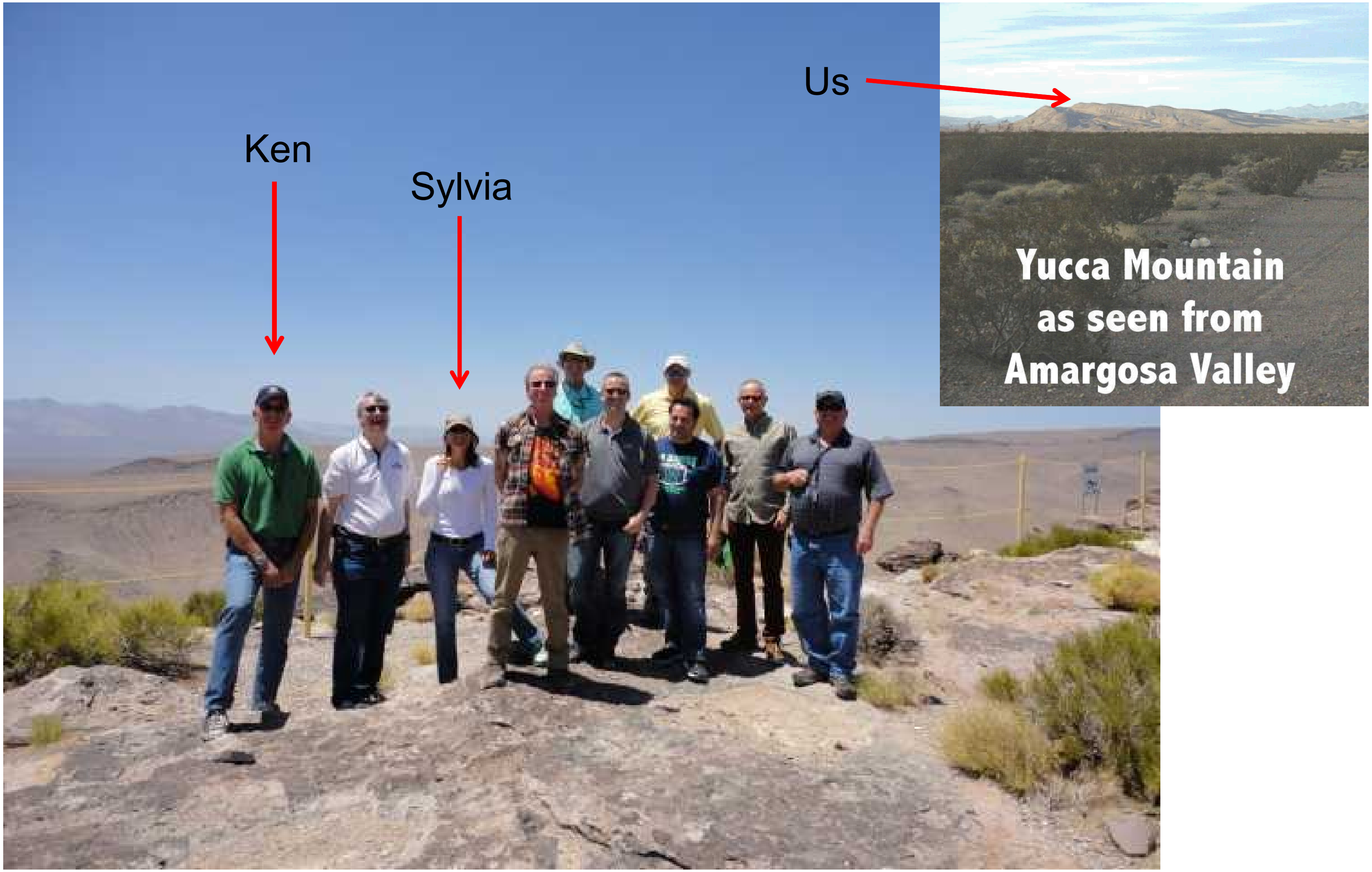
Private Fuel Storage NRC-licensed design
Goshute Reservation, Utah

http://www.world-nuclear-news.org/WR-Rethink_on_Utah_used_fuel_storage_project-0408104.html

# Repository


http://sanjindumisic.com/onkalo-spent-nuclear-fuel-repository-future-of-monuments
Onkalo Facility, Finland

# Not a Repository



# There Will Be Lots of High Burnup Assemblies

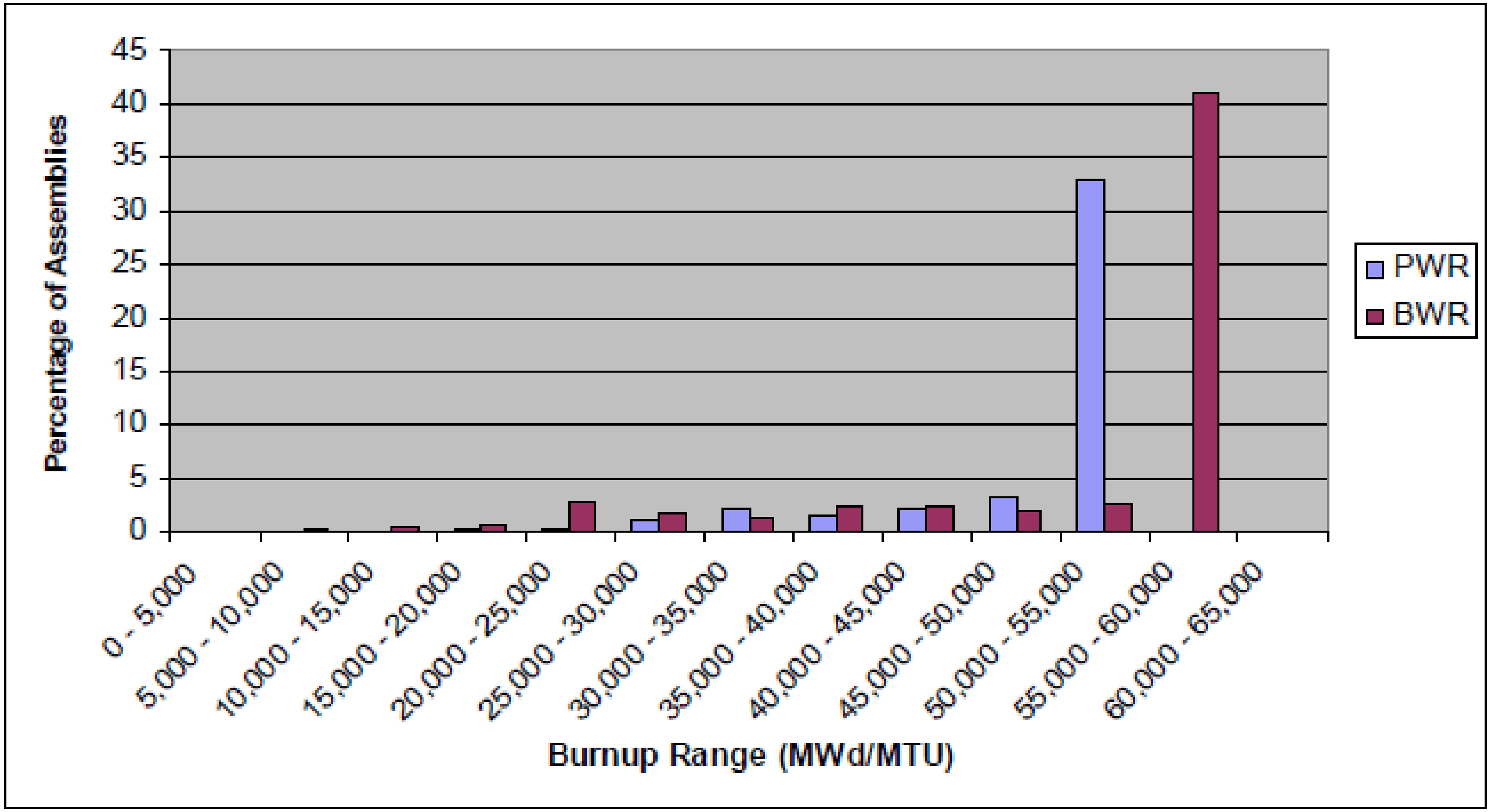



Figure 3-7 Percentage of Assemblies per Burn-up Range – Maintain Current Nuclear Generation Case

# Motivation for assembly testing

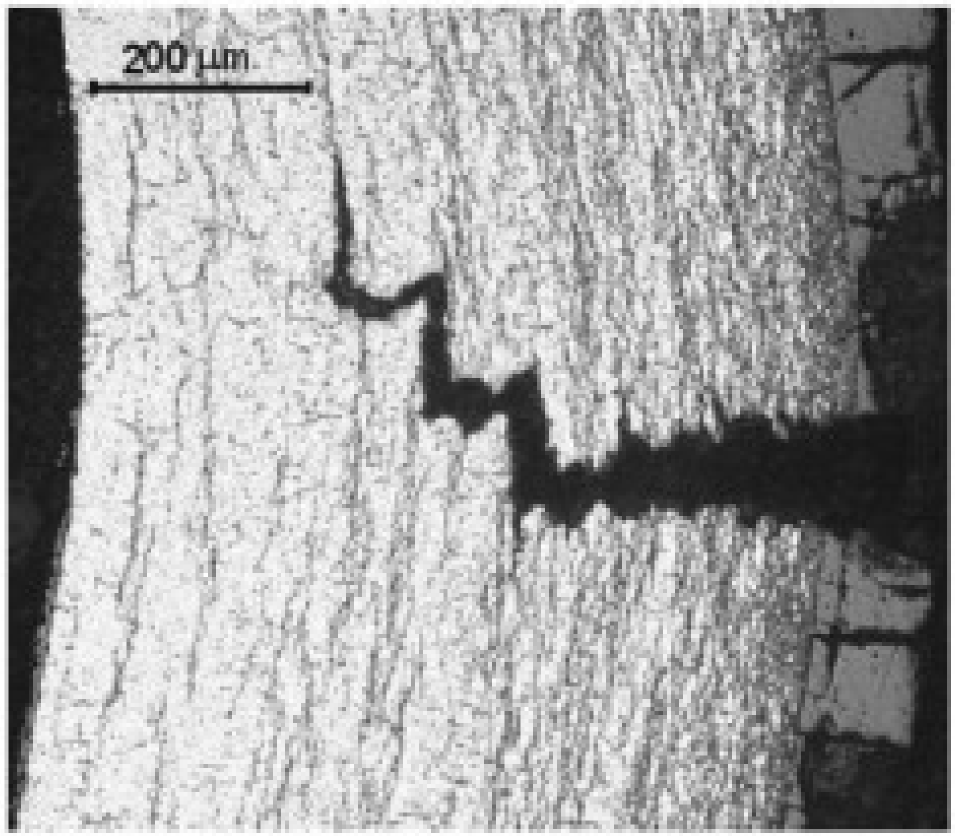
- Federal Regulations require an assessment of
  "*Vibration* - Vibration normally incident to transport"…
  …imposed on transport packages and contents during "normal conditions of transport". (10CFR71.71)

- The NRC has approved normal transport of low burnup spent fuel.

- However, the technical community needs to establish a technical basis to demonstrate that high burnup fuel rods can withstand all normal conditions of transport.

- Vibrations and shocks have been measured on truck trailers and railcars but not directly on fuel assemblies, baskets, or fuel rods.

# In other words, could Zircaloy cladding fracture during normal conditions of transport?




http://sanonofresafety.org/nuclear-waste/

# Application of Fuel Assembly Test Results (1)

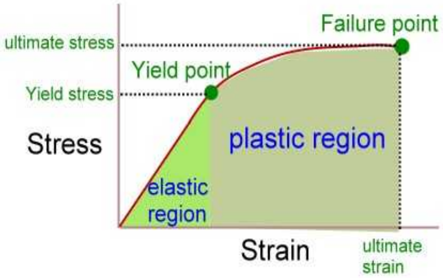
The margin of safety between the applied loads on fuel rods during transport and the material properties of Zircaloy rods has not been quantified.

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

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

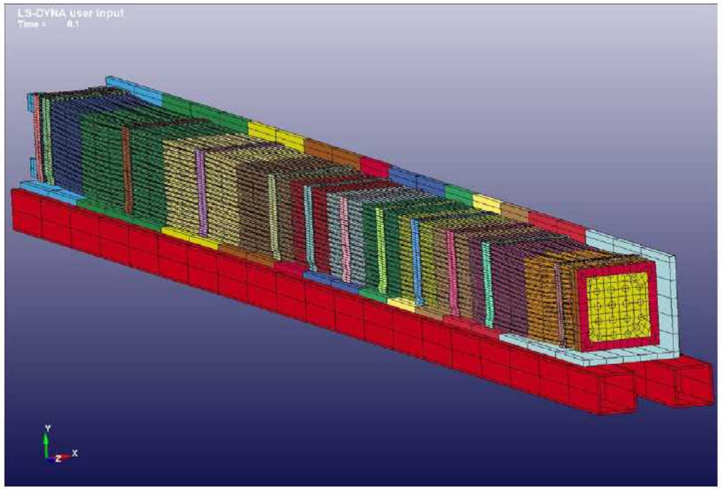
Material property test programs at other national laboratories shall measure properties of high burnup cladding:

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



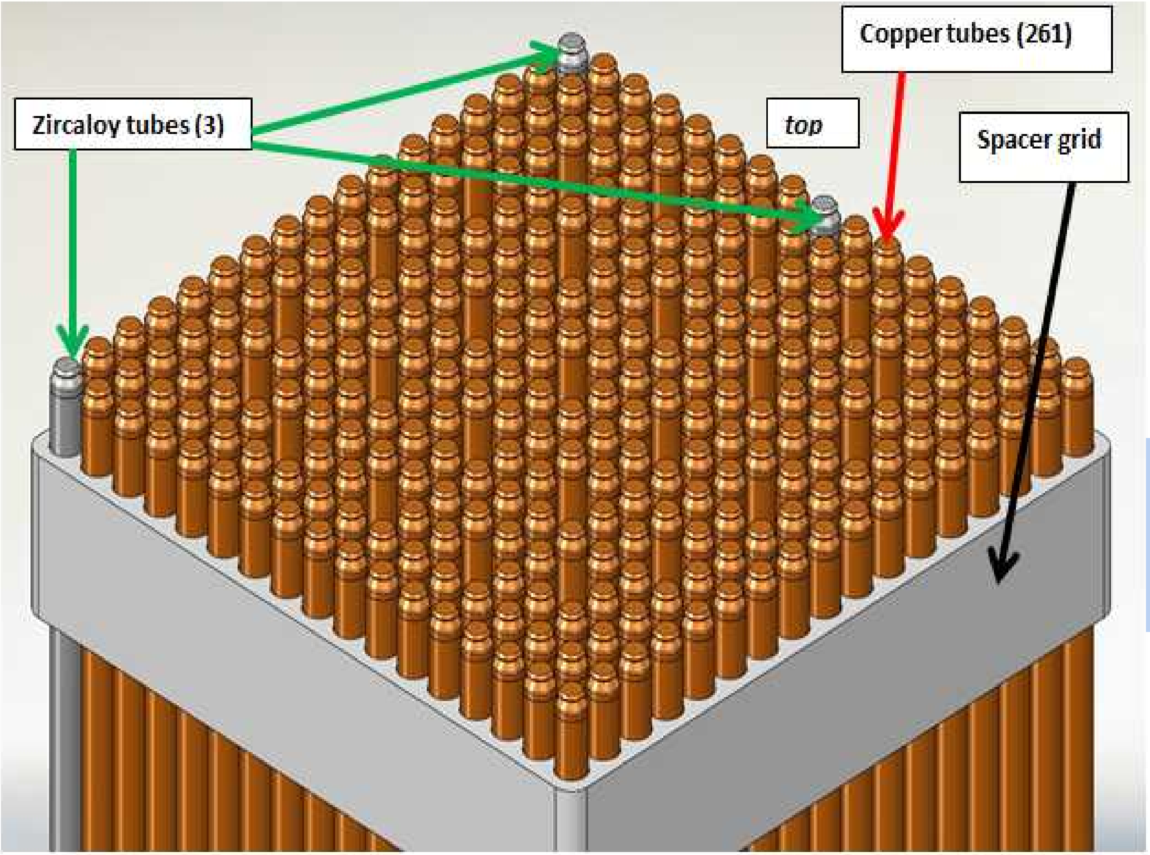
# Application of Fuel Assembly Test Results (2)

- 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



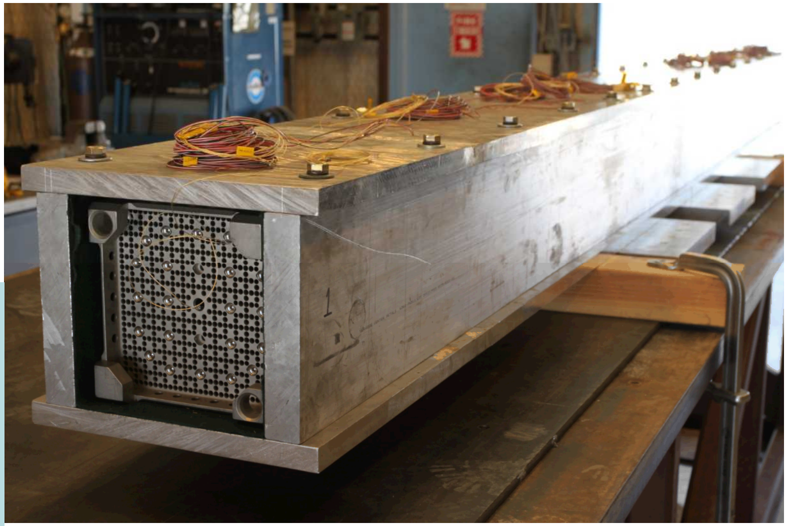

Only Zircaloy rods were instrumented with strain gauges and accelerometers

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

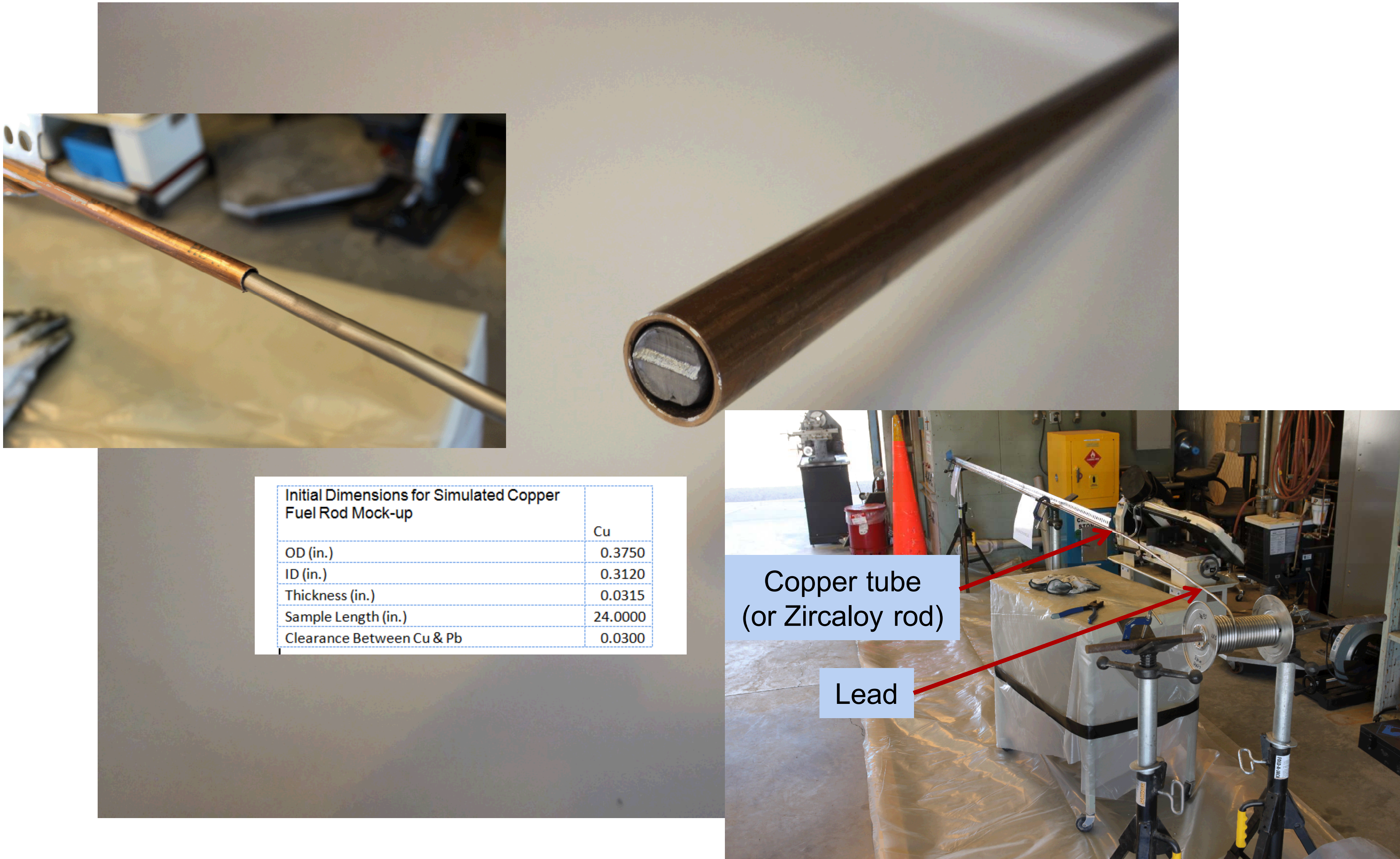
# Basket/Assembly Test Unit

- 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

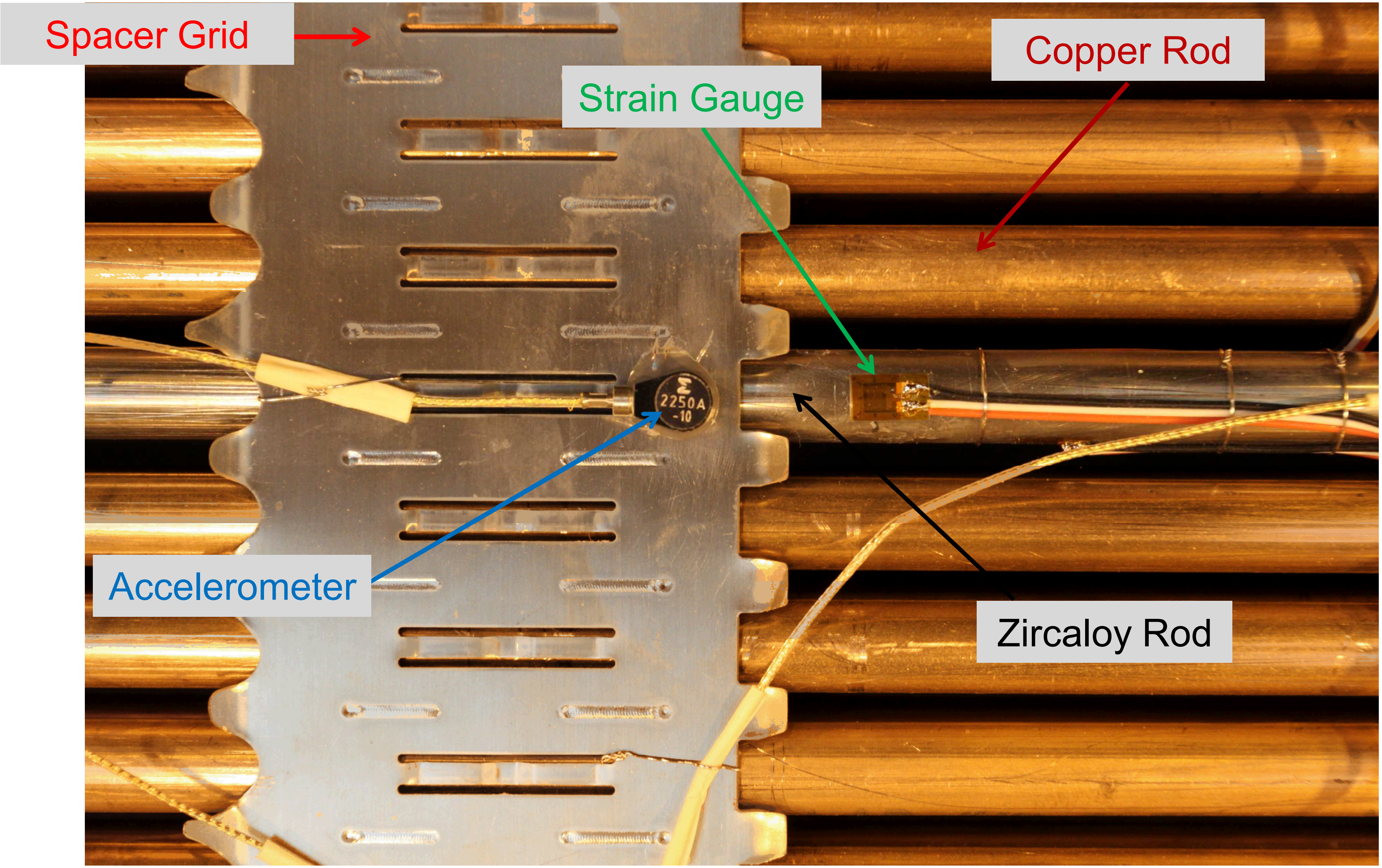


# Lead Rod within Copper Tube to Simulate Mass of $UO_2$
## (Zircaloy-4 tubes also contained Lead)

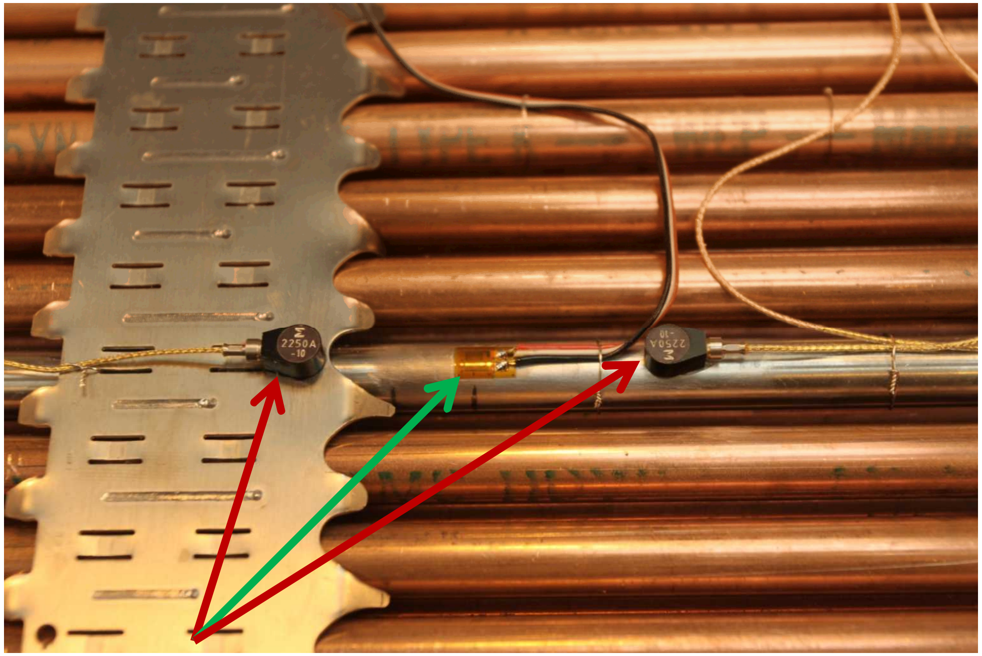


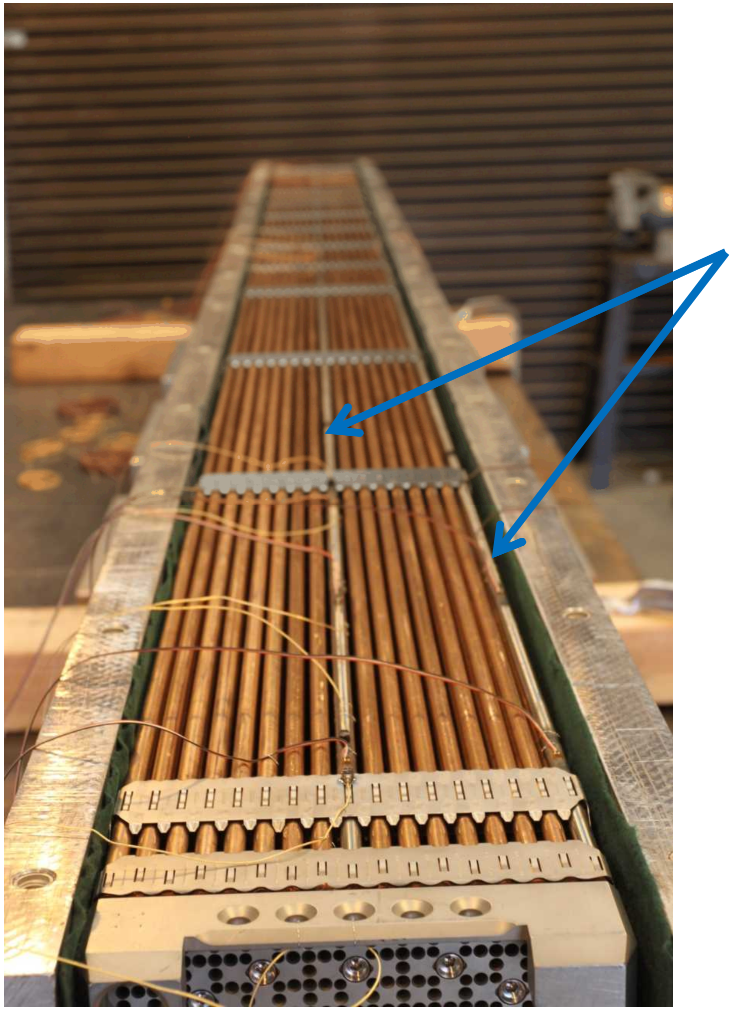

| Initial Dimensions for Simulated Copper Fuel Rod Mock-up | Cu |
|---|---|
| OD (in.) | 0.3750 |
| ID (in.) | 0.3120 |
| Thickness (in.) | 0.0315 |
| Sample Length (in.) | 24.0000 |
| Clearance Between Cu & Pb | 0.0300 |

# Uniaxial Accelerometer and Strain Gauge on Test Assembly



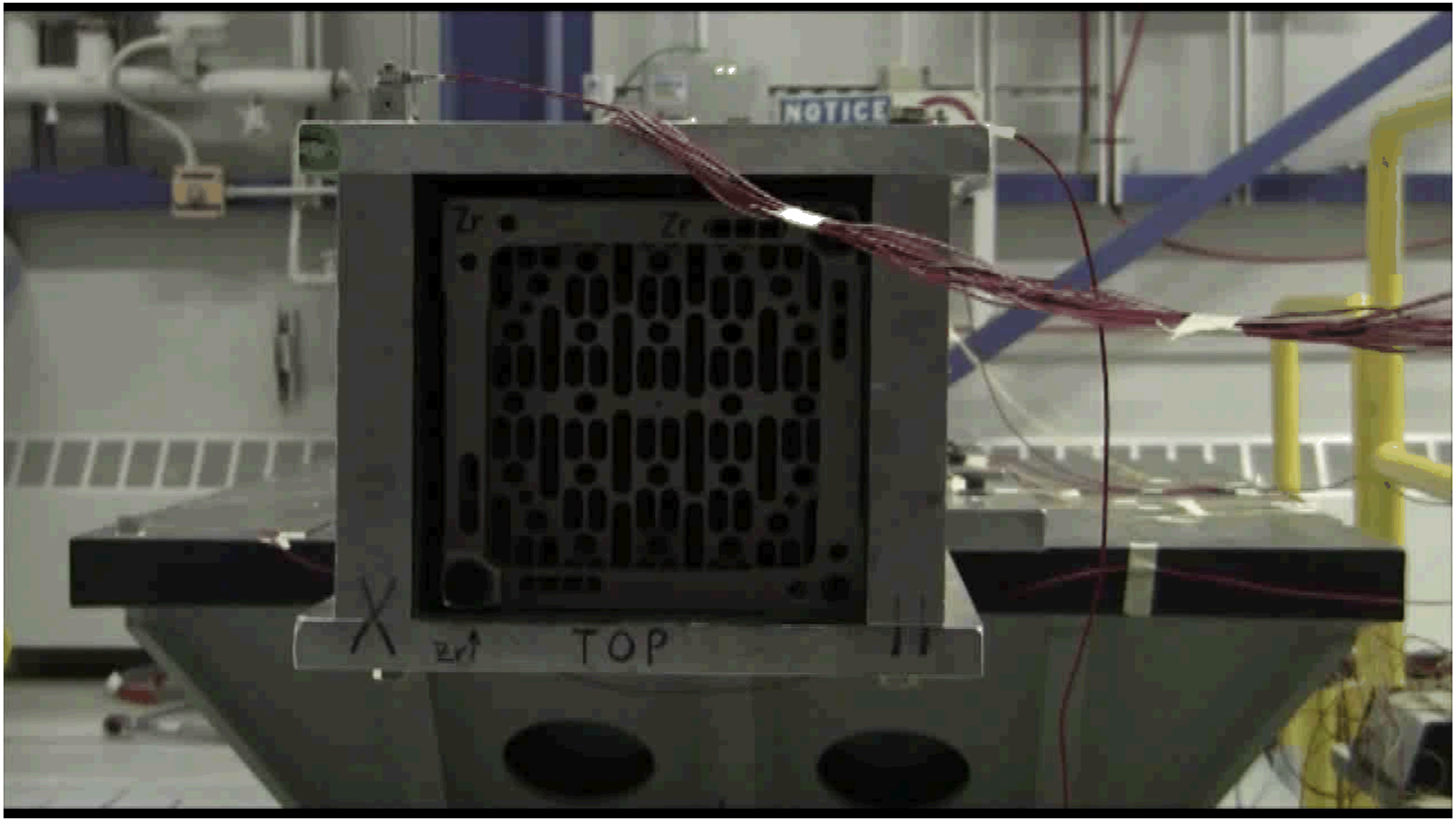
# Left: Accelerometers and Strain Gauge on Top-Center Zircaloy Tube and Spacer Grid
# Right: Assembly within Open Basket. Note the two Zircaloy-4 rods with instrumentation attached





# Shaker Shock Test Video

Top-end view of assembly in basket



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

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| 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

# Test Unit on Concrete Blocks on Trailer

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# Truck Test Route

## *65 km in Albuquerque area*

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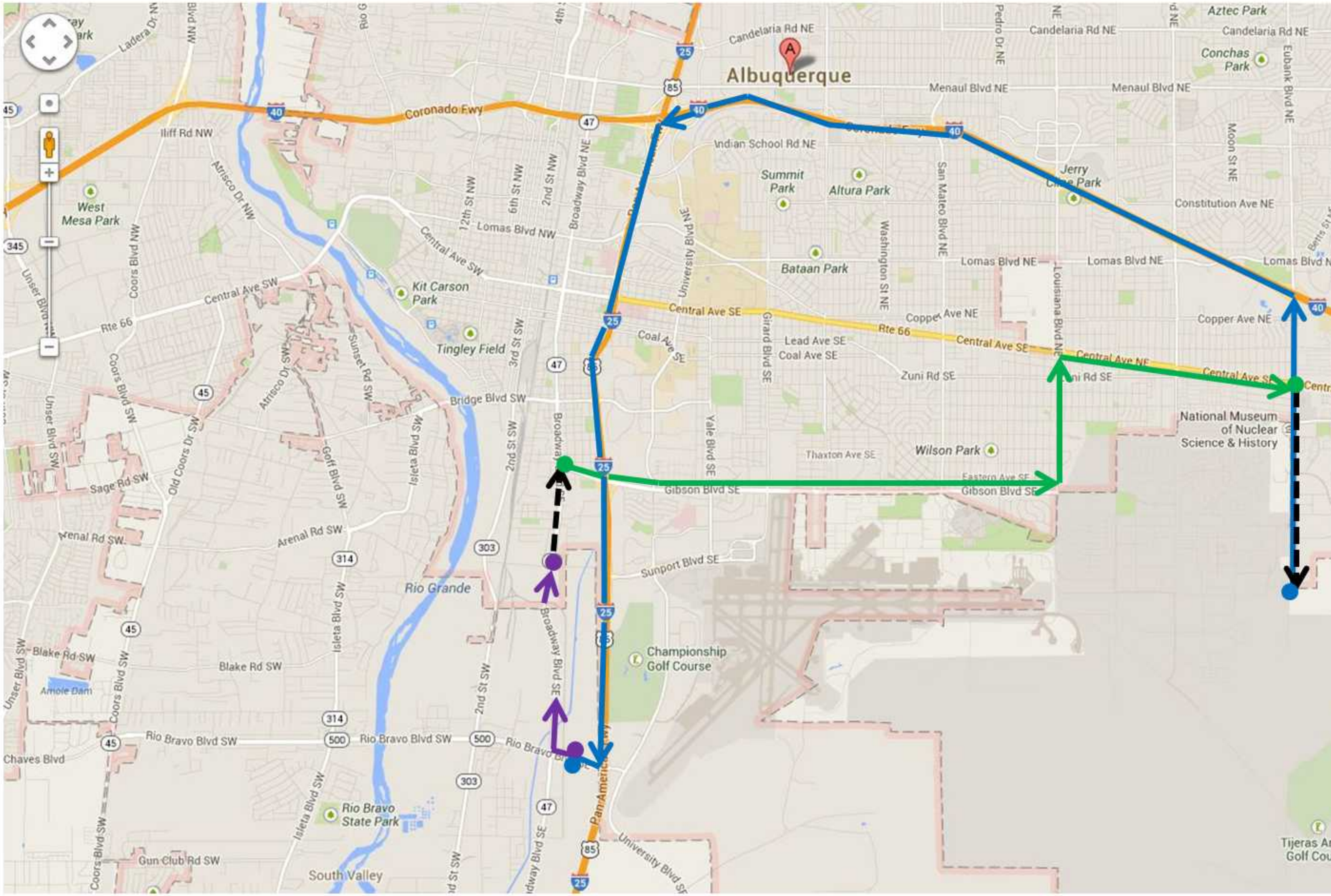
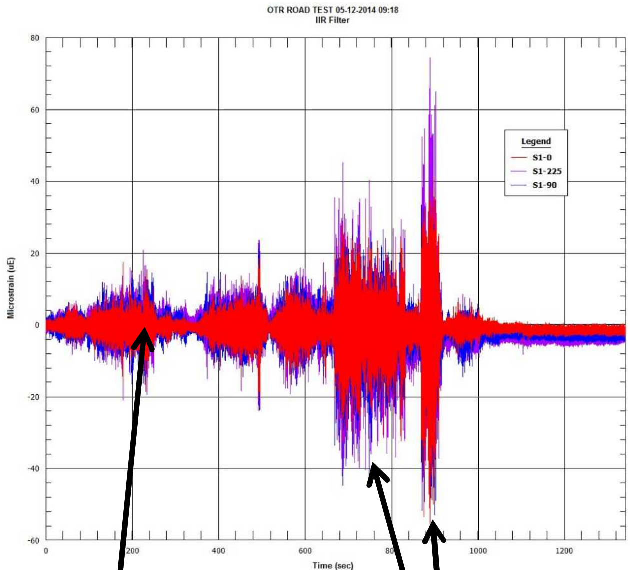


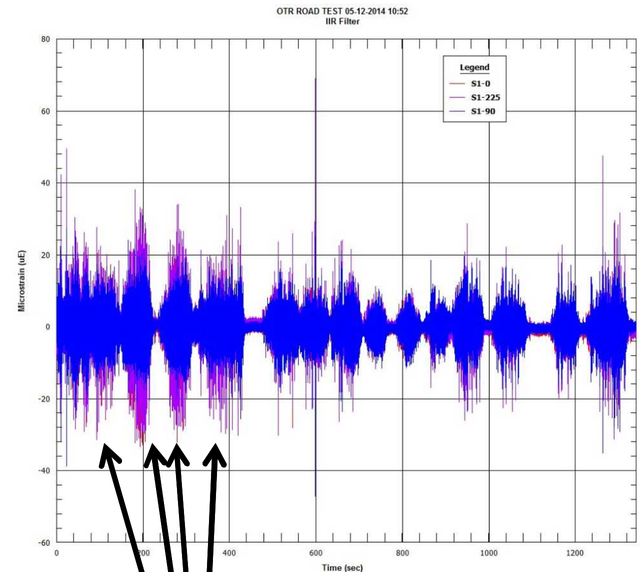
# Range of Road Conditions

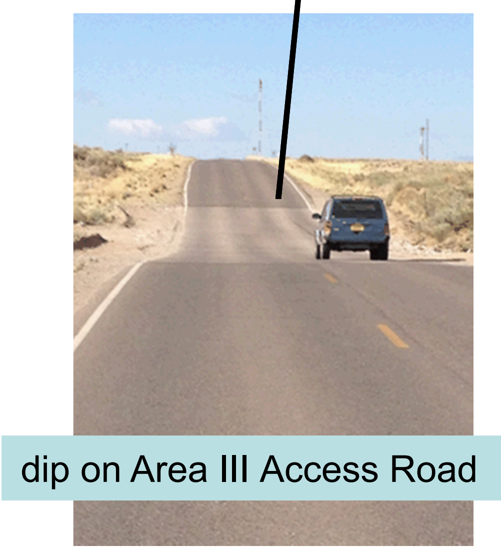
# Route included railroad crossings…

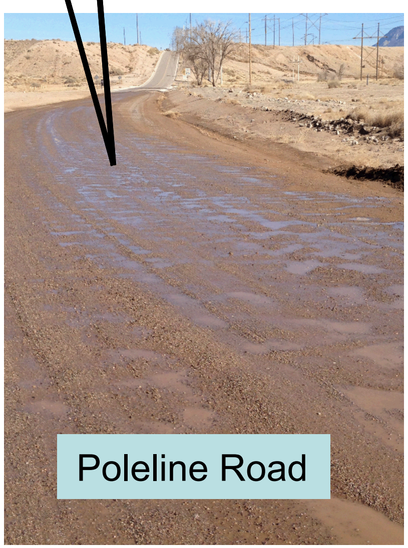
# …and rough dirt roads

# Strains measured on instrumented rod



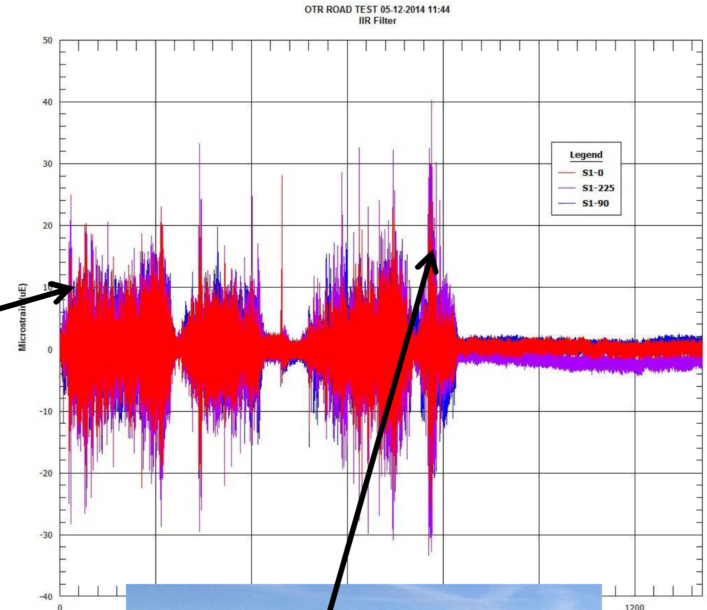





Strains correlated with road conditions

# Strains correlated to road surfaces


Pennsylvania St. bridge

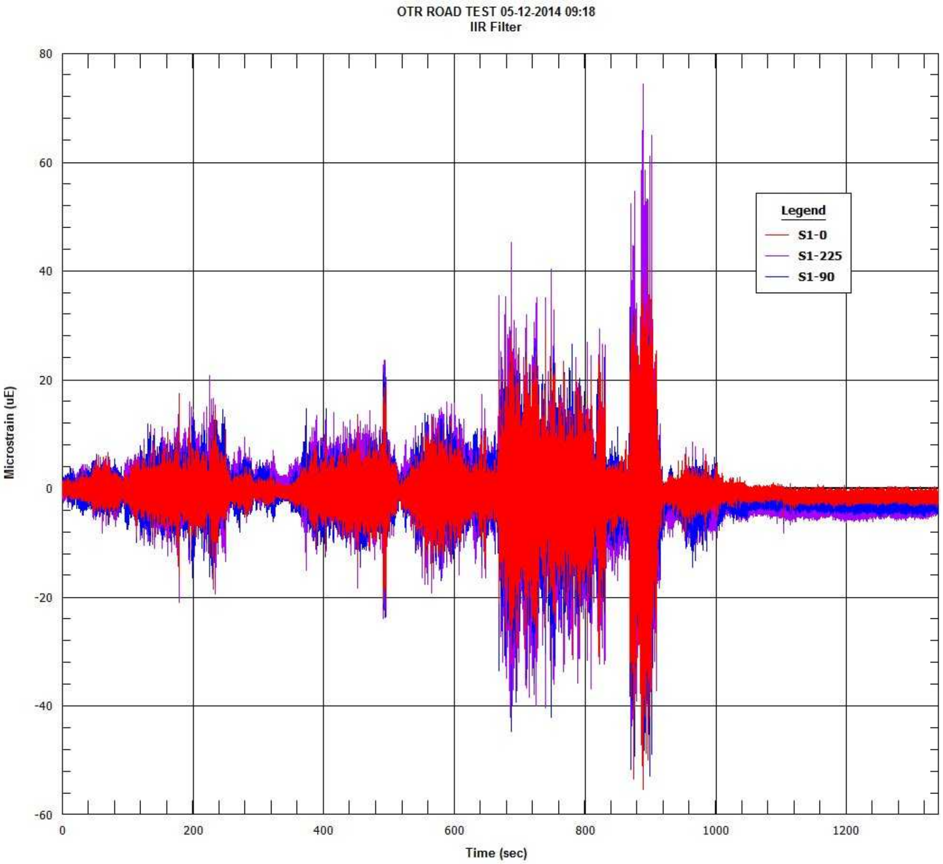


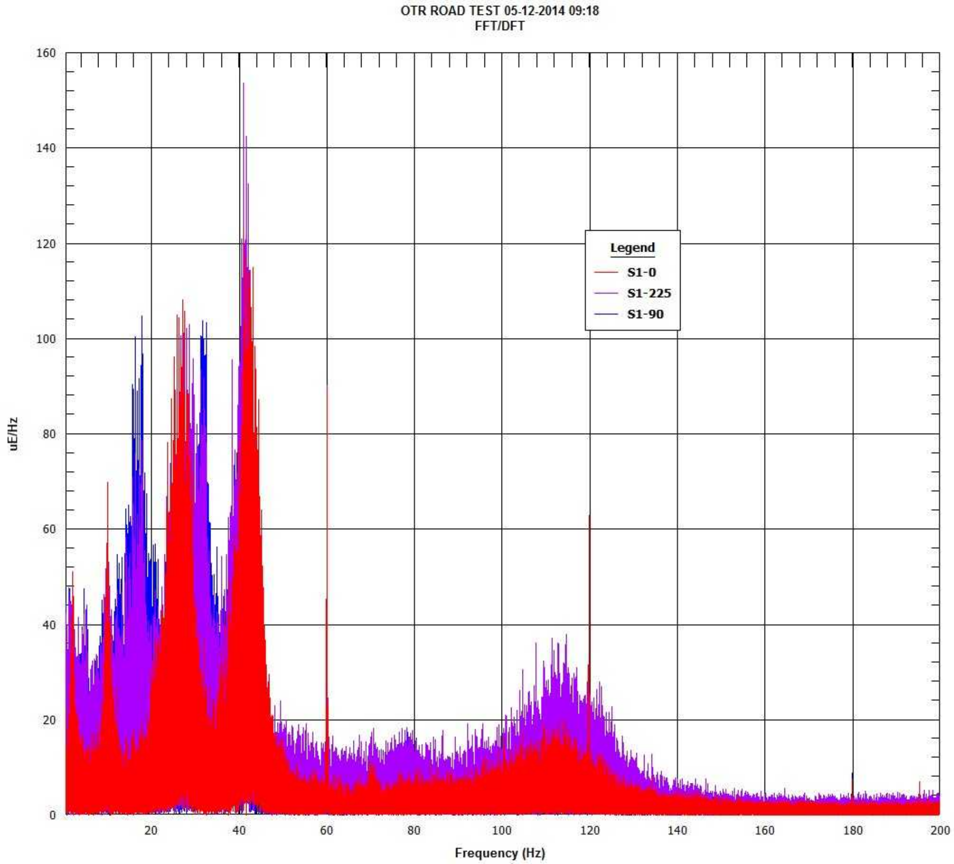


speeding to Building 6922


8-inch rut

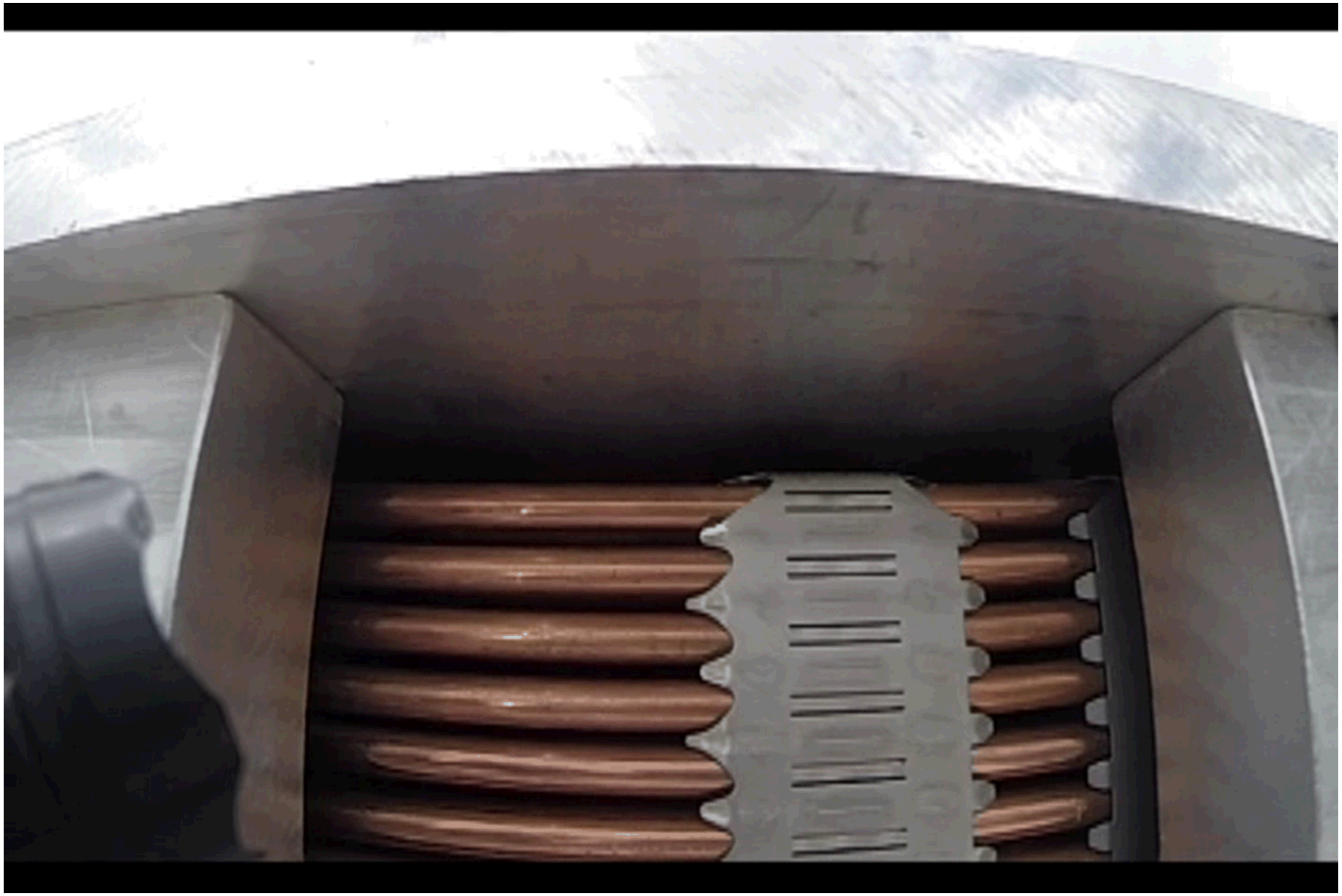
# Rod Strains and FFT
## *maximum strains occurred at low Hz*



# Side Basket Showing Cutout for Filming Assembly during Truck Test

# *Langweilig* Video of Assembly during the Truck Test

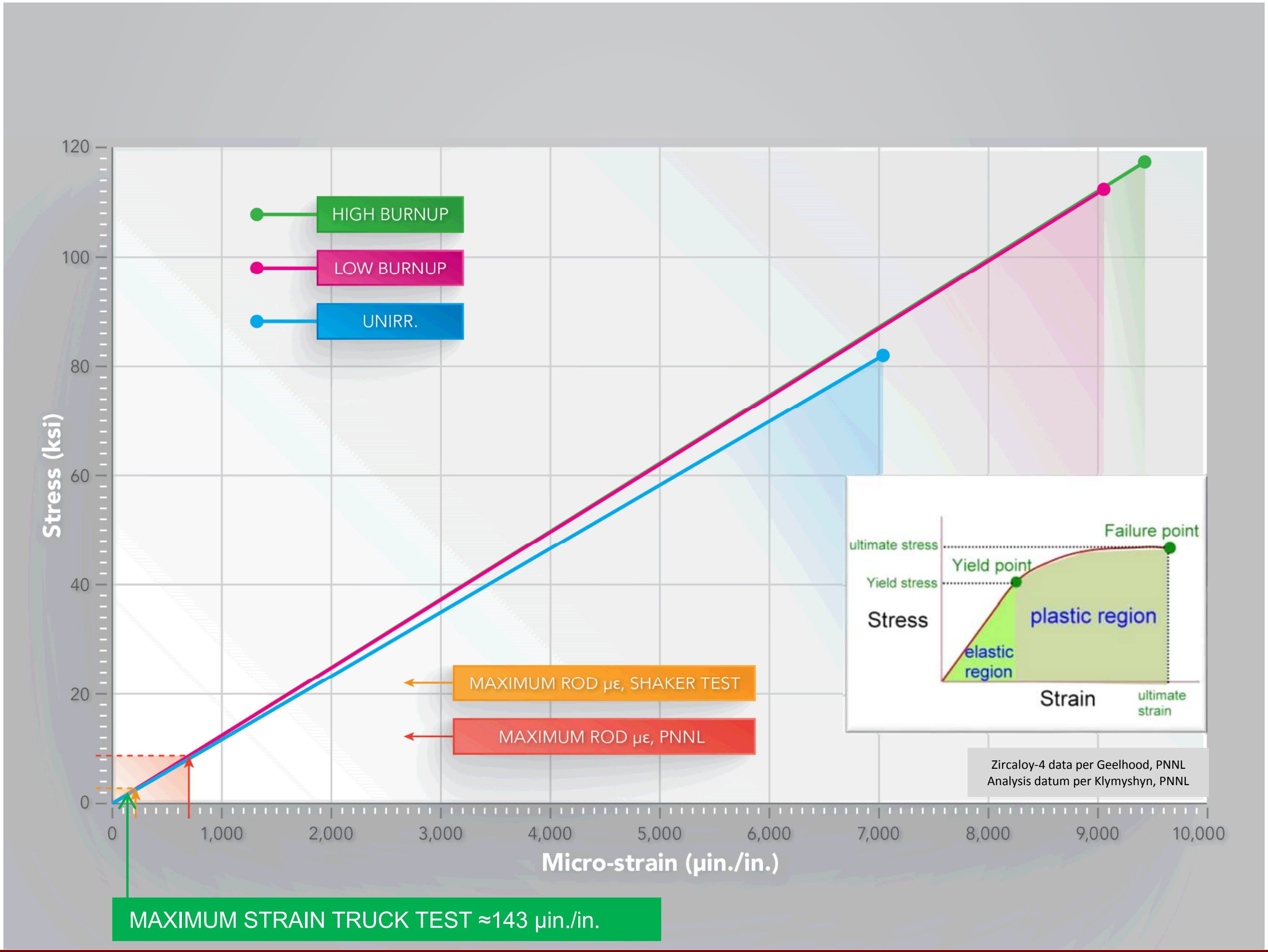


# Maximum Strains Measured during Truck Test *similar to shaker results*

| 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).

# Measured Strains are Very Low Relative to the Elastic Limit of Zircaloy-4



# Irradiated rods would experience lower strains during truck test than unirradiated tube

- **Bending stiffness (=EI) of high burnup irradiated Zircaloy-4 *with pellet-clad interaction* (per ORNL):**

  **$EI_{Zirc4\text{-}irr}$ = 52 N-m²** **(I based upon rod geometry)**

  **$E_{Zirc4\text{-}irr}$ = 83 – 101 GPa**

- **Bending stiffness of unirradiated Zircaloy-4 tube:**

  **$EI_{Zirc4\text{-}unirr}$ = 15.9 N-m²** **(I based upon tube geometry)**

  **$E_{Zirc4\text{-}unirr}$ = 99 GPa**

- **Bending stiffness Zircaloy-4 (irradiated rod/unirradiated tube) = 52/15.9 = 3.27**

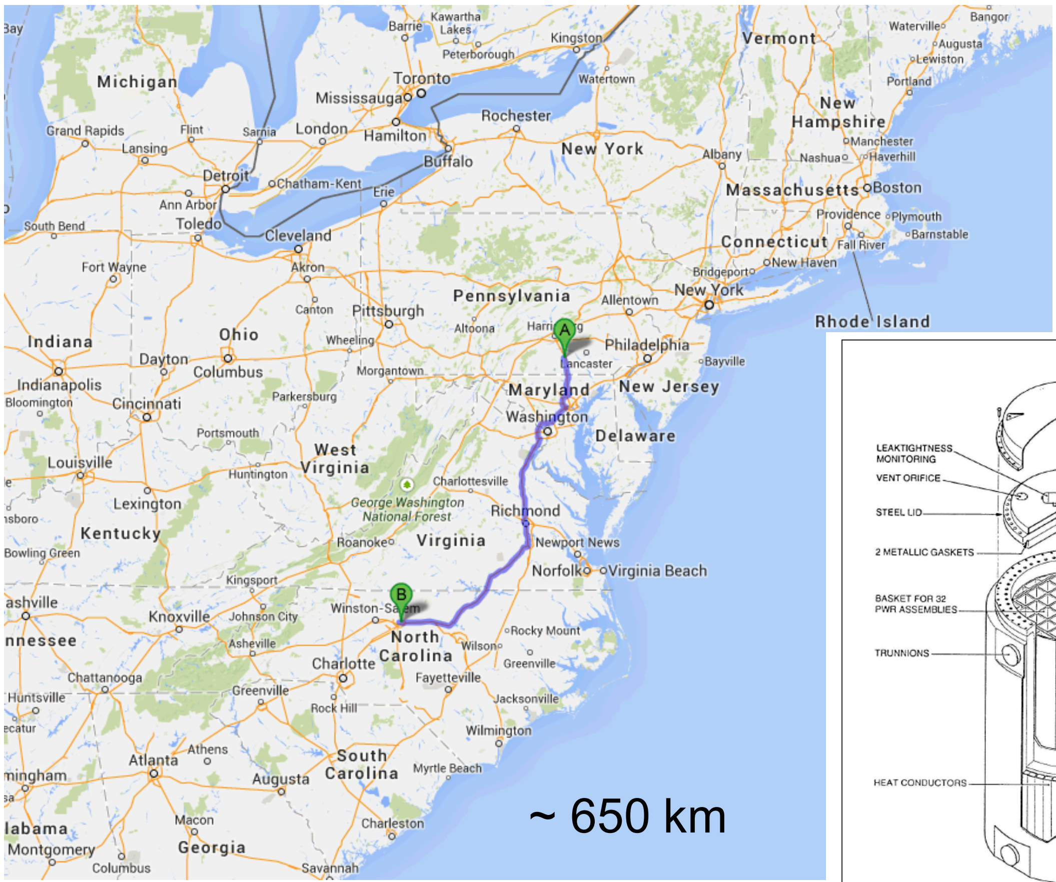
**This implies that for a given applied moment, strains on an irradiated rod would be approximately 0.3 (1/3.27) of those on an unirradiated Zircaloy-4 tube.**

**The maximum strain measured on the Zircaloy-4 tube in the truck test was 147μm/m, so for the same applied loads, the strain on an irradiated rod would be:**

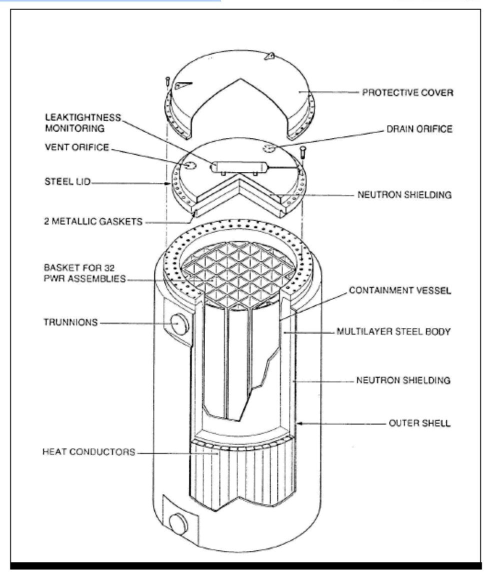
**147(15.9/52) = 45 μm/m**

# Rail Test Options

TN-32 cask transport from Pennsylvania to North Carolina




North Anna ISFSI




TN-32 Used Fuel Storage Cask

# Rail Test Options

- NLI-10/24 cask tests at Tri-City Railroad near PNNL

Augusta, Georgia

# TCRY Railyard
## Richland, Washington

- Controlled test environment
- Variety of track conditions
- Repeatability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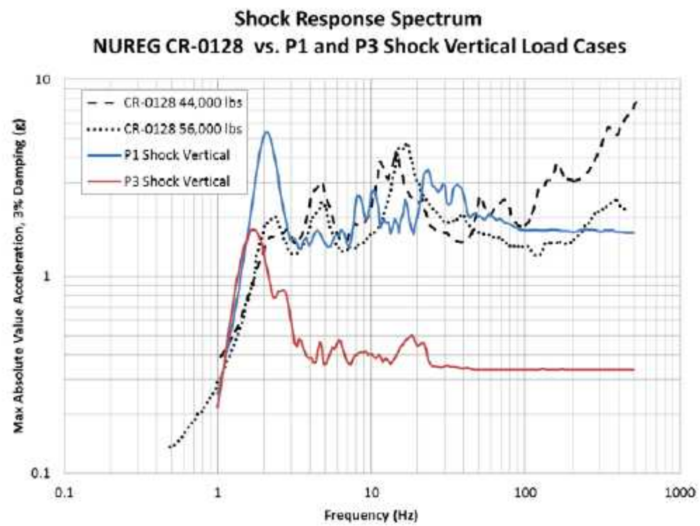
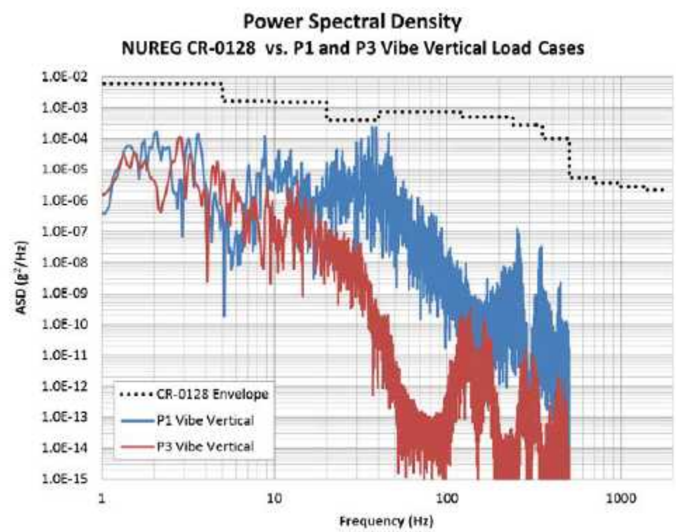



(a) Shock

Rail loadings less severe than truck loads




(b) Vibration

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

# Fracture Mechanics & Fatigue Assessments Based Upon Experimentally-Measured Strains

| Crack depth/Zircaloy wall thickness | Applied stress intensity at crack tip, (MPa-√m) | Lower bound Zircaloy-4 fracture toughness, (MPa-√m) |
|---|---|---|
| 0.10 | 0.3 | 20 - 30 |
| 0.25 | 0.4 | |
| 0.50 | 0.6 | |