U.S. DEPARTMENT OF ENERGY | Nuclear Energy

SAND2016-6551PE

# Normal Conditions of Transportation Questions

***NWTRB/DOE Cladding Discussion Meeting***

***Las Vegas, NV***

***July 12-14, 2016***

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2014-XXXX*

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

# How is the Shaker Table Testing 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) and “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 assembly, populated with rods, and placed within a surrogate truck-cask basket. Zircaloy-4 rods were filled with lead “rope” or lead pellets or Molybdenum pellets. They were instrumented with strain gauges and accelerometers.

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

The Sandia shaker tests simulated normal conditions of transport (NCT) truck shock and vibration. The DCL tests simulated NCT truck and rail shock and vibration.

# What are the results of the testing?

Strains on Zircaloy-4 rods when subjected to simulated NCT (truck or rail) were consistently very low – well below the elastic limit of the alloy.

Maximum strains were typically 100 – 300 μm/m for shock and typically below 10 μm/m for NCT vibration.

# How does this testing integrate the road, rail, and fatigue testing and input to the structural modeling?

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 cased fatigue failure in the ORNL tests.

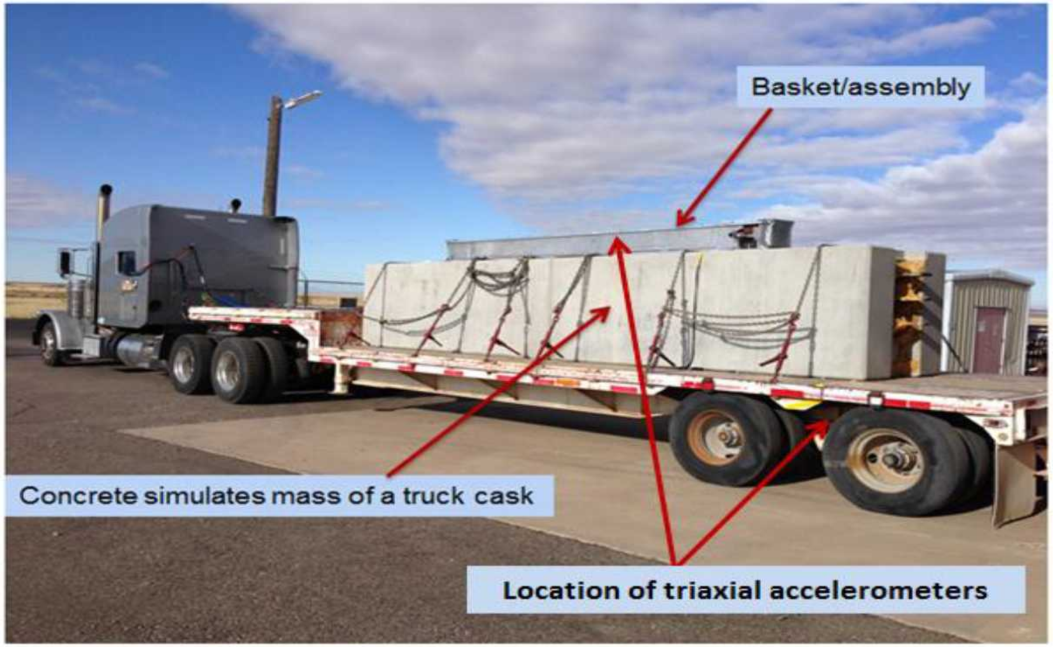
| ORNL Zircaloy-4 fatigue test data | | | | | | |
|---|---|---|---|---|---|---|
| Specimen | Burnup (GWd/MTU) | Applied bending moment (N-m) | Curvature of rod ($m^{-1}$) | Strain on rod (μm/m) | Fatigue cycles $x10^6$ | Rod Failure? |
| D2 | 63.8 | 5 | 0.16 | 862 | 6 | NO |
| D4 | 66.5 | 7.6 | 0.23 | 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 $x10^6$

# Give a physical description of the surrogate cask and fuel used in the road tests

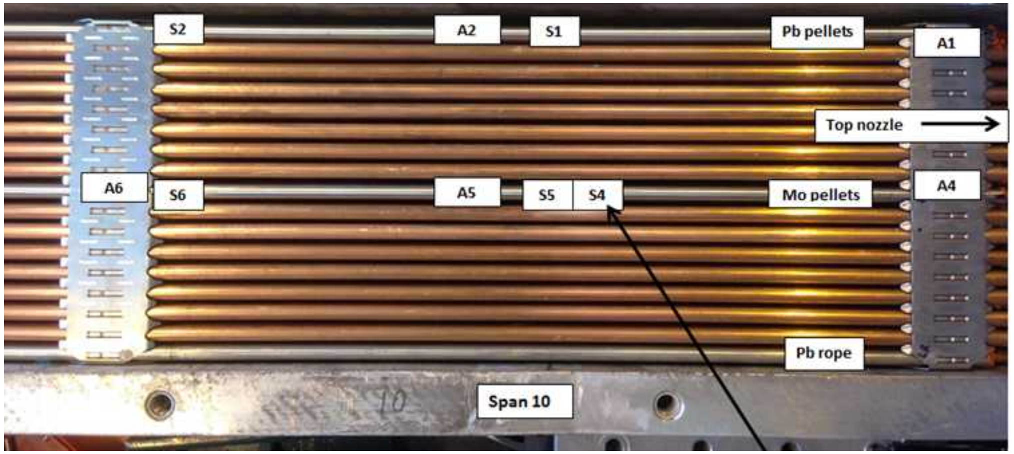
- The truck test is described in "Normal Conditions of Transport Truck Test of a Surrogate Fuel Assembly", SAND2014-20495, FCRD-UFD-2014-000066, Revision 0.1, December 15, 2014.
- The assembly used in all tests was an surrogate 17 X 17 PWR assembly, populated with three Zircaloy-4 tubes. The remaining tubes were copper. All the tubes were filled with material to simulate the mass of fuel.
- These tubes were instrumented with strain gauges and accelerometers.



# What modeling was done before the shaker table and road tests to determine what to do?

- PNNL modeled the assembly and rods before the first set of tests. Their analyses indicated that all the rods within the assembly would experience similar strains during testing and so the position of the rods within the assembly which were instrumented was arbitrary.

- The modeling did indicate that strains may be higher near spacer grids. Accordingly, in all tests strain gauges on a given rod were placed near spacer grids and at the mid-span between spacer grids.



# How were decisions made on the assembly design?

***The purpose of the first test was to see where vibration and strain data compare to yield points.***

- Sandia had 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 lead rope **since simulating the weight of uranium oxide was the primary factor** for simulating 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/cm³) | 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) | | | | |

# *What are the effects of compromises of design?*

No significant differences in the strains measured on rods within the surrogate assembly and those that rods in an actual irradiated assembly would experience are anticipated.

***However, a validated model could ultimately resolve this question.***

# What is the relationship between the shaker table tests and the truck test?

- The shaker table tests were conducted using inputs for truck and rail tests based on shock and vibration data obtained from published data on accelerations during truck or rail transport.

- The truck test was a measure of actual shocks and vibrations experienced by the assembly on a truck trailer.

- Test results from all three sets of tests were essentially identical.

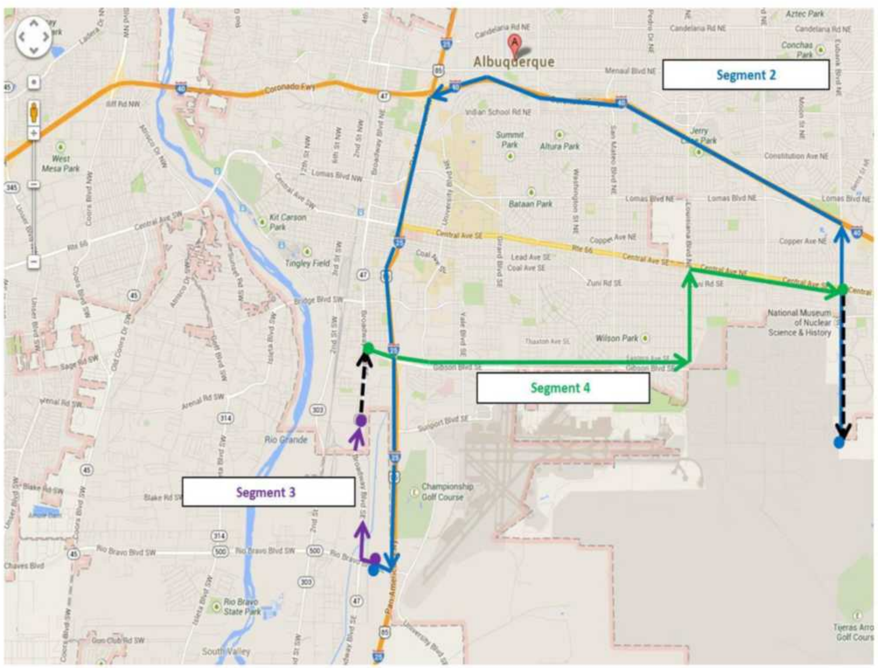
| Strain Gauge ID | Location on Assembly: Adjacent to first spacer grid, Span 5 | Sandia Shaker Truck Shock Test Maximum Strain Absolute Value (μin/in) | Truck Test Maximum Strain Absolute Value (μin/in) | DCL Shaker Truck Shock Test Maximum Strain Absolute Value (μin/in) |
|---|---|---|---|---|
| S3 - 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 |

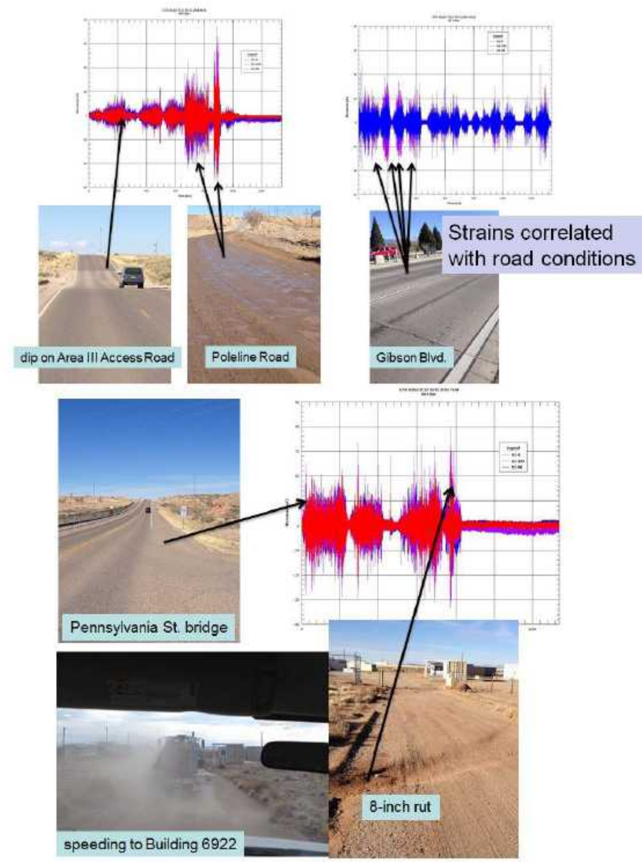
# What are the differences between the physical, chemical, and mechanical properties of the surrogates and the real transportation components?

- Everything in out test was unirradiated.
- The assembly had only three Zircaloy-4 rods. The remaining rods were copper. The Zircaloy-4 rods were filled with either lead rope, lead pellets, or molybdenum pellets.
- The Zircaloy rods were instrumented. The assembly was in a surrogate truck-cask basket, but not within a cask.

# What instrumentation was used and what variables were measured at what locations during the tests? How where the road tests conducted?

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.



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# What were the results of the tests? How would you expect the results to differ if the surrogate was set to represent a different system?

A different surrogate test configuration would likely yield low strains just as with the configuration used. Modeling can resolve this issue.

**Table 5.1 Strain gauge maximum values for truck test**

| Strain Gauge | Location on Assembly | Maximum Micro-strain Absolute Value (μin./in.) | Road Segment |
|---|---|---|---|
| S1 - 0° | Adjacent to first spacer grid, Span 10 | 55 | 1 |
| 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 | 1 |
| Average 90° | | 83 | |
| Average 225° | | 90 | |

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

# Describe the upcoming testing with the Spanish cask. What components will be actual components and which ones are surrogates? What are the tradeoffs?

- An actual rail-cask with a basket and two actual assemblies with instrumented rods will be used.
- Tests will include heavy-haul truck, intercoastal ship, trans-oceanic ship, and rail transport modes.
- Data will also be collected during transfer of the cask from one transport platform to another.
- Data will be collected to simulate positioning the cask onto an ISFSI pad.
- We will not be testing on a 2043 rail car because none exist, but the railcar we will use will create a ride with greater shocks and vibrations.

# Give a description of the testing route with dates.

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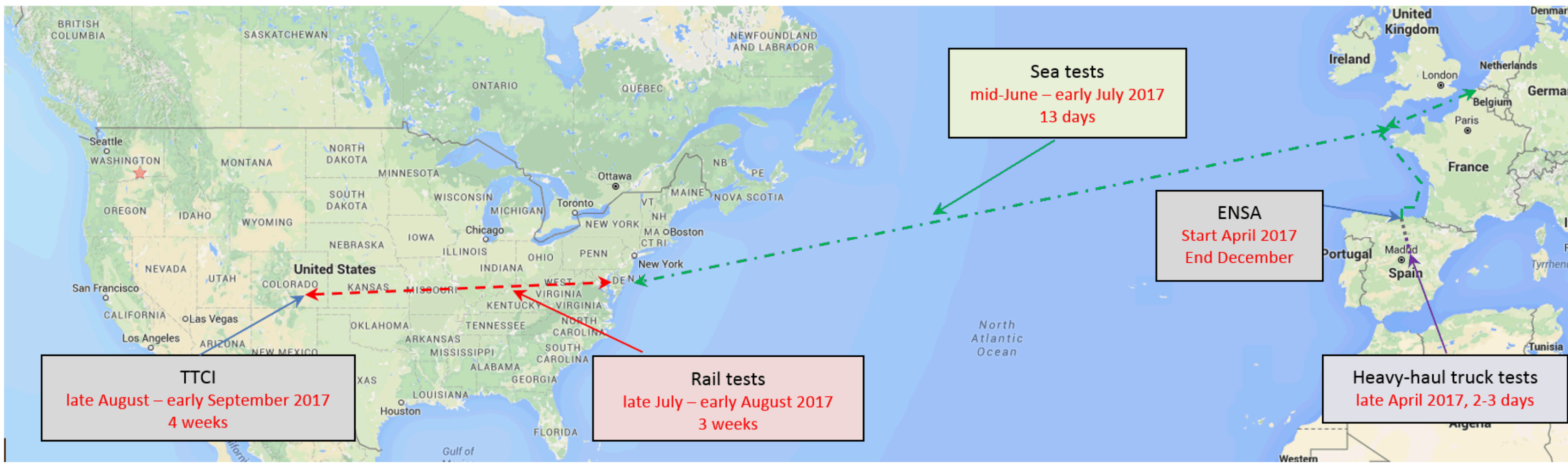
***April – September 2017.***
***We must send the cask back to ENSA by Thanksgiving 2017.***



# What instrumentation will be used? Where will it be placed, and when will data be gathered?

- Two surrogate unnirraditated assemblies will be in the 32-cell rail-cask basket.
- Each assembly will have rods instrumented with strain gauges and accelerometers. The basket, cask, cradle, and transport platform (e.g., rail car) will be instrumented with accelerometers.
- The most sensitive strain gauges and accelerometers that can fit in the space limitations will be used.
- Modeling results will determine the placement of the accelerometers and strain gauges.
- Data will be collected essentially continuously. Data will be available for analysis at the point of each transport-mode transfer.

# What are the expected results of the tests?

- Low strains during road and rail tests.
- Possible higher shocks during trans-oceanic shipment, but still below yield point.
- Possibly higher shocks during transfer operations, but still below yield point.