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Sandia Shaker Table and Over-the-Road Vibration Studies

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NUCLEAR WASTE TECHNICAL REVIEW BOARD
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Tests simulated normal conditions of transport to measure strains on fuel rods in a surrogate assembly

SNL Shaker 2013	Over-the-Road Truck 2014	DCL Multi-Axis Shaker 2015
 Normal Conditions of Transport Truck	 Normal Conditions of Transport Truck	 Normal Conditions of Transport Truck and Rail

All tests used a surrogate PWR assembly which was placed within a surrogate truck-cask basket.

The assembly and rods were instrumented with strain gauges and accelerometers.

Comparison of test parameters for each set of tests

SNL Shaker	Over-the-Road Truck Test	DCL Multi-axis Shaker
Truck NCT shock and vibration: • Loadings taken from NUREG/CR-0128: "Shock and Vibration Environments for a Large Shipping Container During Truck Transport" • **Simulated mass of an assembly and truck basket** • **Vertical accelerations only** • **6 vibration / 5 shock tests** • **≥ 3 Hz to 2000 Hz**	**Over-the-road truck test:** • **Simulated over-the-road test to compare strains with the shaker table tests** • **Simulated mass of a truck cask** • **Conducted test over 40 miles to simulate various road conditions and speeds**	**Multi-axis (6) shaker tests:** • **Truck NCT shock and vibration: NUREG/CR-0128** • **Rail NCT shock and vibration: constructed load vibration and shock data from TTCI to simulate railcar-deck loading expected on the S-2043 rail car** • **Filled lead pellets and Mo pellets into two Zircaloy rods to better simulate fuel** • **Six degrees shaker table motion** • **5 truck shock / 5 truck vibration** • **5 rail shock / 5 rail vibration** • **rail coupling shock** • **<1 Hz to 100 Hz**

Multi-axis shaker tests

Simulated rail shock

Non-normal transport condition

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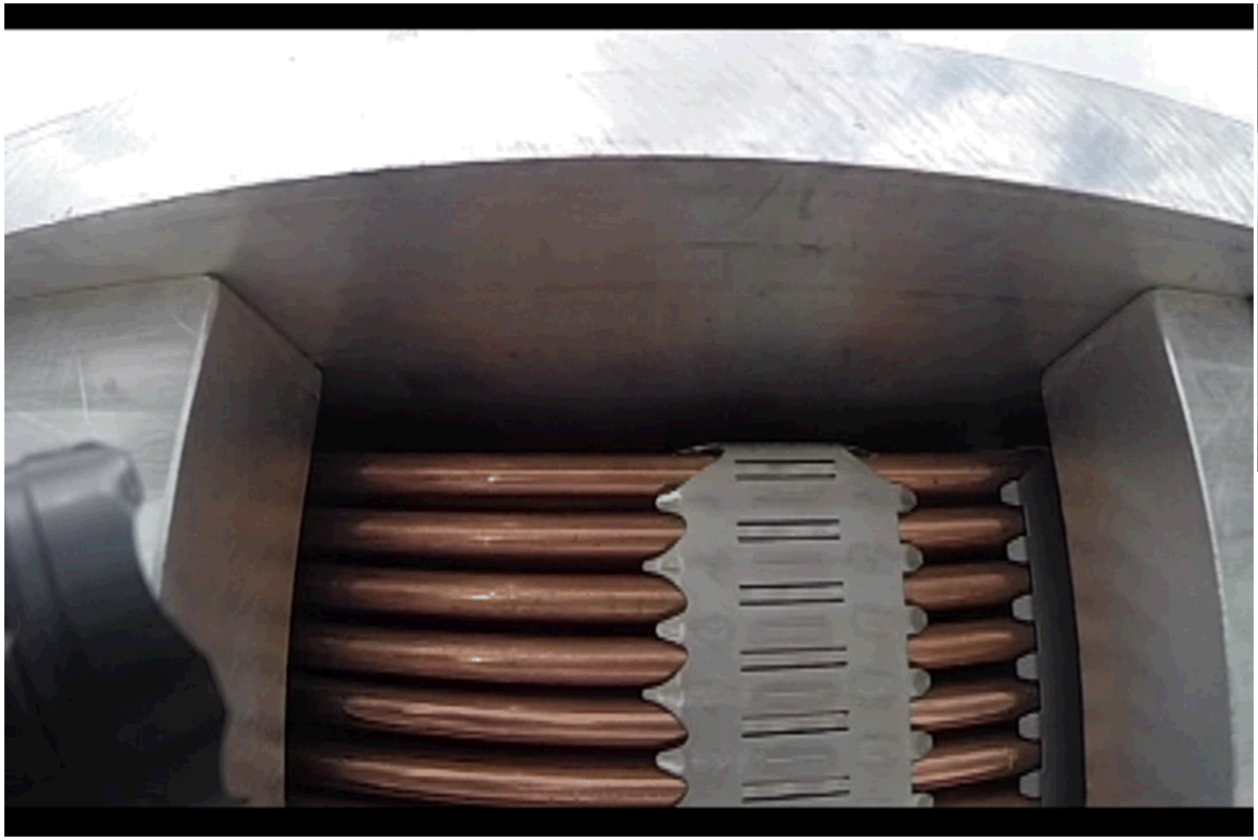
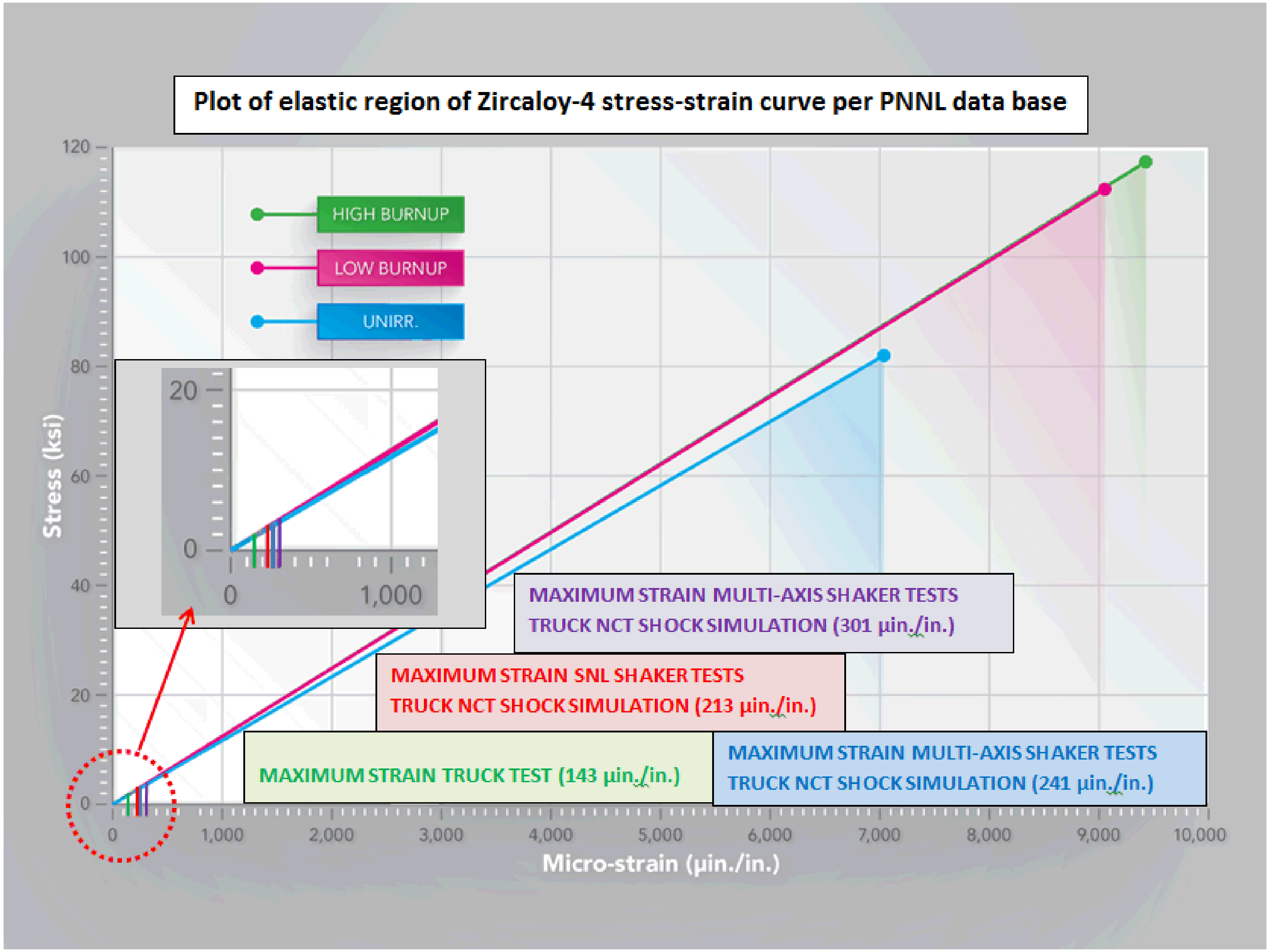
Over-the-road truck test video



Maximum strains measured in all three series of tests

Strains on Zircaloy rods were very low in all tests

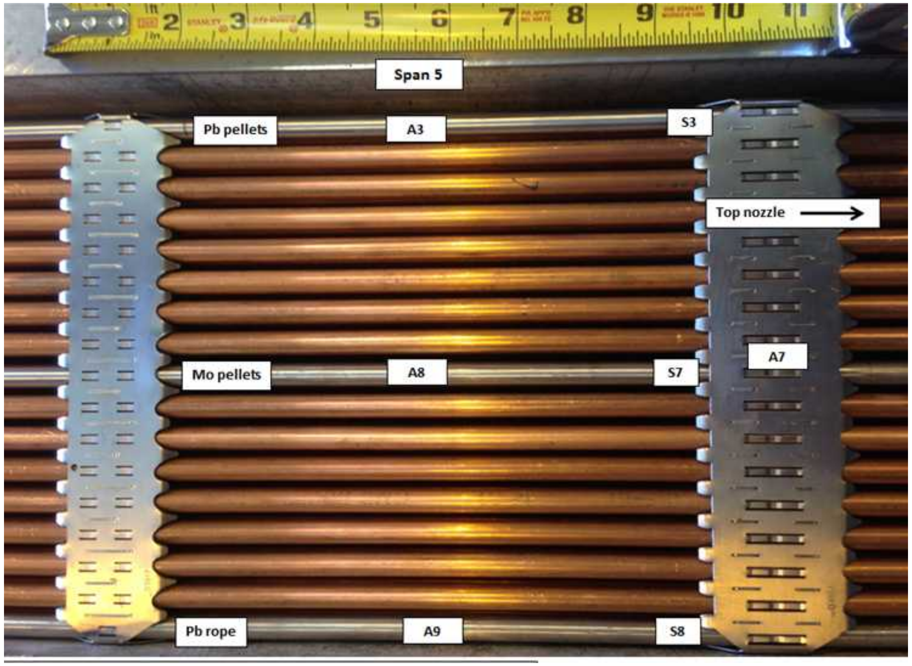


Comparison of strains from all three test series at *similar locations* on assembly: strains essentially identical in all tests

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

Comparison of 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

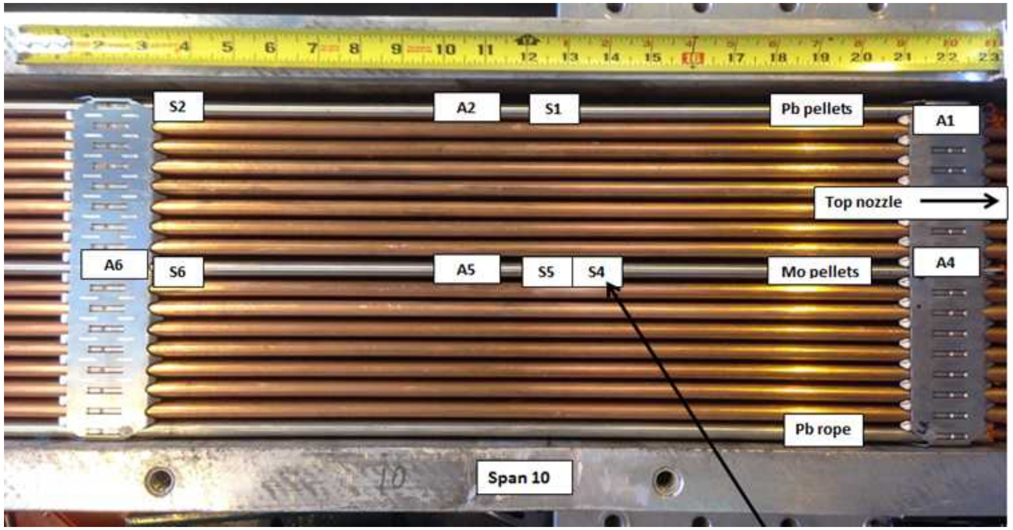


TEST 10xyz-3 Rail coupling	Pb-"rope" rod	Mo-pellet rod	Pb-pellet rod
	S8	S7	S3
0°	130	91	104
90°	82	34	30
225°	208	47	77

Comparison of 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



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Fatigue assessment:

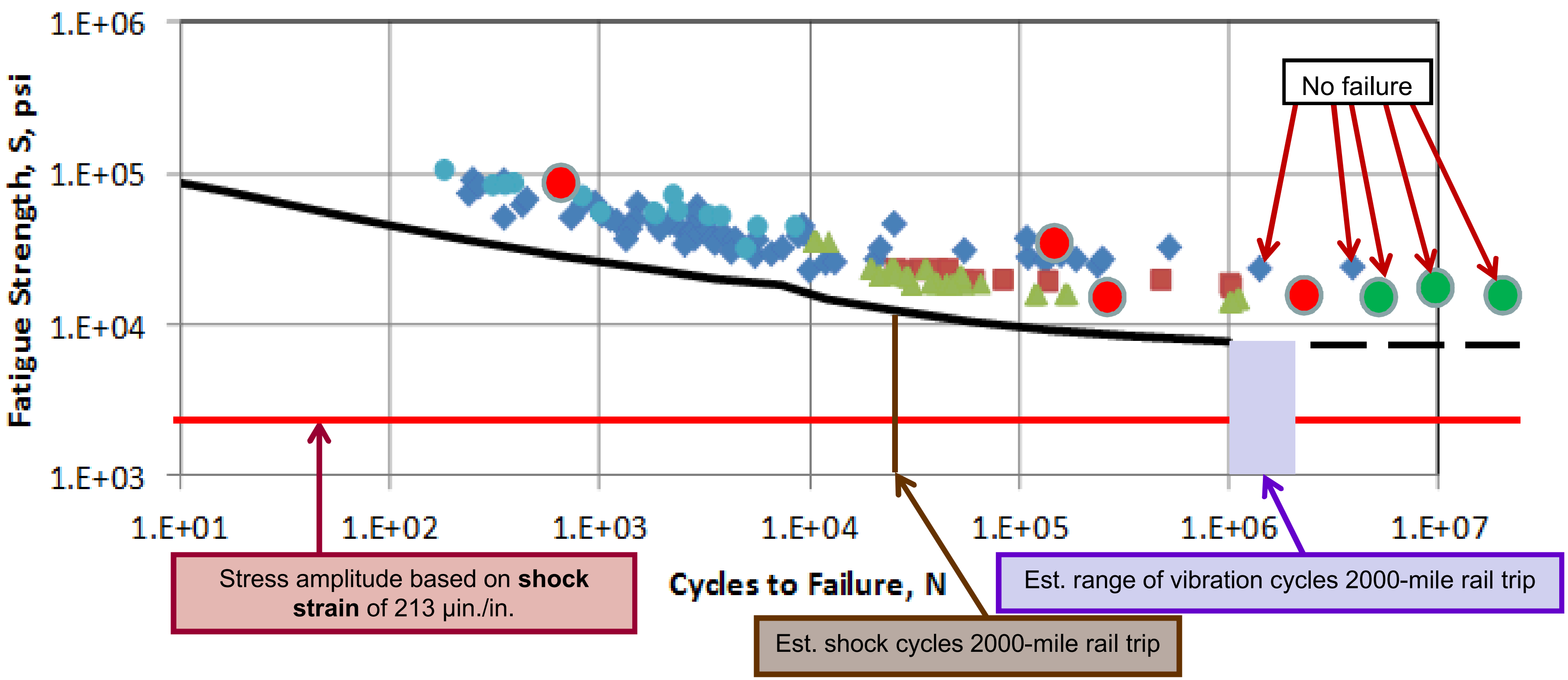
Bending moments applied in ORNL irradiated fuel tests exceed NCT bending moments

Selected ORNL HB Robinson Zircaloy-4 fatigue test data							
Specimen	Burnup (GWd/MTU)	Applied Bending Moment, M (N-m)	Curvature, (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			

Question: How many cycles to failure for a bending moment of 0.7 N-m, which approximates NCT?

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).

This curve and the data points were generated with irradiated Zircaloy with circumferential hydrides. It is also considered valid for irradiated Zircaloy with <u>radial hydrides if the material is above the DBTT</u>.

The large circles are ORNL HBR data.

What these tests tell us:

- The strains measured on the rods during the NCT test simulations were in the micro-strain levels – well below the elastic limit for irradiated Zircaloy-4
- Fatigue during transport does not appear to be an issue
- Based upon the test results, which simulated normal vibration and shock conditions of truck and rail transport, failure of fuel rods during normal transport seems unlikely

However,

These tests…

…are only simulations of the configuration of actual UNF transport modes , i.e.:

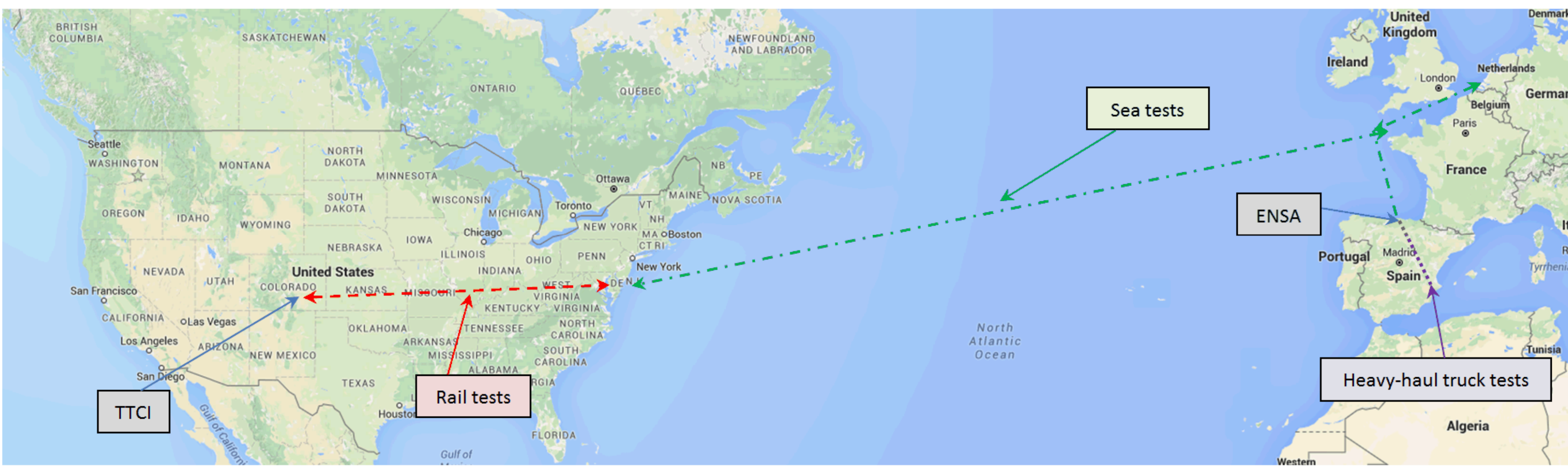
Potential international multi-transportation mode tests with a rail cask

- **Spanish-government company *Equipos Nucleares* (ENSA) will provide an ENUN 32P rail cask, basket, and cradle for an international test program**
  - The ENUN 32P is similar to an existing NRC-licensed cask currently in use in the USA

- **Testing to be conducted by DOE laboratories**
- **These tests are significantly different than the previous tests:**
  - instrumented surrogate assemblies will be…
    - within a rail-cask basket which is…
    - within an actual rail cask which will be on…
      1) a heavy-haul truck, and
      2) two different ships, and
      3) a railcar

Potential international multi-transportation mode tests with a rail cask

- **Heavy-haul truck tests in Spain** (ENSA participation)
- **Sea transport tests between Spain and USA** (both directions)
- **Trans-continental rail tests within USA** (both directions; not on a S-2043 railcar)
- **Special rail tests at AAR's Transportation Technology Center, Inc.**
- **Same cask, instrumented assemblies, & data acquisition system for all tests**
- **Data to be collected continuously**



Potential international multi-transportation mode tests with a rail cask

The ENSA-cask tests would:

- **provide data for all transport modes** (road, rail, sea)
- **add to the library of NCT rail and truck loadings**
- **reduces uncertainty in the existing data by testing under more real-life conditions**
- **support future licensing and transport of high burnup UNF** (e.g., demo cask)
- **eliminate many of the compromises inherent to the previous tests**