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International Multi-Modal Surrogate Spent Nuclear Fuel Transportation Test: The SNF Transportation Test Triathlon

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PRESENTED BY

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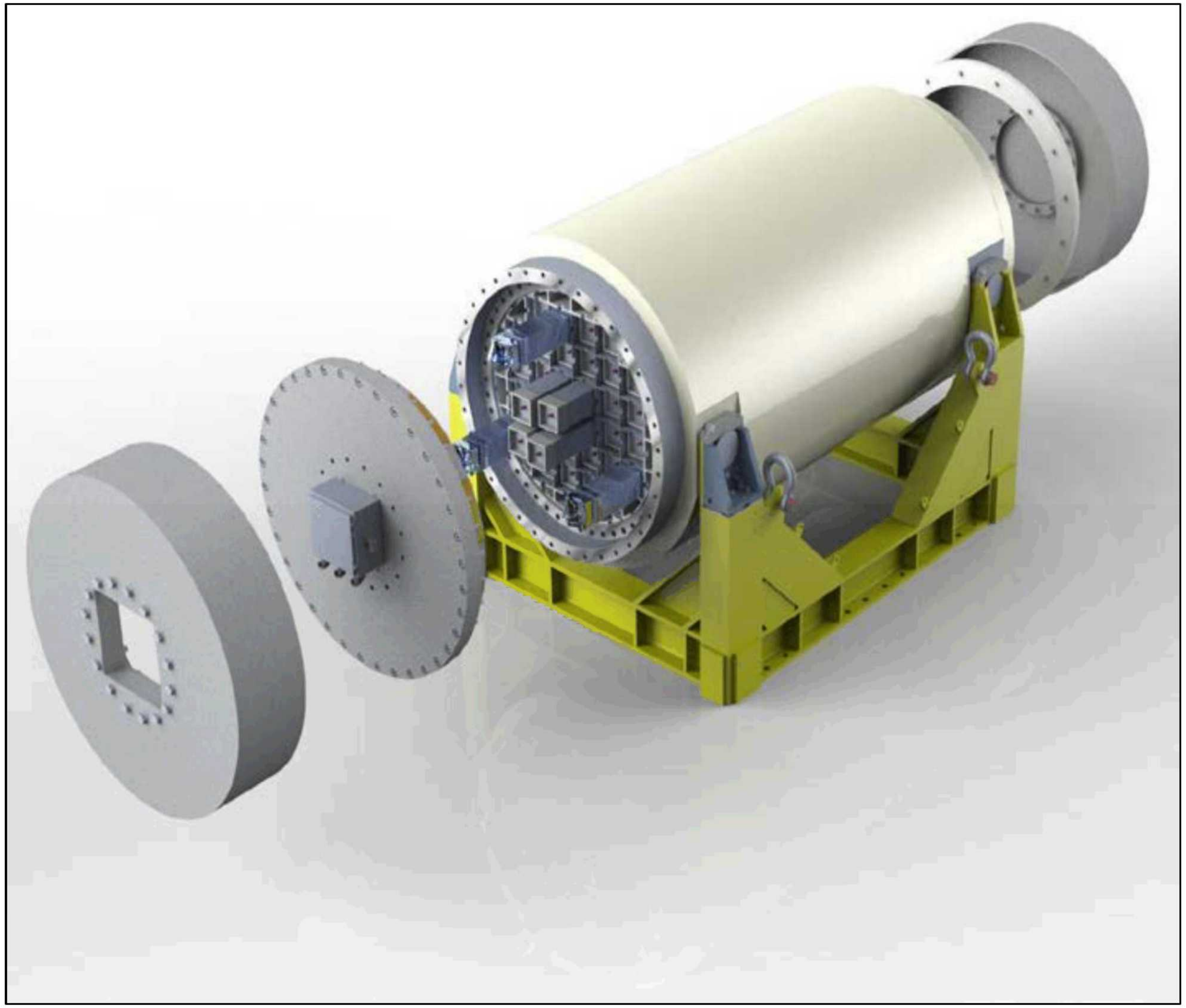
Collaborators

- U.S. Department of Energy
- Pacific Northwest National Laboratory (PNNL)
- Equipos Nucleares Sociedad Anónima (ENSA)
- Korea Hydro and Nuclear Power (KNNP)
- Korea Radioactive Waste Agency (KORAD)
- Korea Atomic Energy Research Institute (KAERI)
- Coordinadora Internacional de Cargas, S.A.
- Empresa Nacional de Residuos Radiactivos S.A. (ENRESA)
- ENUSA Industrias Avanzandas S.A.
- Transportation Technology Center, Inc. (TTCI)
- Sandia National Laboratories (SNL)

Link to video documenting the major test events: https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be

Test System Characteristics

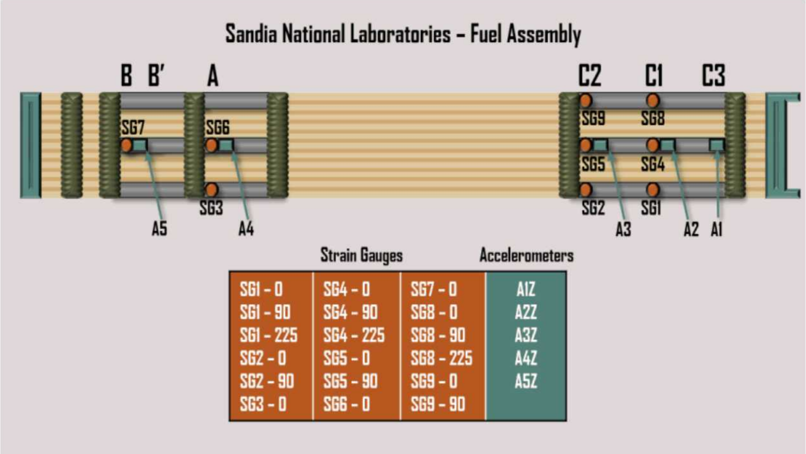


The ENUN-32P cask was used

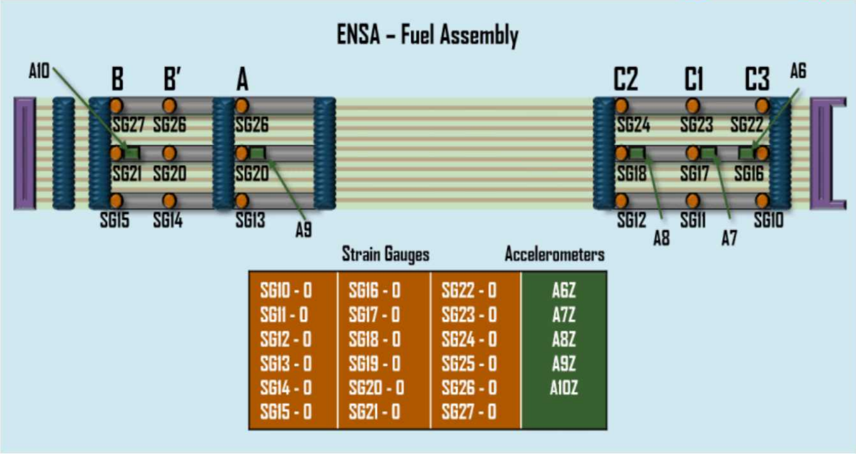
- Length: 5 m
- Body diameter: 2.65 m
- Loaded weight of carbon steel cask: 120 tons
- Loaded weight with surrogate impact limiters: 137 tons

Purpose: Quantify Strain and Acceleration on Surrogate Fuel Rods During Normal Conditions of Transport

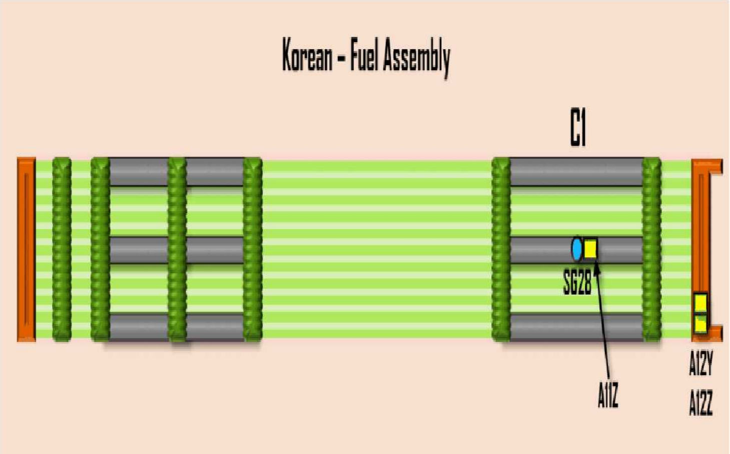
40 accelerometers, 37 strain gauges

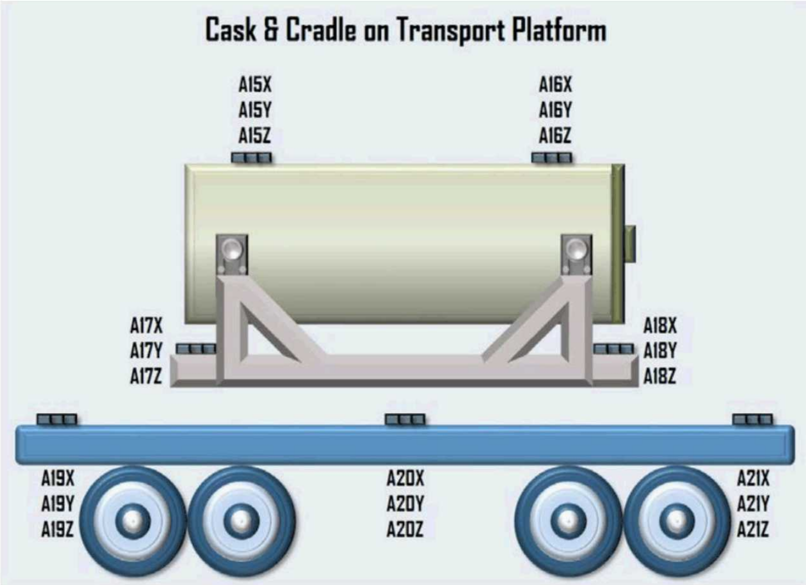


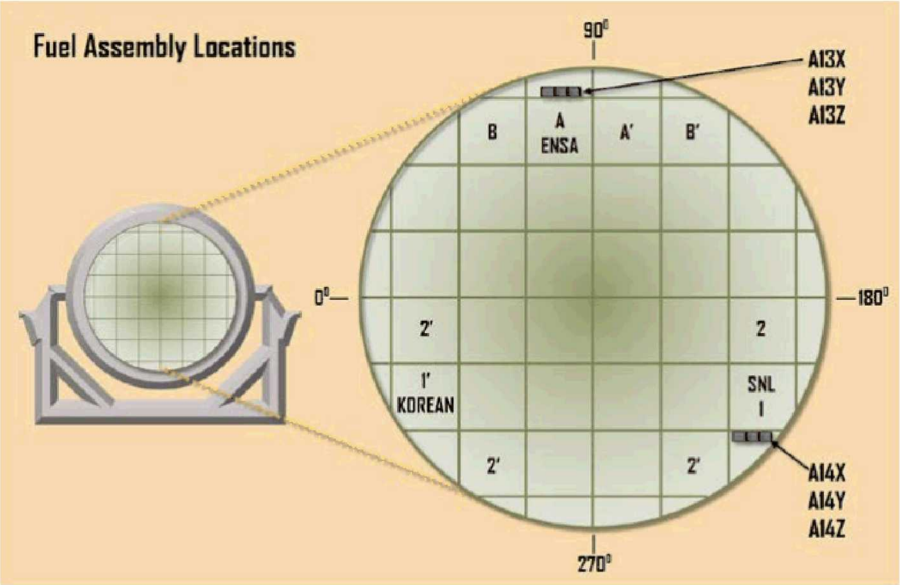
Strain Gauges			Accelerometers
SG1 - 0	SG4 - 0	SG7 - 0	A1Z
SG1 - 90	SG4 - 90	SG8 - 0	A2Z
SG1 - 225	SG4 - 225	SG8 - 90	A3Z
SG2 - 0	SG5 - 0	SG8 - 225	A4Z
SG2 - 90	SG5 - 90	SG9 - 0	A5Z
SG3 - 0	SG6 - 0	SG9 - 90	

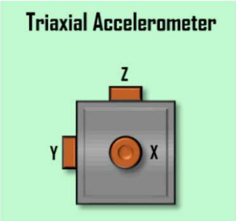


Strain Gauges			Accelerometers
SG10 - 0	SG16 - 0	SG22 - 0	A6Z
SG11 - 0	SG17 - 0	SG23 - 0	A7Z
SG12 - 0	SG18 - 0	SG24 - 0	A8Z
SG13 - 0	SG19 - 0	SG25 - 0	A9Z
SG14 - 0	SG20 - 0	SG26 - 0	A10Z
SG15 - 0	SG21 - 0	SG27 - 0	









Images not to scale

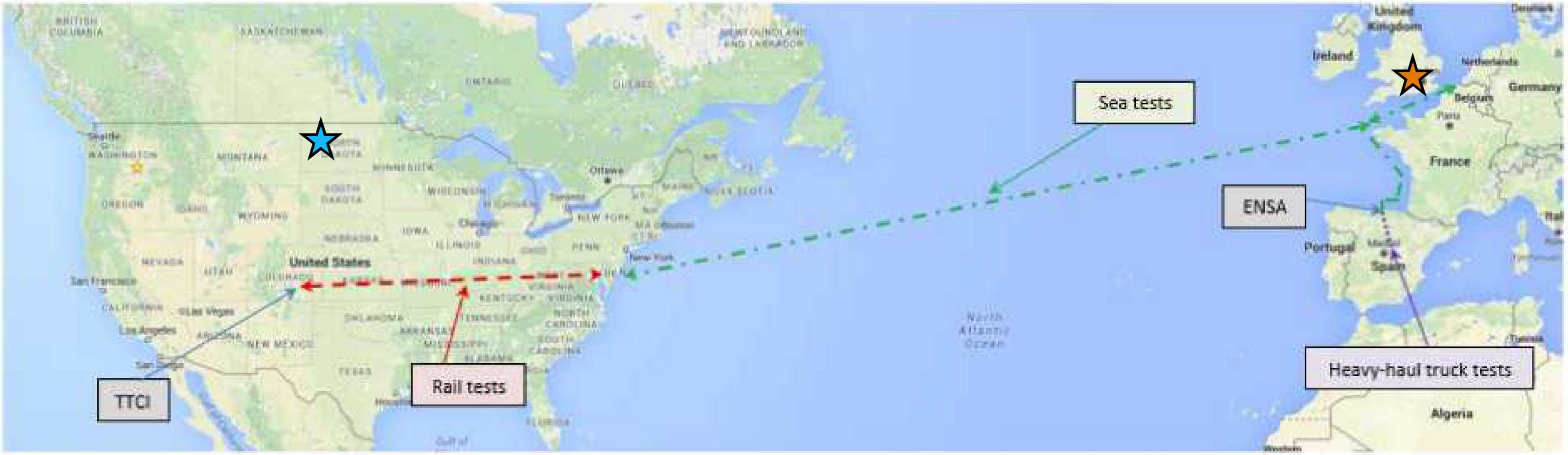
Transportation Configurations

16-axle heavy haul truck transport through Spain

Barge and ocean ship transport

Rail transport and testing in the US – Kasgro 12-axle railcar

Transportation Triathlon Route



- Cask handling tests at ENSA, Santander/Spain ★
- Heavy-haul truck tests in Northern Spain (245 mi/394 km)
- Barge transport from Spain to Belgium (929 mi/1,495 km)
- Ocean ship transport from Belgium to Baltimore (4,290 mi/6,904 km)
- Rail shipment from Baltimore to TTCI (Rail 1, 1,950 mi/3,138 km)
- Testing at TTCI ★
- Rail shipment from TTCI to Baltimore (Rail 2, 1,125 mi/1,811 km)
- Return ocean transport from Baltimore to Spain (not recorded)

Total distance traveled with data acquisition: 8,539 mi (13,742 km)

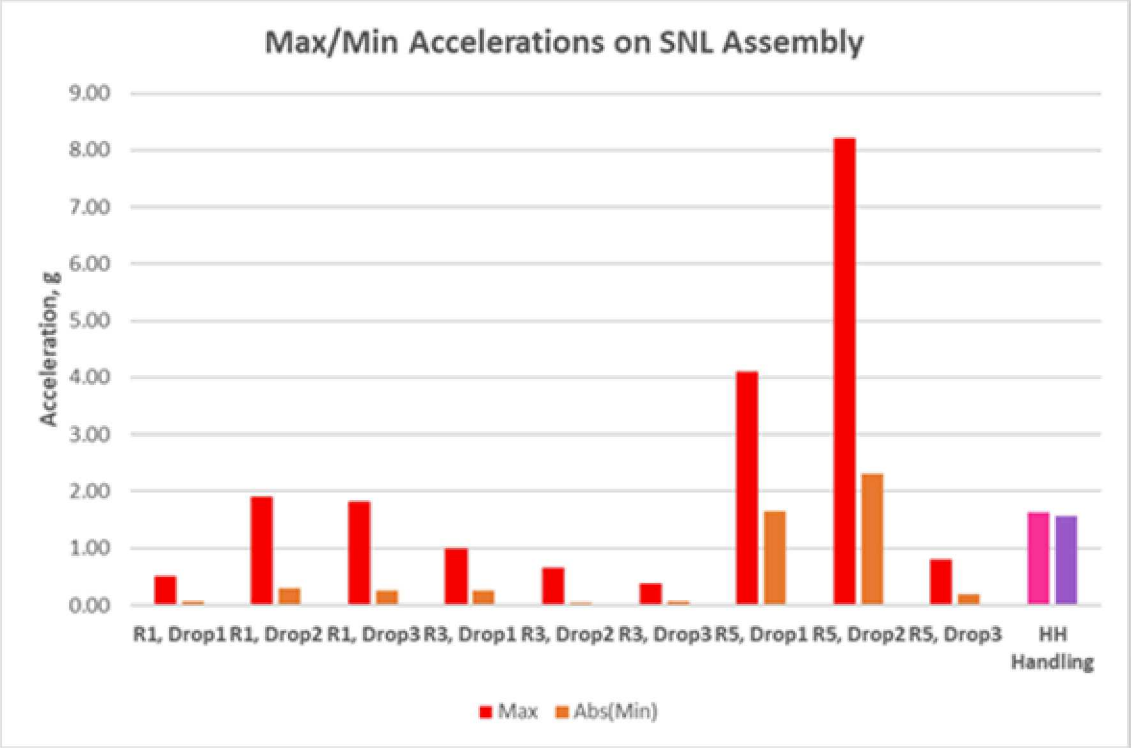
Cask Handling Tests (Max 50μE and 8g)

Dry Storage Cask Handling Tests

- 3 ENSA crane operators conducted one run each (R1, R3, R5) in which each raised and lowered the cask 3 times, with varying levels of "aggressiveness"
- Run 5 (R5) Drop 2 experienced the highest recorded SNL assembly strain: 40 μE

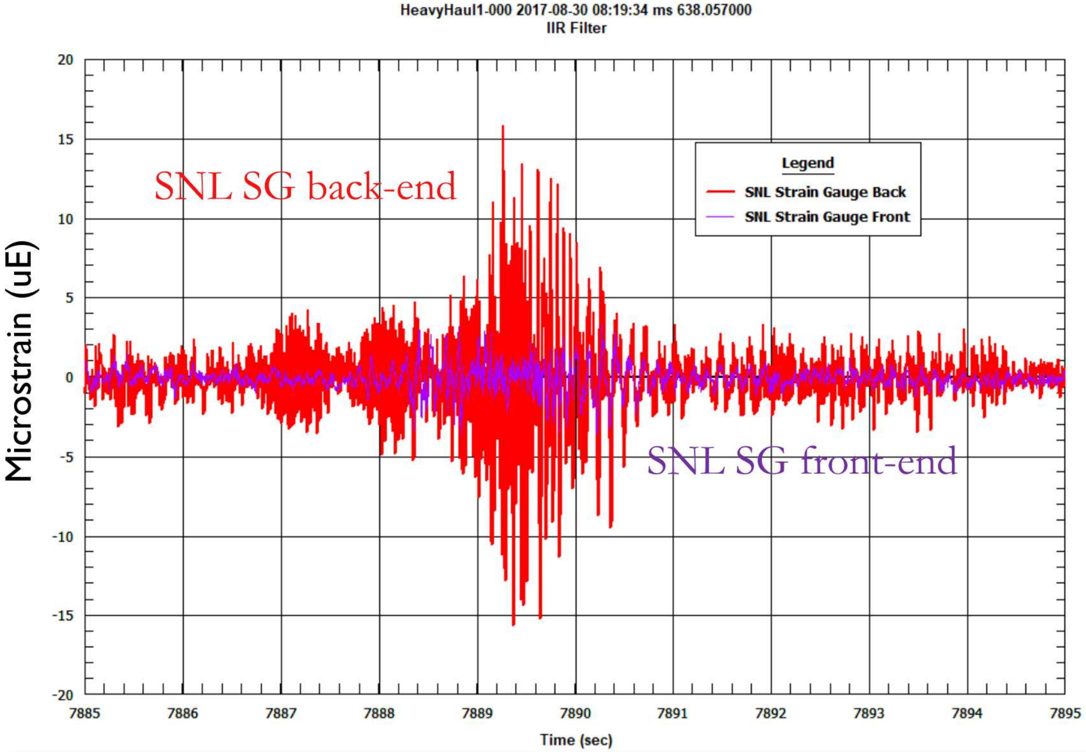
Heavy-Haul Handling Test

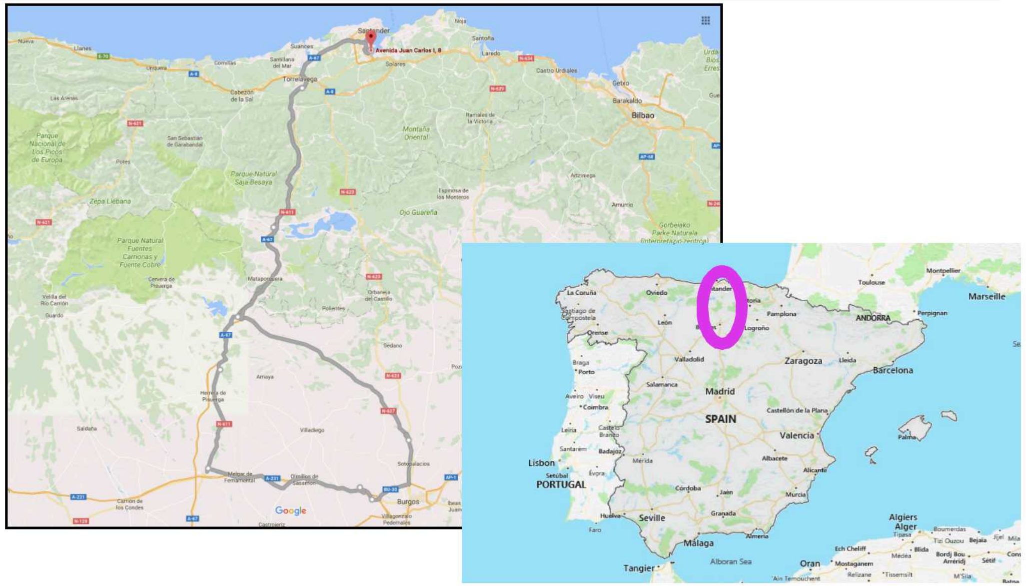
- Cask was placed vertically into the cradle and lowered to the horizontal position in preparation for heavy-haul truck tests.



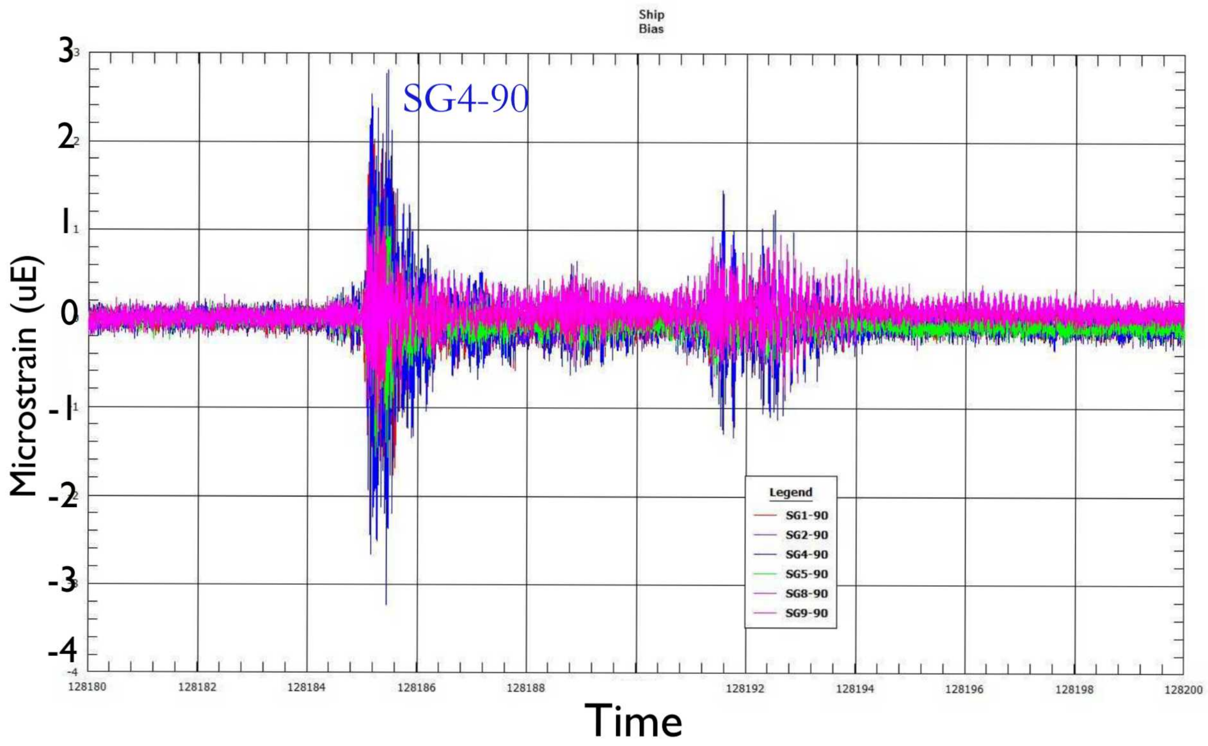
Heavy-Haul Truck Transport: (Max 15.6μE and 0.52g)

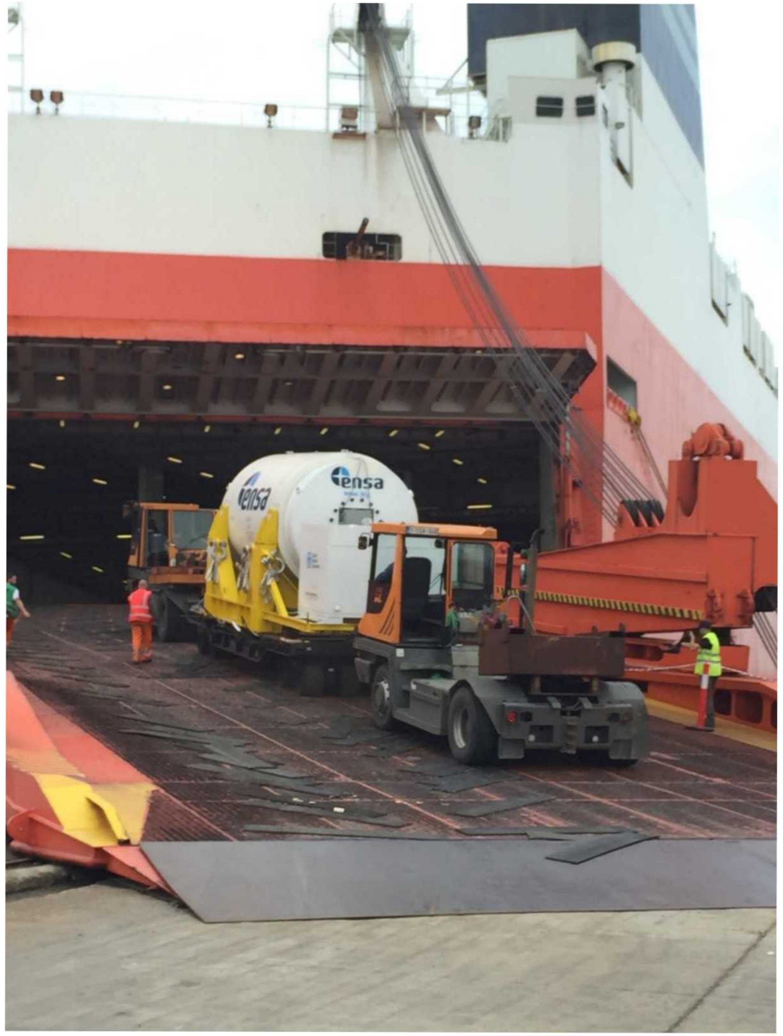
- 36 shock events
- 78% caused by vertical upset in the road, 11% associated with turns, 11% unidentifiable but with low overall response.
- Maximum SNL assembly strain: 15.6 μE
- Maximum acceleration:
  - Platform: 4.52 g (back-end)
  - SNL Assembly: 0.52 g





Barge and Ocean Ship Transport (Max 3.8μE and 0.12 g)

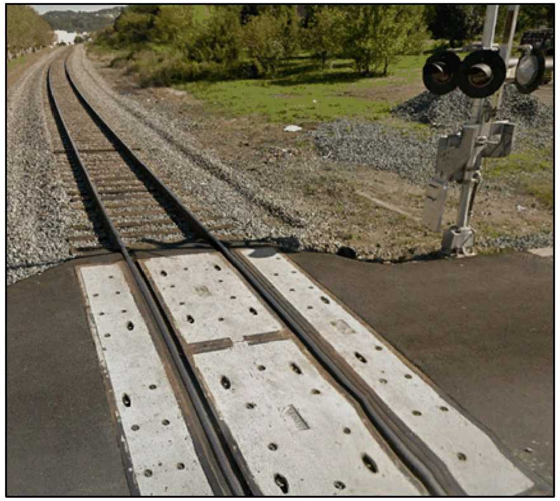




- Observed accelerations and strains were overall very low
- Accelerations (mostly) ≤ 0.3 g, and strains consistently ≤ 4 μE
- Maximum acceleration:
  - Transport platform: 0.38 g
  - Assembly: 0.12 g
- Maximum strain on the SNL assembly: 3.8 μE

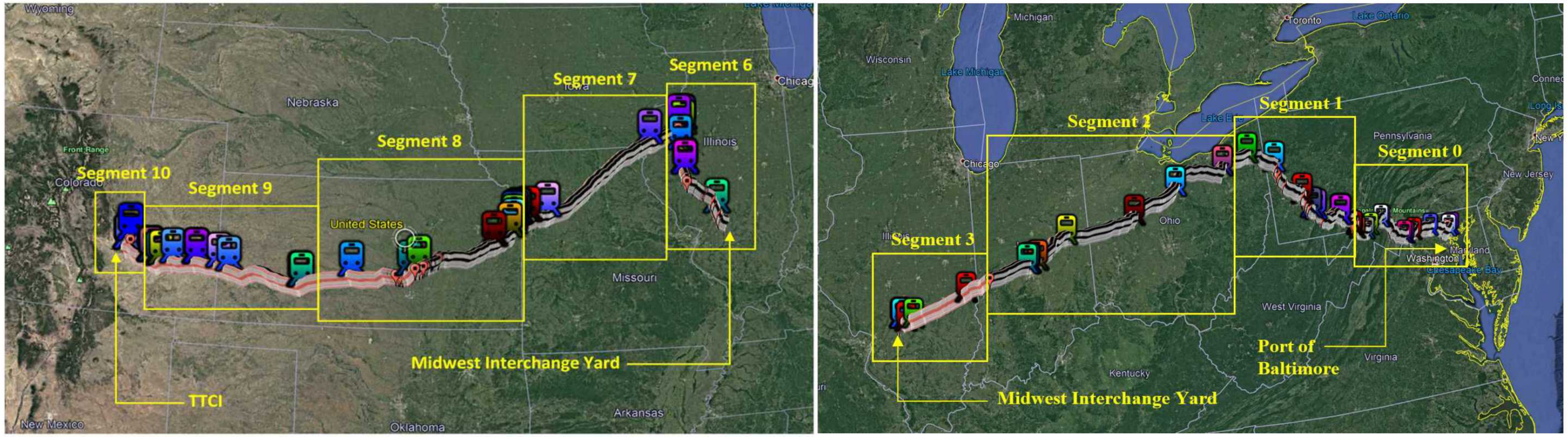
Rail 1: Baltimore to Colorado, USA

- Total distance: 1,950 miles (3,138 km)
- Total recording time: 518,400 sec (144 hours)
- Railcar was moving: 59 hours
- Number of grade crossing shock events: 1,029
- Number of track switch shock events: 629
- Number of coupling events: 1



Grade crossing

Track switch



Train icons indicate places the train stopped.

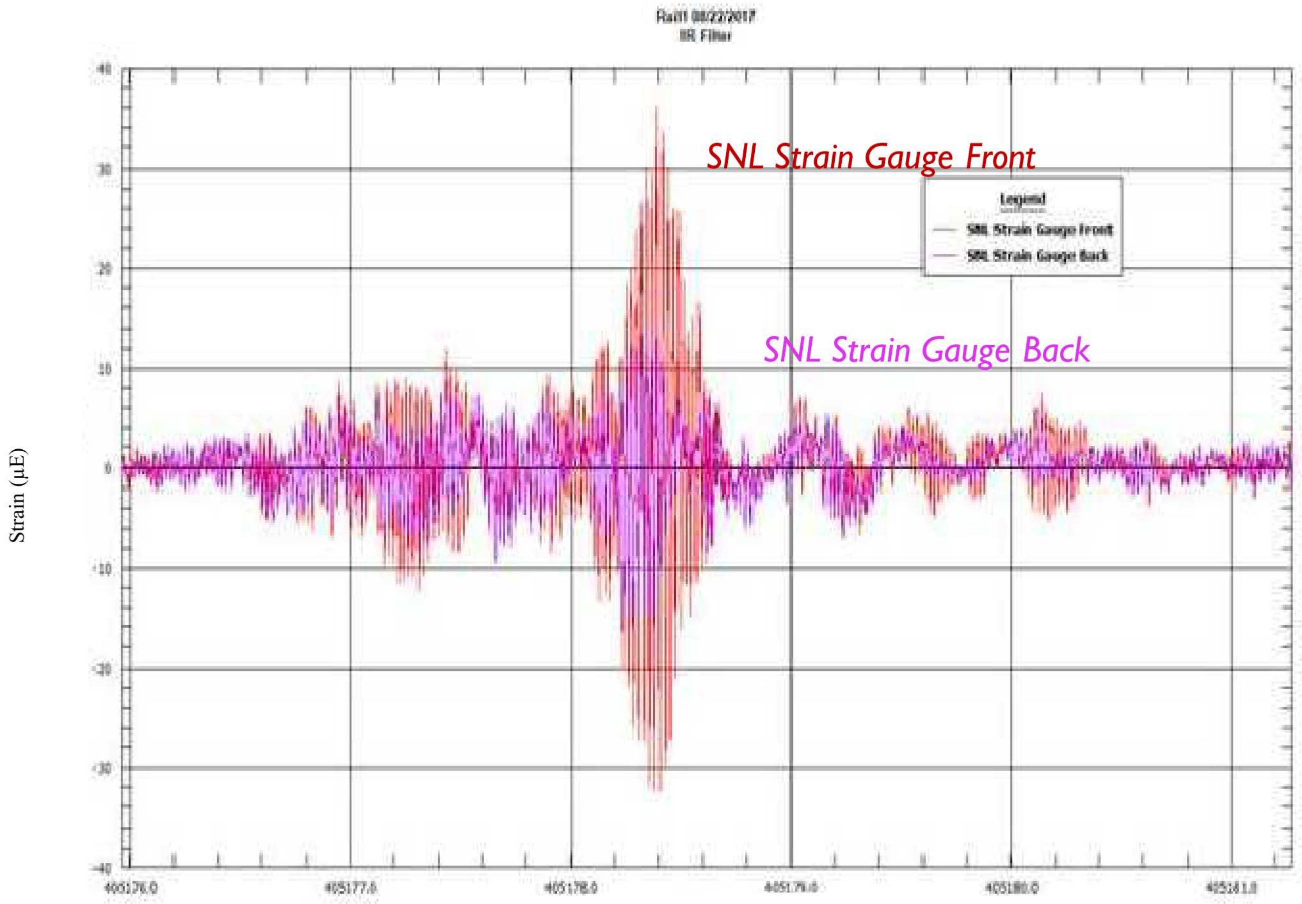
Rail 1: Baltimore to Colorado: (Max 35.8µE and 0.95g)

Max Strain Event

- Caused by a track switch in Kendall, Kansas
- Rail 1 traveling 45 mph
- Max absolute acceleration:
  - Platform: 3.78 g (front-end)
  - Assembly: 0.66 g (ENSA)
- Max absolute strain: 35.8 µE in the SNL assembly

Max Acceleration Event

- Caused by a diamond crossing in Jacksonville, Illinois
- Rail 1 traveling 36 mph
- Max absolute strain: 20.7 µE in SNL assembly front
  - Max absolute acceleration:
    - Platform: 8.68 g (front-end)
    - Assembly: 0.95 g (ENSA)

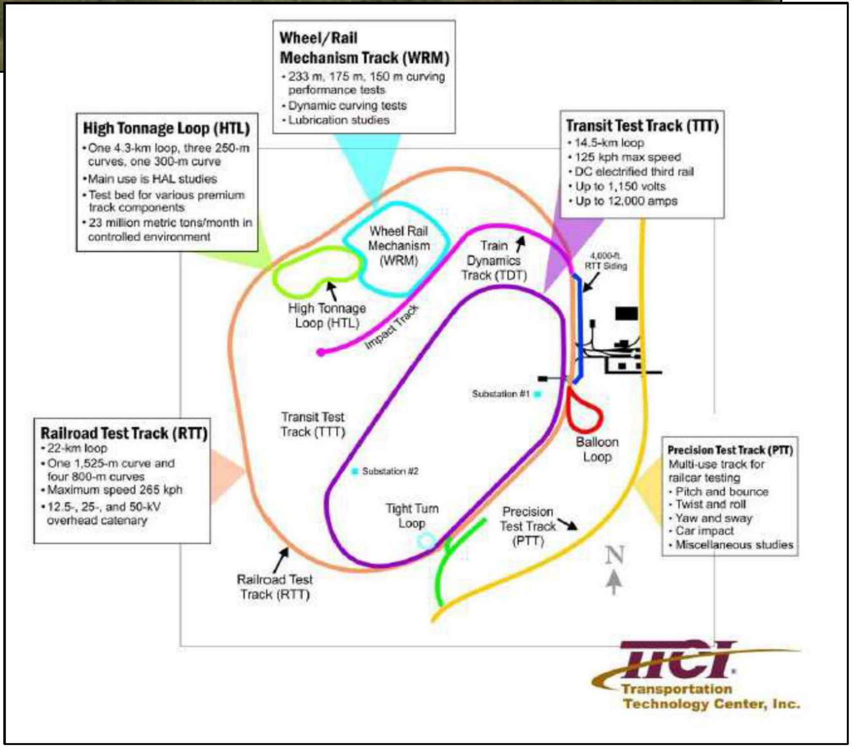


Maximum Strain Event Time History

Rail Tests at the Transportation Technology Center Inc. (TTCI) in Pueblo, Colorado

- Short duration tests with known conditions and design parameters more extreme than expected on commercial railroads

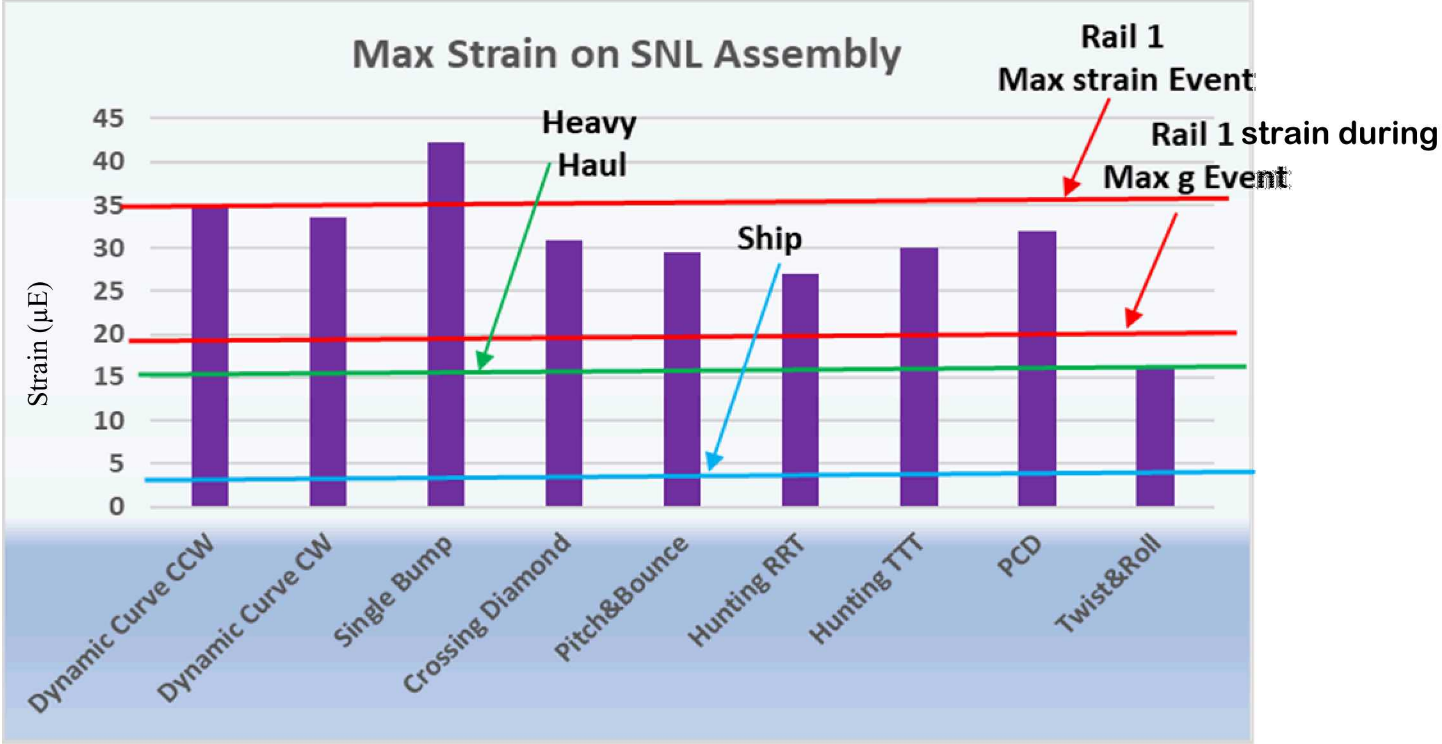
- Tests conducted at varying speeds to capture specific resonant speed



Test Description	Number of Tests
Twist and Roll	19
Pitch and Bounce	9
Dynamic Curve	24
Class 2 Rail Track (PCD)	17
Single Bump	8
Crossing Diamond	6
Hunting	23
Coupling Impact	10

Rail Tests at the TTCI - Results

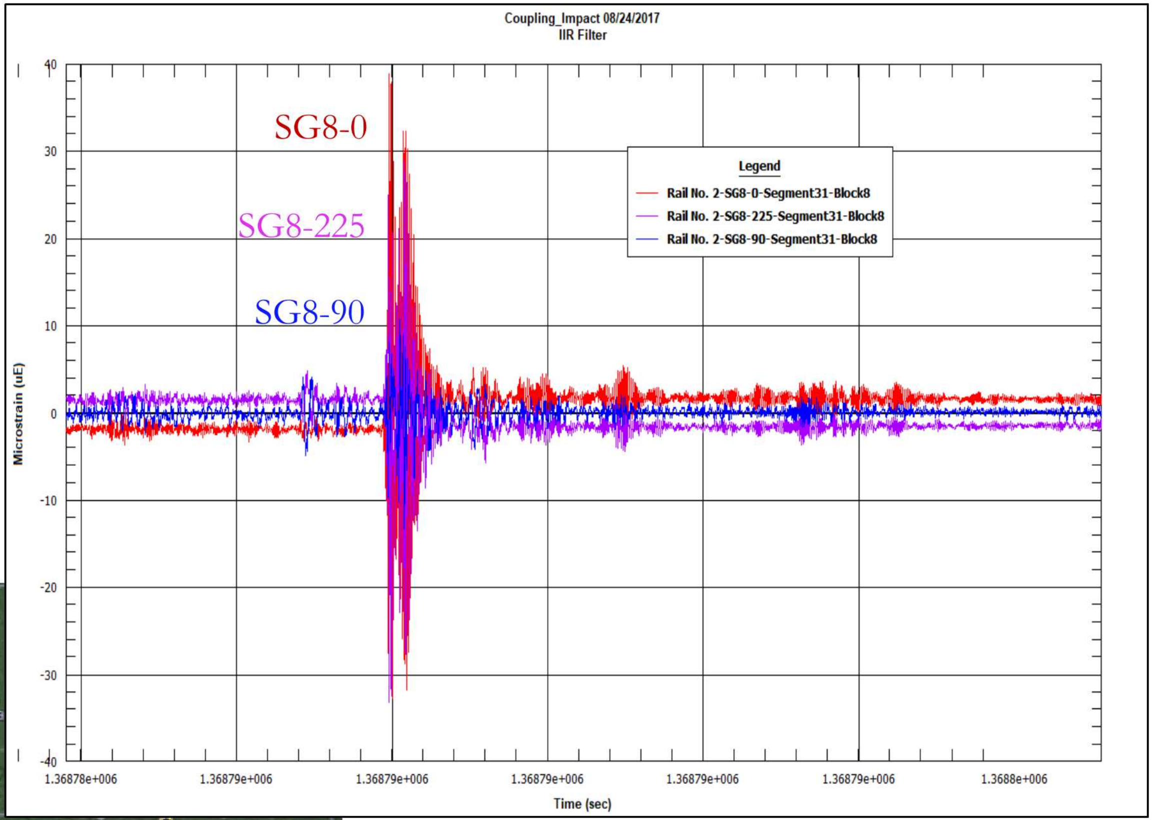
- Testing provided valuable insight of system response to a multitude of transient inputs
- Understanding these inputs made possible the comparison and analysis of rail, heavy-haul, and ship transport data
- TTCI testing bounded all other rail data

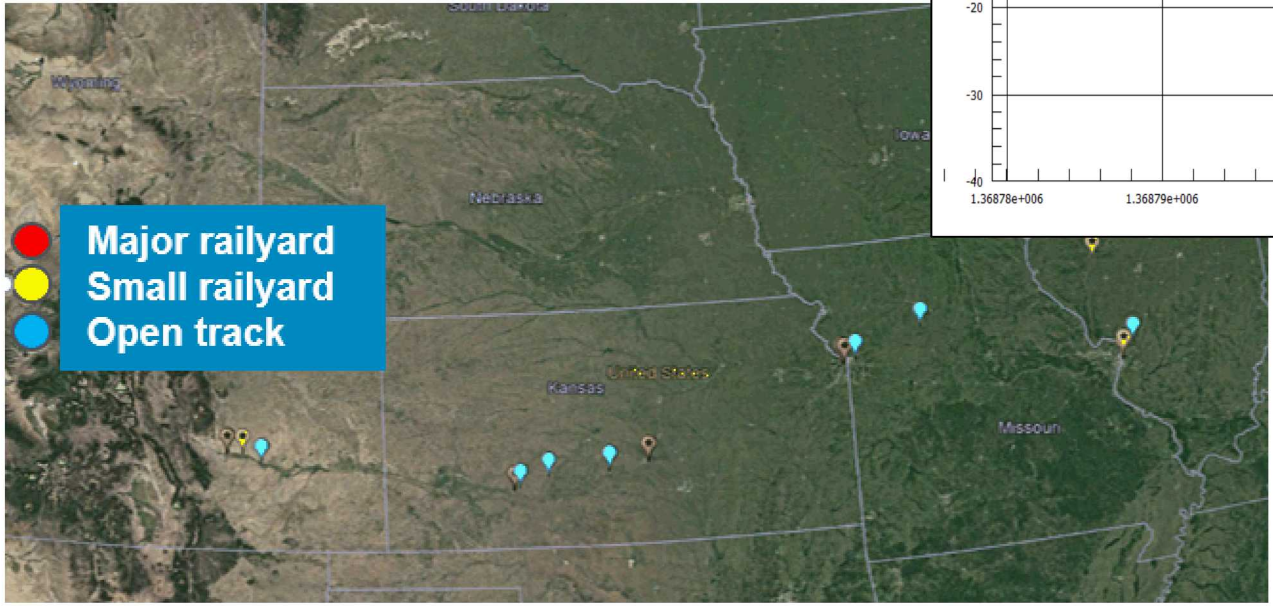


Maximum strains from TTCI tests compared to maximum strains from different modes of transportation

Rail 2: TTCI (Pueblo, CO) to Baltimore

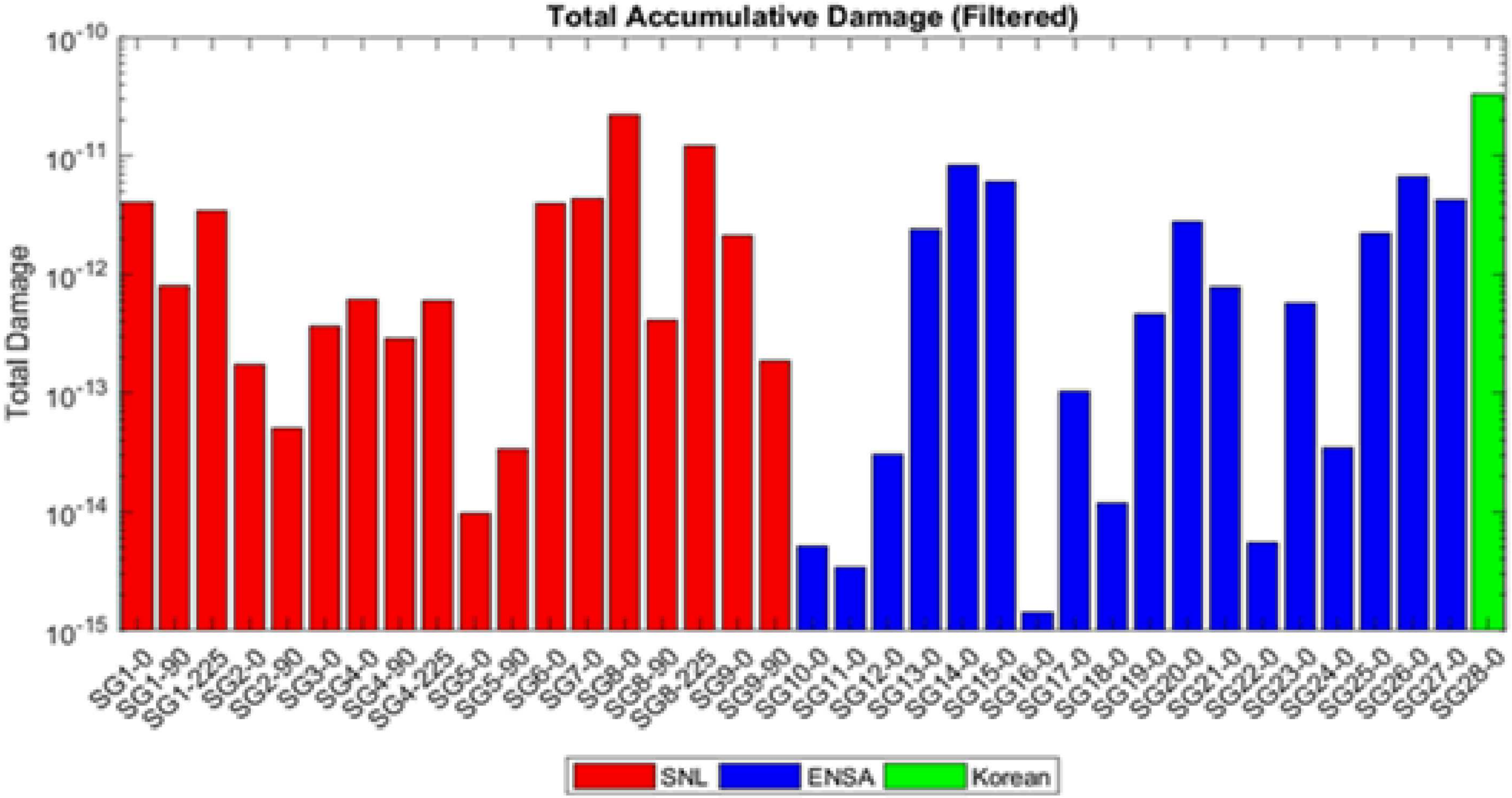
- 18 days (1,125 mi/1,811 km) of data collected from TTCI to near Illinois
- 30 coupling events analyzed at railyards
- Max SNL acceleration: 1.05 g
- Max SNL strain: 38 μE
  - Note: Max TTCI coupling strain: 99 μE at 7.5 mph





Locations of shock events.

Fatigue Analysis



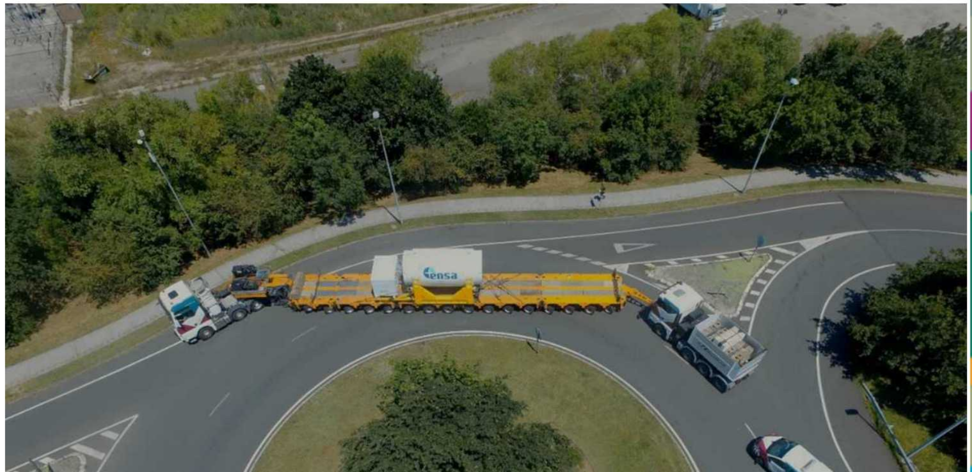
Strain data collected during the multi-modal transportation test were used to perform fatigue analysis on the fuel cladding. The ASTM Standard E1049 rainflow counting method was used to count the number of strain cycles in the data. Accumulated fatigue damage was calculated according to Miner's Rule

- Damage fraction of 1.0 indicates fatigue failure. Accumulated damage in all cases is below 1E-10
- This calculation estimates it would take 10 billion cross-country (2,000-mile) trips to challenge the fatigue strength of irradiated fuel cladding.

Summary of What We Learned

The observed strains were well below the yield points for spent nuclear fuel cladding.

- The greatest strains and accelerations were seen during rail coupling tests at TTCI.
- The handling tests were somewhat higher than the most extreme rail tests, except coupling.
- Heavy haul and rail transport strains and accelerations were comparable.
- Water transport strains and accelerations were the lowest.
- Cladding fatigue is not an issue



Questions?