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# Results of the Normal Conditions of Transport of Spent Nuclear Fuel Multi-Year Experimental Program

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Presented by Elena Kalinina

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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# Multi-Year Experimental Program

Single Assembly | Actual Transportation System

2013 1-DOF Shake Table Test → 2014 Over-the-Road-Test → 2016 6-DOF Shake Table Test → 2017-2018 MMTT → 2018-2020 30 cm Drop Test

**Funded by the U.S. Department of Energy (DOE)**

## Collaborators

- Bundesanstalt für Materialforschung und -prüfung (BAM)
- Equipos Nucleares Sociedad Anónima (ENSA)
- Empresa Nacional de Residuos Radiactivos S.A. (ENRESA)
- ENUSA Industrias Avanzandas S.A.
- Coordinadora Internacional de Cargas, S.A.
- Sandia National Laboratories (SNL)
- Pacific Northwest National Laboratory (PNNL)
- Transportation Technology Center, Inc. (TTCI)
- Korea Radioactive Waste Agency (KORAD)
- Korea Atomic Energy Research Institute (KAERI)
- Korea Nuclear Fuel Company Ltd. (KNFC)

## Test results

- Provided a compelling technical basis for safe transport of spent fuel under normal conditions of transport (NCT).
- Demonstrated that cladding integrity is not an issue during NCT.
- Became reference data for many organizations in the U.S. and outside the U.S.

**DOE Secretary's Achievement Award for the MMTT**

# 2013-2016 Tests

## 2013

**One Degree-of-Freedom Shake Table Test**

Normal Conditions of Transport **Truck**

## 2014

**Over-the-Road Truck Transport Test**

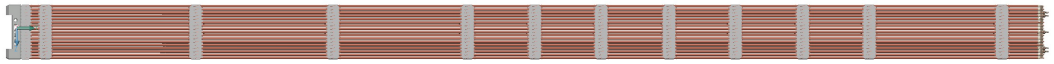
Normal Conditions of Transport **Truck**

## 2016

**Six Degree-of-Freedom Shake Table Test**

Normal Conditions of Transport **Truck and Rail**

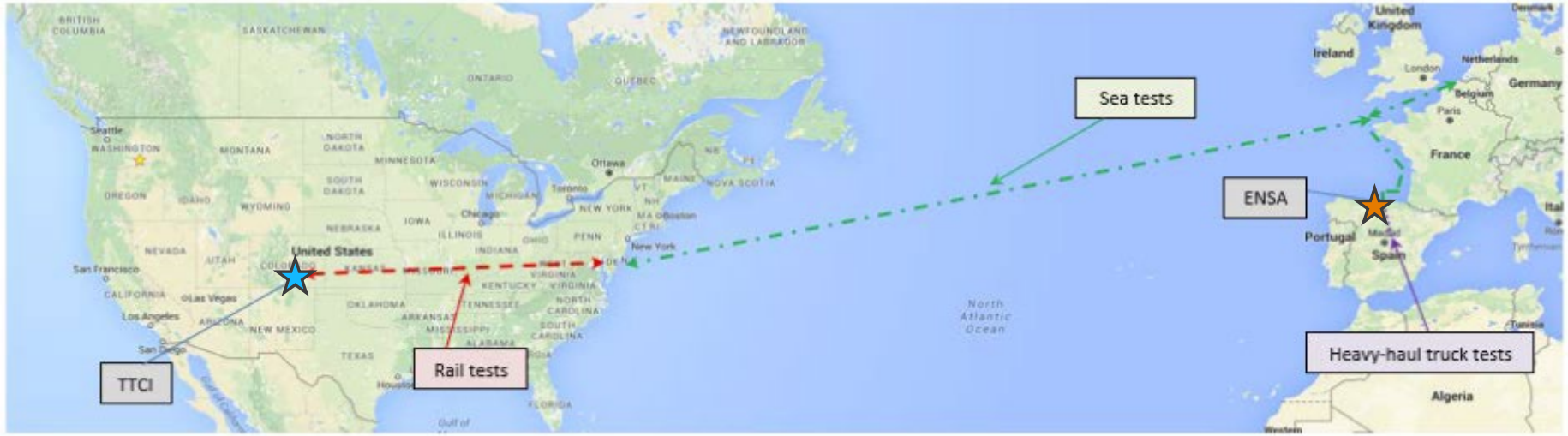
Shake table inputs: 700-mile over-the-road truck test (1977) and rail data from Transportation Technology Inc, TTCI.



- ❑ All tests used a surrogate PWR assembly placed within a surrogate basket
- ❑ The assembly rods were instrumented with strain gauges and accelerometers

| Test | Max Microstrain |
|---|---|
| 2013 truck | 213 |
| 2014 truck | 143 |
| 2016 truck | 301 |
| 2016 coupling | 208 |
| 2016 rail | 241 |

# Multi-Modal Transportation Test (MMTT)




Ship Transport Configuration

Rail Transport- Kasgro 12-Axle Railcar

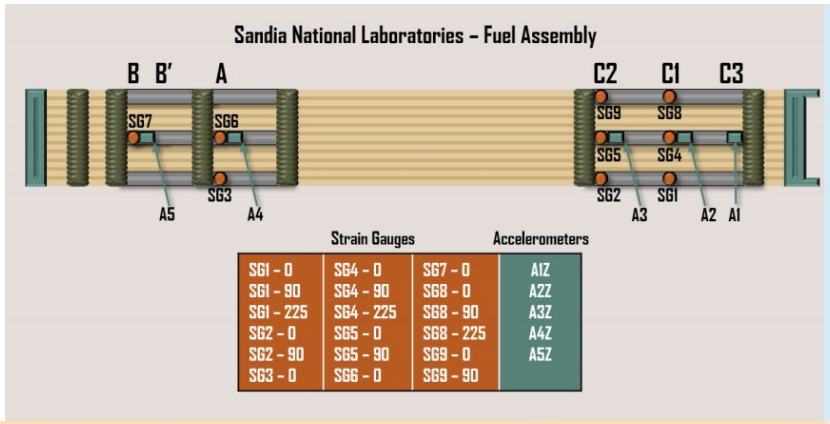
Heavy Haul Transport

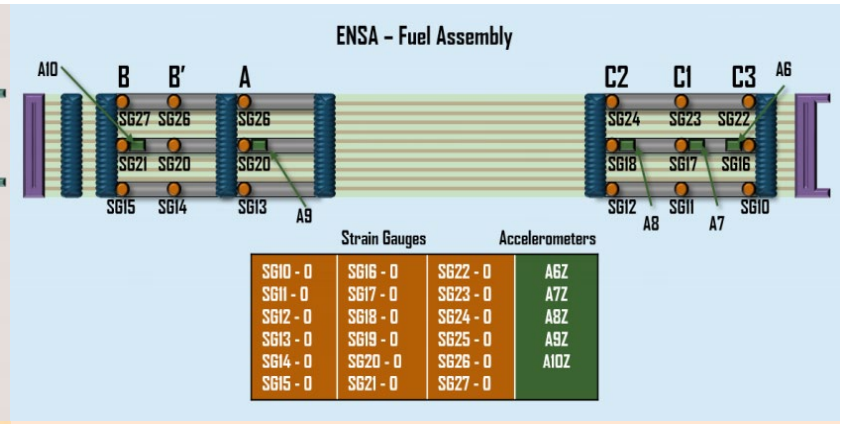
## Transportation Routes

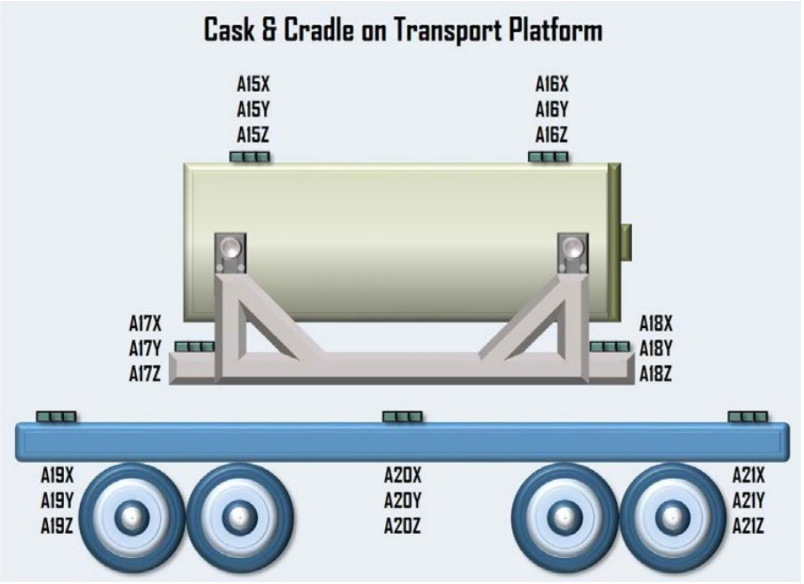
- Cask handling tests at ENSA, Santander/Spain ★
- Heavy-haul truck tests in Northern Spain (245 miles)
- Coastal vessel transport from Spain to Belgium (929 miles)
- Ocean ship transport from Belgium to Baltimore (4290 miles)
- Rail shipment from Baltimore to TTCI (Rail 1, 1950 miles)
- Testing at TTCI ★
- Rail shipment from TTCI to Baltimore (Rail 2, 1125 miles)
- Return ocean transport from Baltimore to Spain (no data collected)

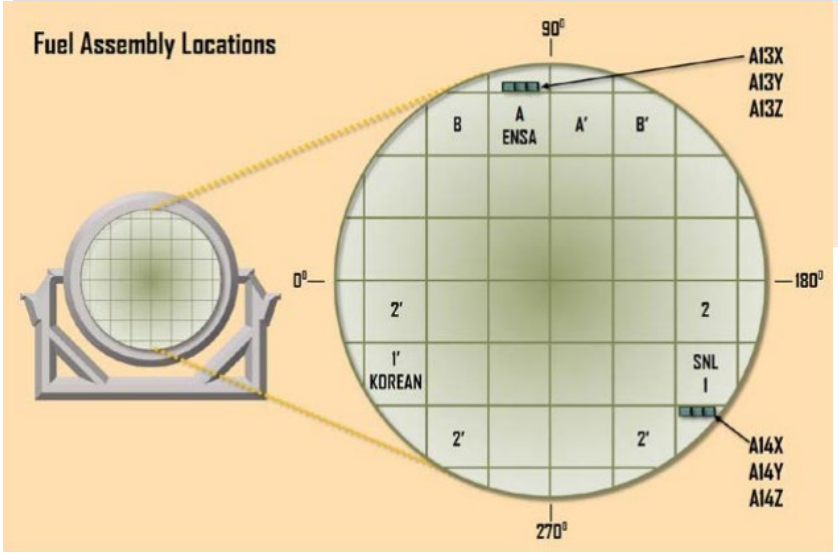
# Transportation System Instrumentation

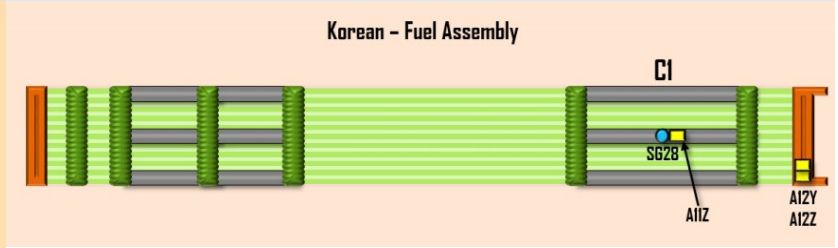
## 40 accelerometers and 37 strain gauges

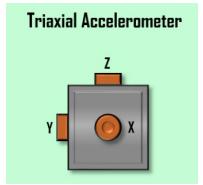


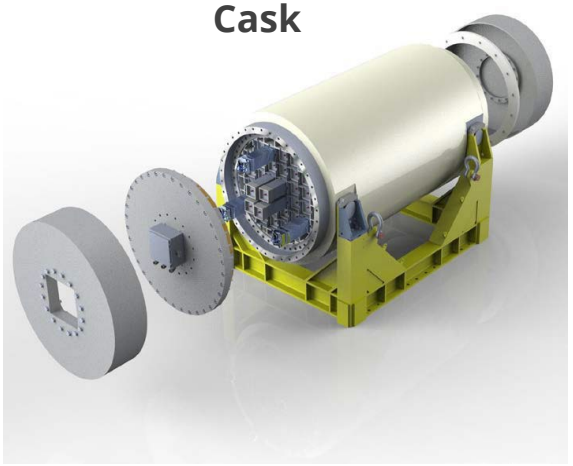




### Cask Parameters

- Length: 5 m
- Diameter: 2.65 m
- Loaded weight: 120 tons
- Dummy impact limiters

### ENUN 32P Dual Purpose Cask



# Cask Handling

Dry Storage Cask Handling Tests

- 3 ENSA crane operators conducted one test each in which each raised and lowered the cask 3 times, with different level of softness.

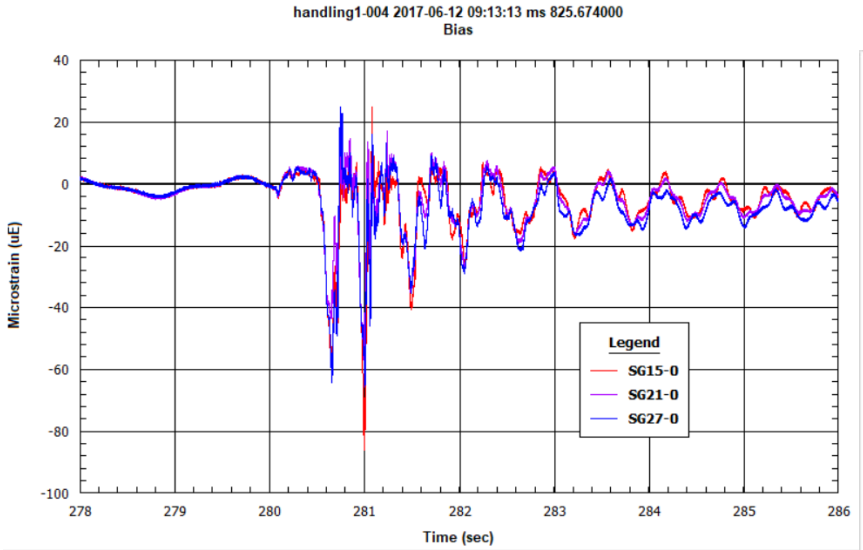
Heavy-Haul (HH) Handling Test

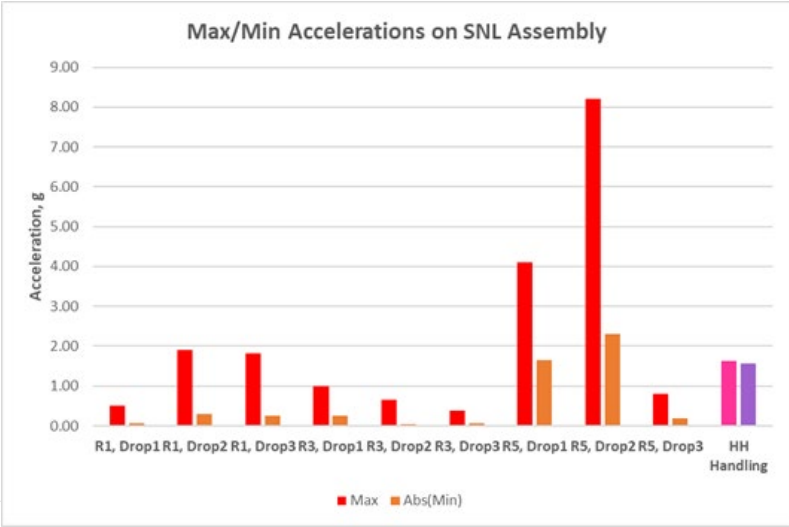
- Cask was placed vertically into the cradle and lowered to horizontal position in preparation for heavy-haul truck tests.
- Accelerometers recorded the 1G change from vertical to horizontal orientation.

| Dry Storage Cask Handling | Heavy Haul Handling |
|---|---|
|  |  |

**Maximum Measured Strain**

- ❑ Cask Handling: 82 microstrain
- ❑ HH Handling: 20 microstrain

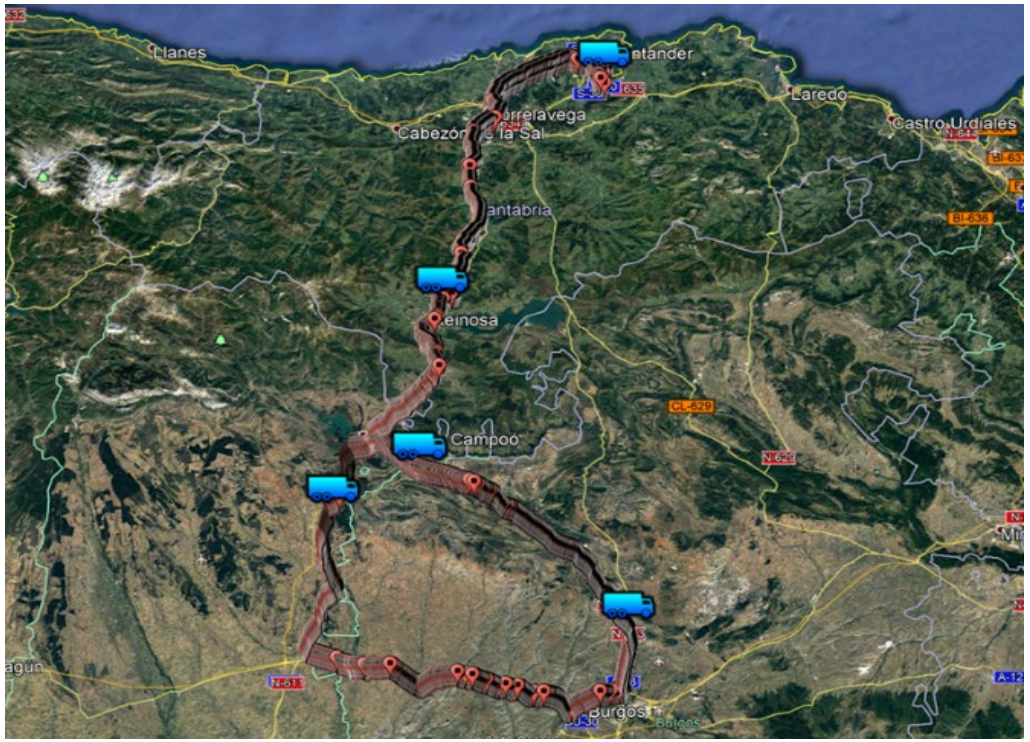


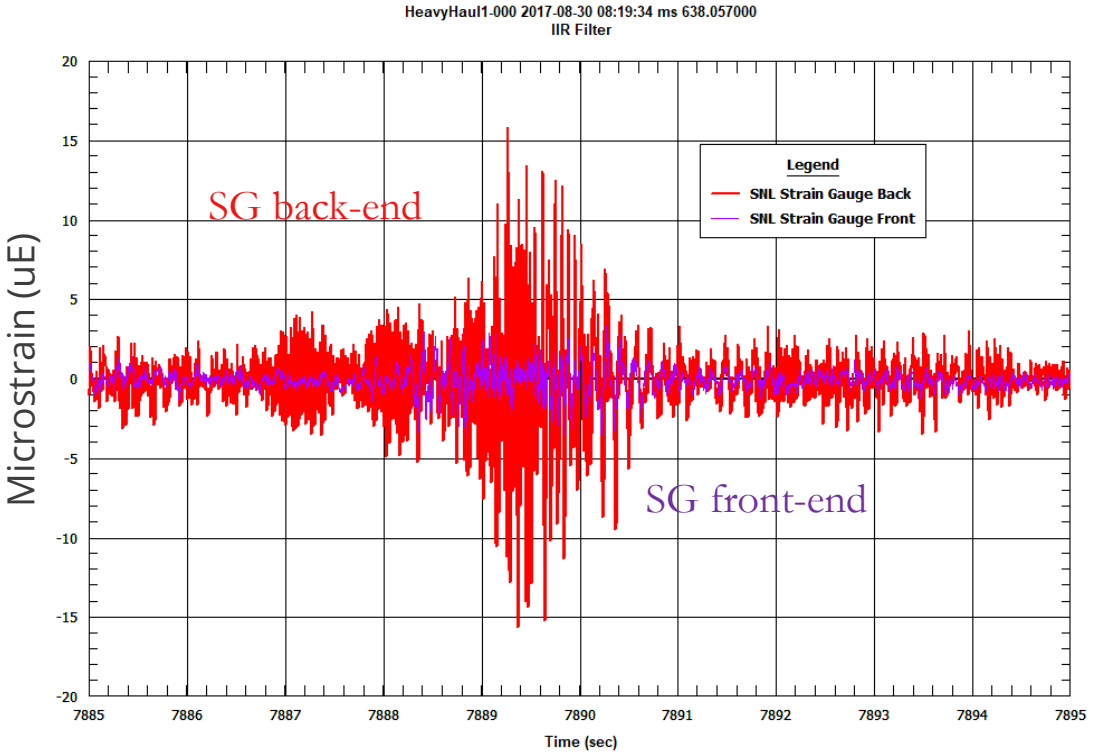
# Heavy-Haul Truck Transport

- 36 shock events
- 78% caused by vertical upset in the road and the majority of others associated with turns
- Maximum assembly acceleration: **0.52 g**
- Maximum assembly strain: **15.6 microstrain**

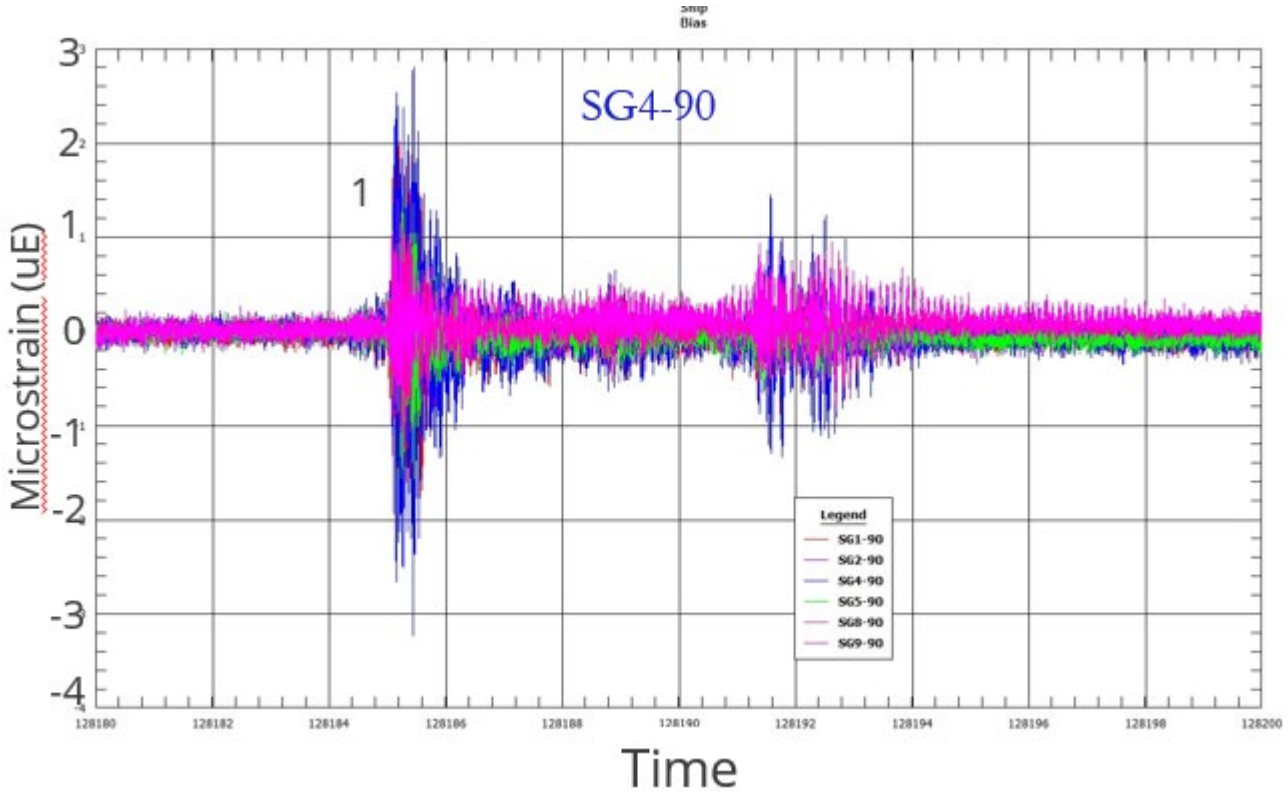
## 245 Mile Heavy-Haul Route

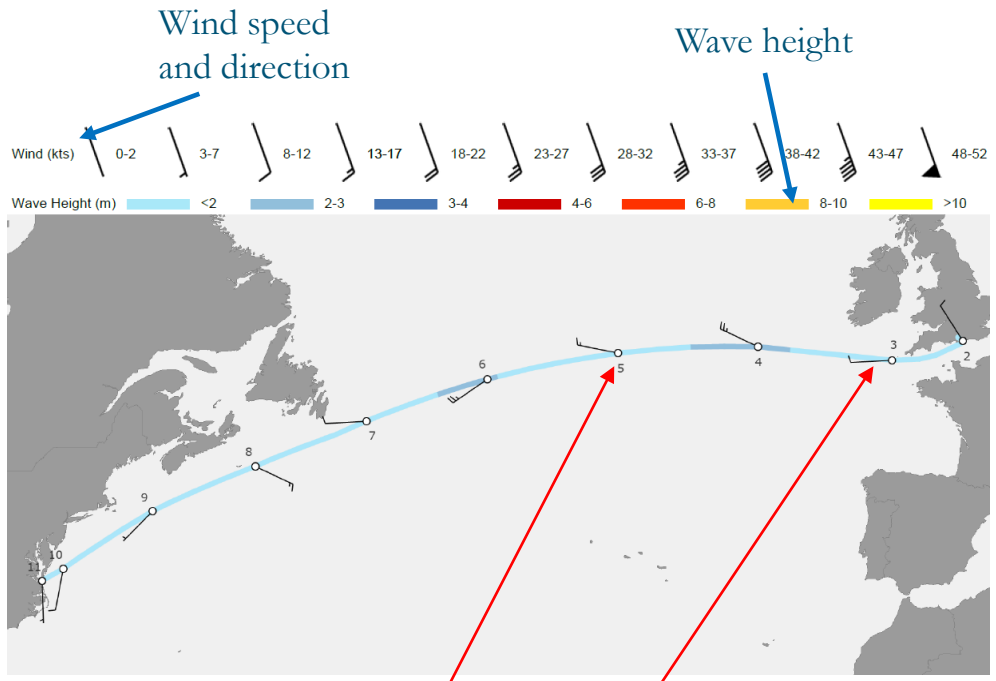


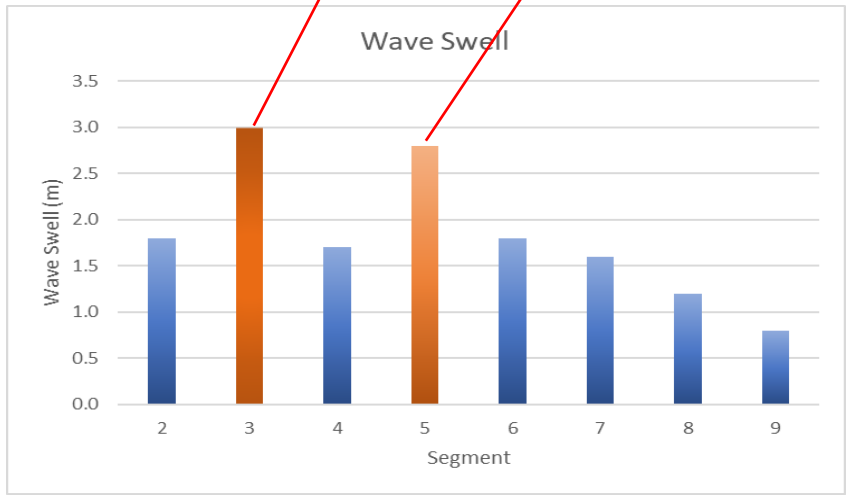

## Maximum Strain Event




# Coastal Vessel and Ocean Ship Transport




- GPS data were not available during ship transport (no reception)
- Weather data was only available for the cross-ocean route
- Observed accelerations and strains were overall very low
- Accelerations (mostly) ≤ 0.3 g, and strains consistently ≤ 4 microstrain

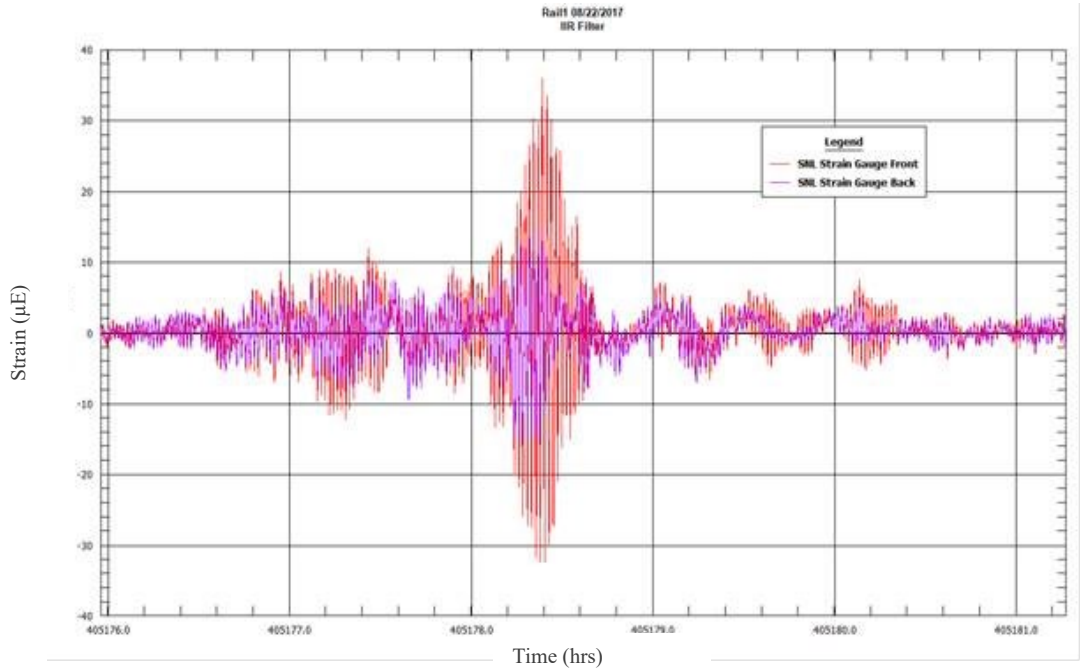
# Rail: Baltimore to TTCI (Pueblo, CO)

- 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**

## Maximum Strain Event



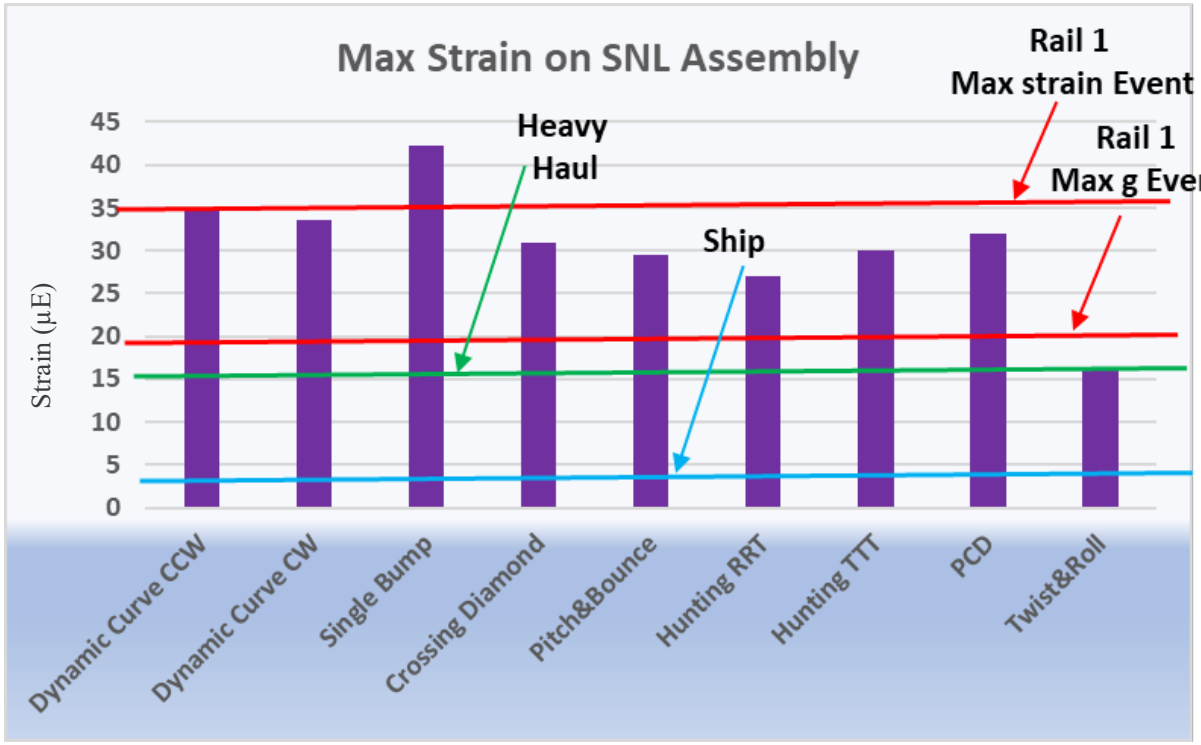

**Max Strain Event**

- Track switch in Kendall, Kansas
- Speed: 45 mph
- Max assembly acceleration 0.66 g
- Max strain: 35.8 microstrain

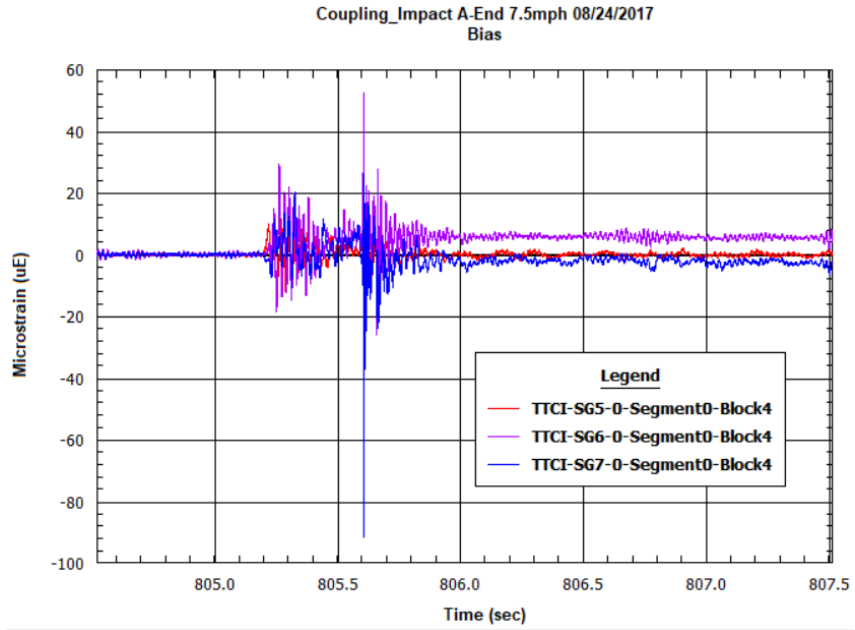
# Rail Tests at TTCI

- Short duration tests with design parameters somewhat beyond those expected on commercial railroads
- Conducted at different speeds to capture the effects of the resonant speed
- 8 Different series of tests with a total of 116 tests
- Max strain was measured during coupling at 8 mph – 99 microstrain

**Maximum Strains from TTCI Tests Compared to the Different Modes of Transport**

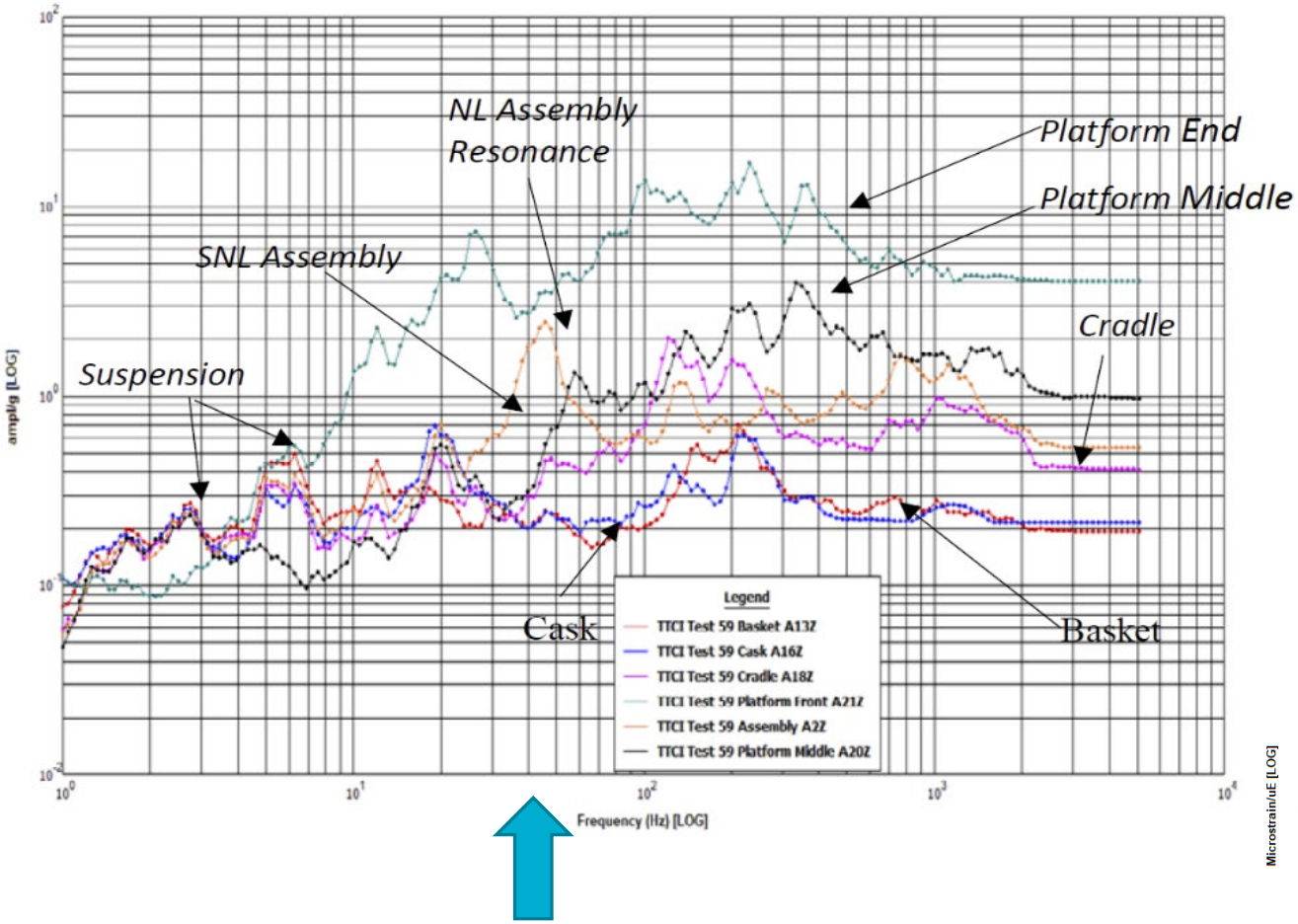



**Maximum Strain Event (Coupling Test)**




# MMTT Findings

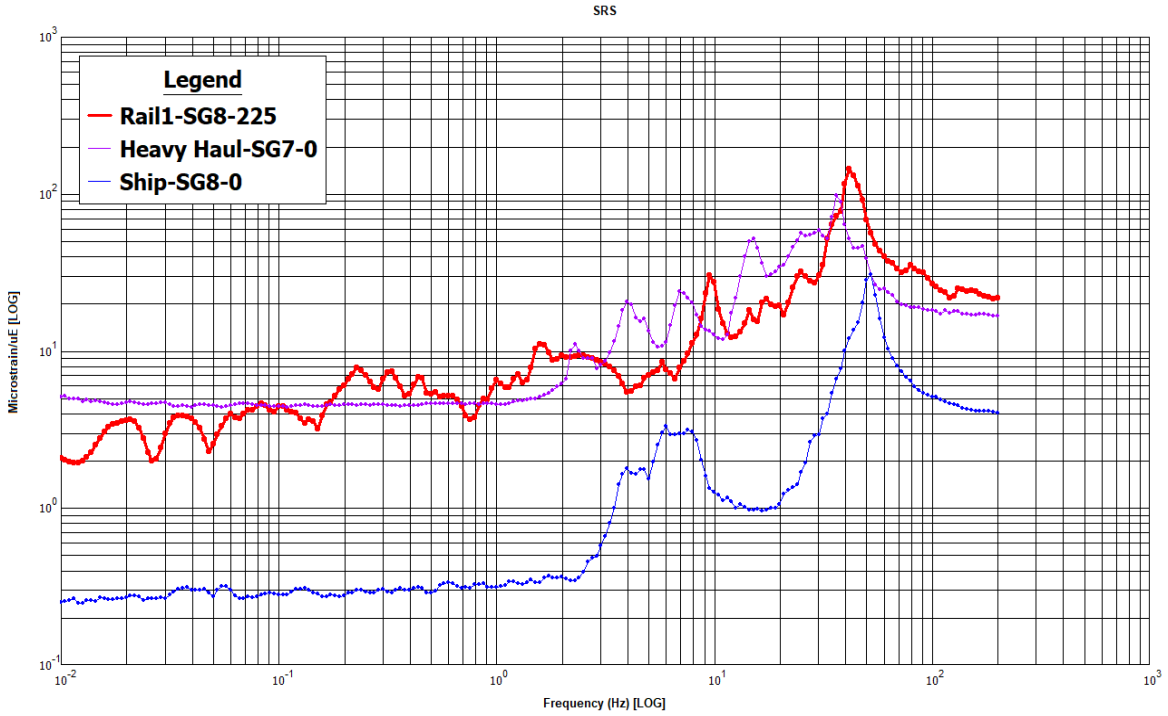
## Acceleration SRS




- The elements of the transportation system respond differently to the transient inputs.
- Amplification is observed from the cask and basket to the assemblies for frequencies above 5 Hz.

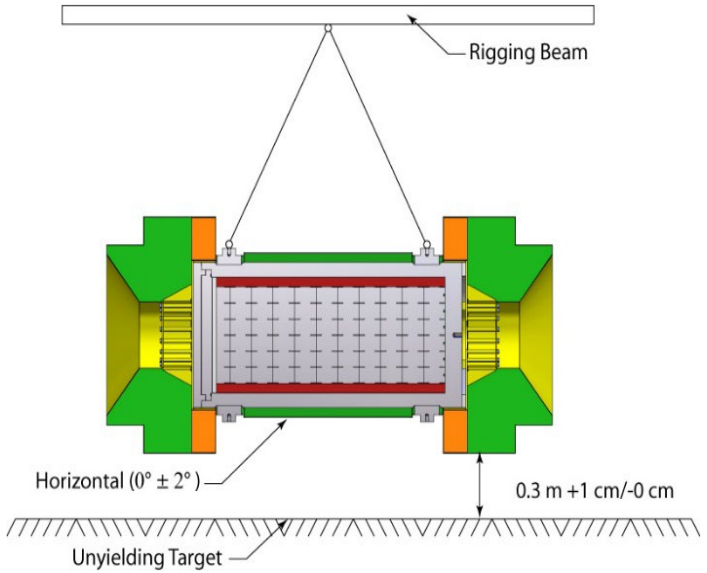
- The maximum assembly strains during different modes of transport and handling operations are small – below 100 microstrain.
- Rail and heavy-haul SRS are very similar.
- The ship SRS is similar in shape, but significantly lower in magnitude.

## Assembly Strain SRS in Max Strain Events

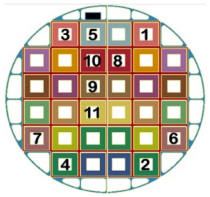


# 30 cm Drop Tests (2019-2020)

## 30 cm Drop Test of 1/3 Scale Cask with 32 1/3 Scale Dummy Assemblies (BAM Berlin Facility, Germany)



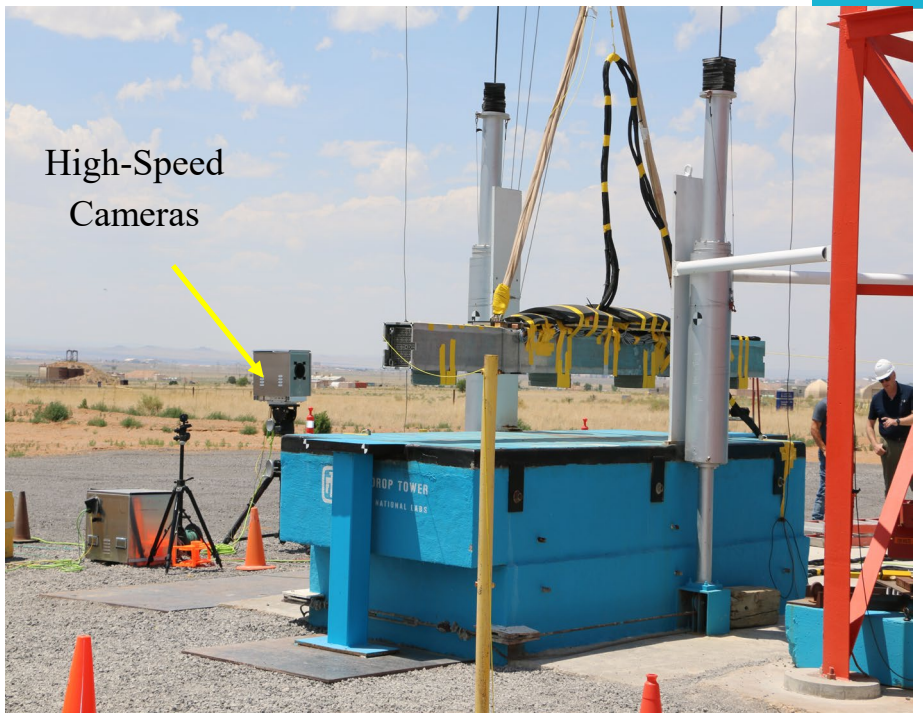

**11 instrumented 1/3 scale dummy assemblies**



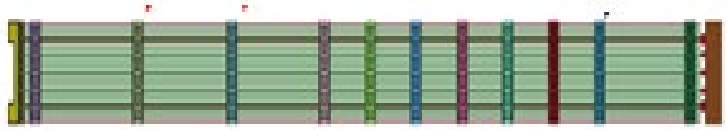

**Max acceleration pulses on 1/3 scale dummy assemblies (top and bottom)**

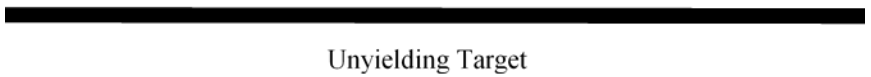
**Scaled maximum acceleration pulses on full-scale dummy as on 1/3 scale dummies**

**SNL Drop Tower**




## 30 cm Drop Test of Full-Scale Dummy and Surrogate Assembly (SNL, Albuquerque)



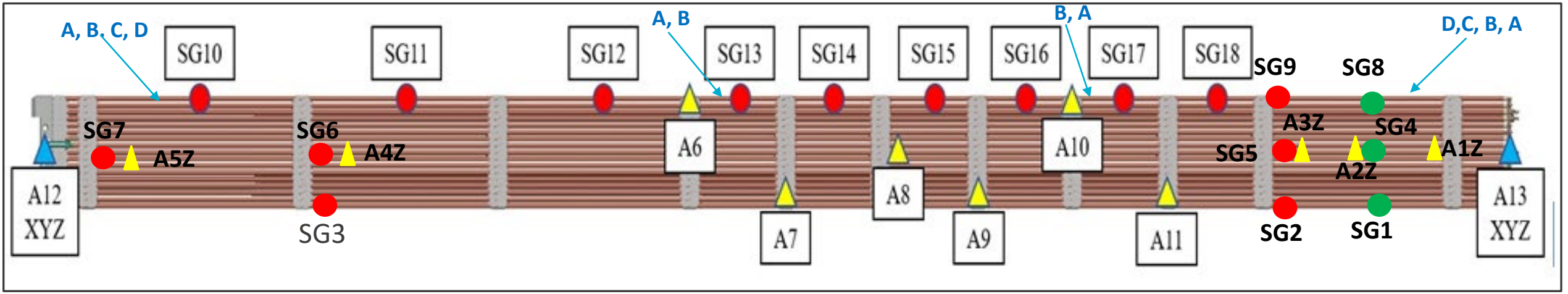



**Felt pads to mimic impact limiters and cask**

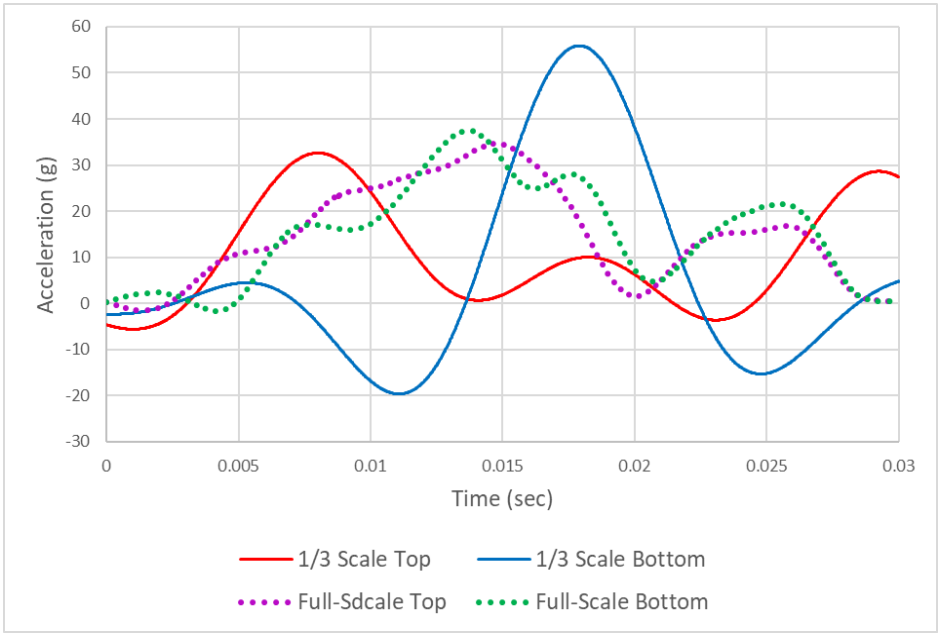
**Obtain strains on the surrogate fuel rods**

# Full - Scale Surrogate Assembly Instrumentation

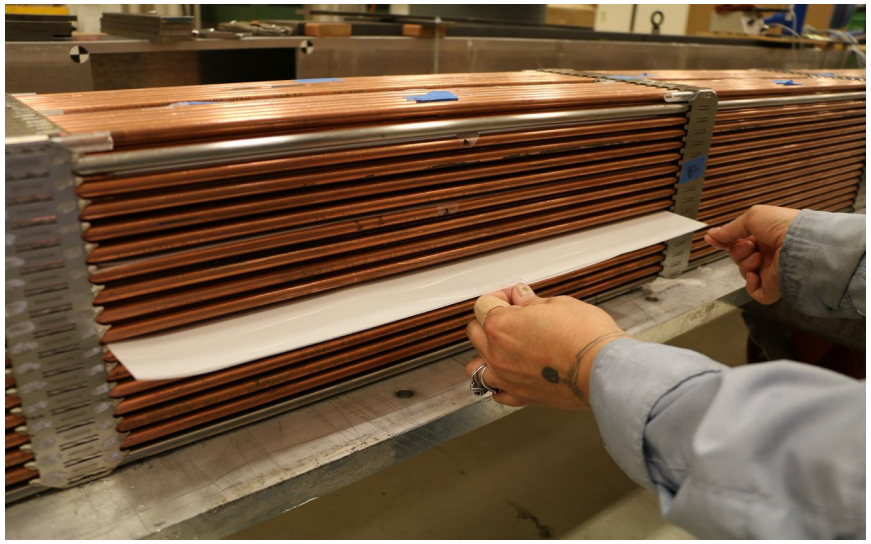
A1Z to A5Z and SG1 to SG9 – same locations as in MMTT




## Dummy Assembly Acceleration Pulses




## Installation of Pressure Paper



Strain Gages at 0°
Uniaxial Accelerometers at 0°
Triaxial Accelerometers at 0°

## Pressure Paper

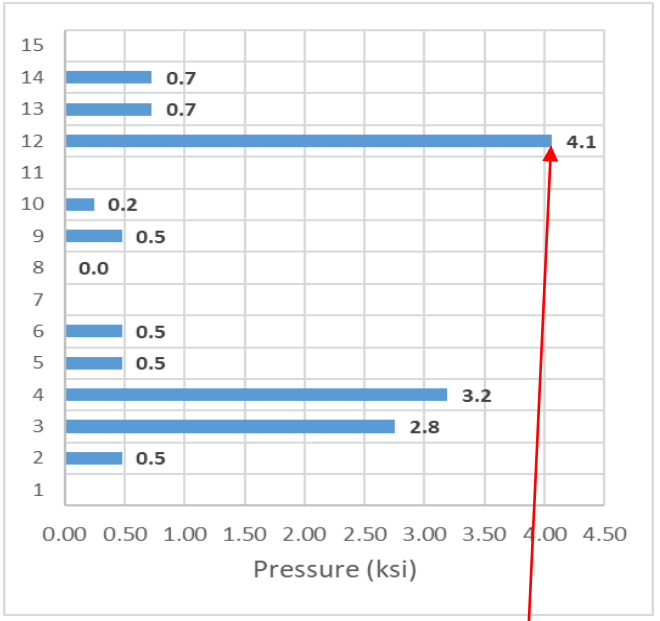
A - Extreme Low: 7.2 – 28 psi
B - Super Low: 70 – 350 psi
C – Low – 350: 1,400 psi
D – Medium: 1,400 – 7,100 psi

# Surrogate Assembly Results

## Grid Deformation

## High-Speed Video

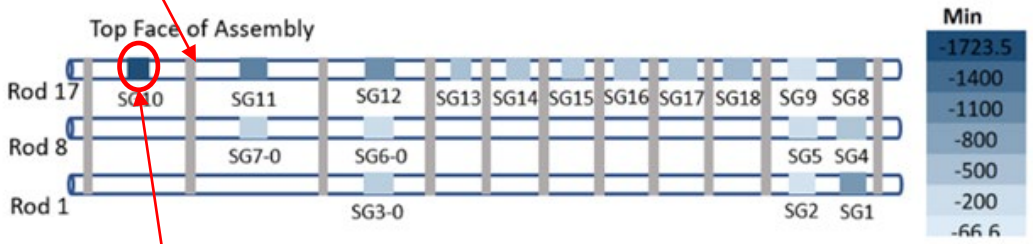
## Contact Pressure




- Max grid deformation: 6.1 mm

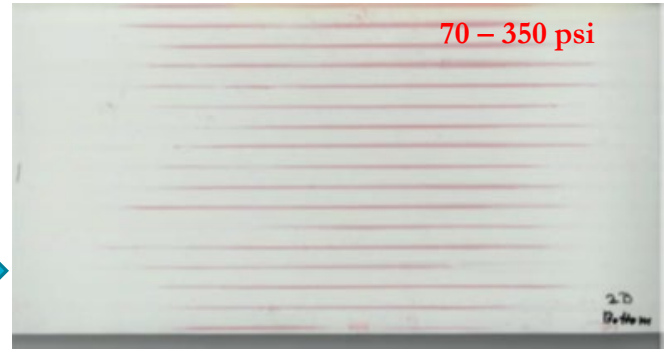
- Max contact pressure: 4.1 ksi

## Peak Strain



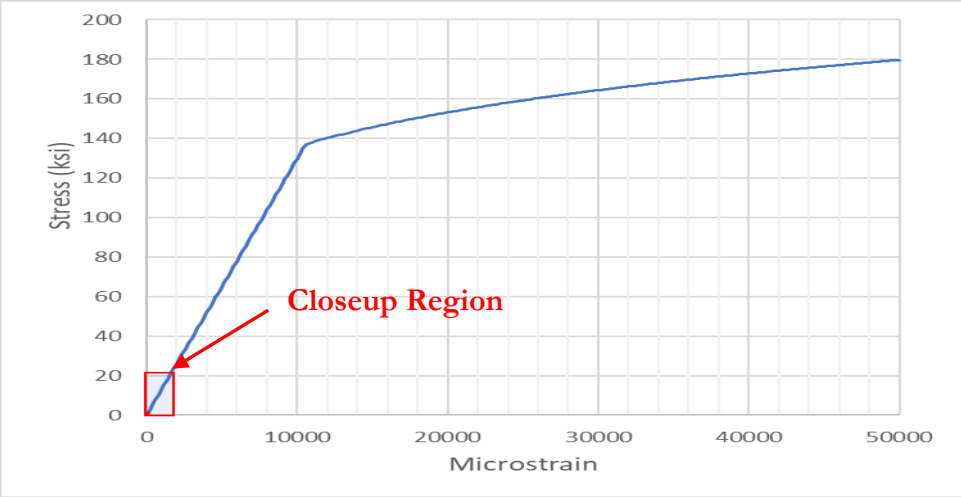

- Maximum strain: 1,724 microstrain

Pressure Paper Example

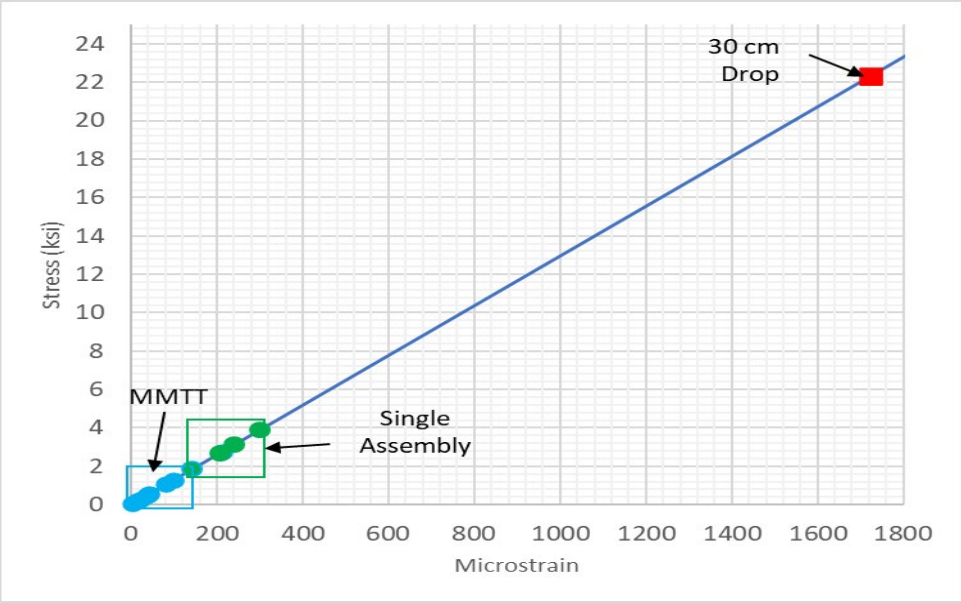


# Conclusions

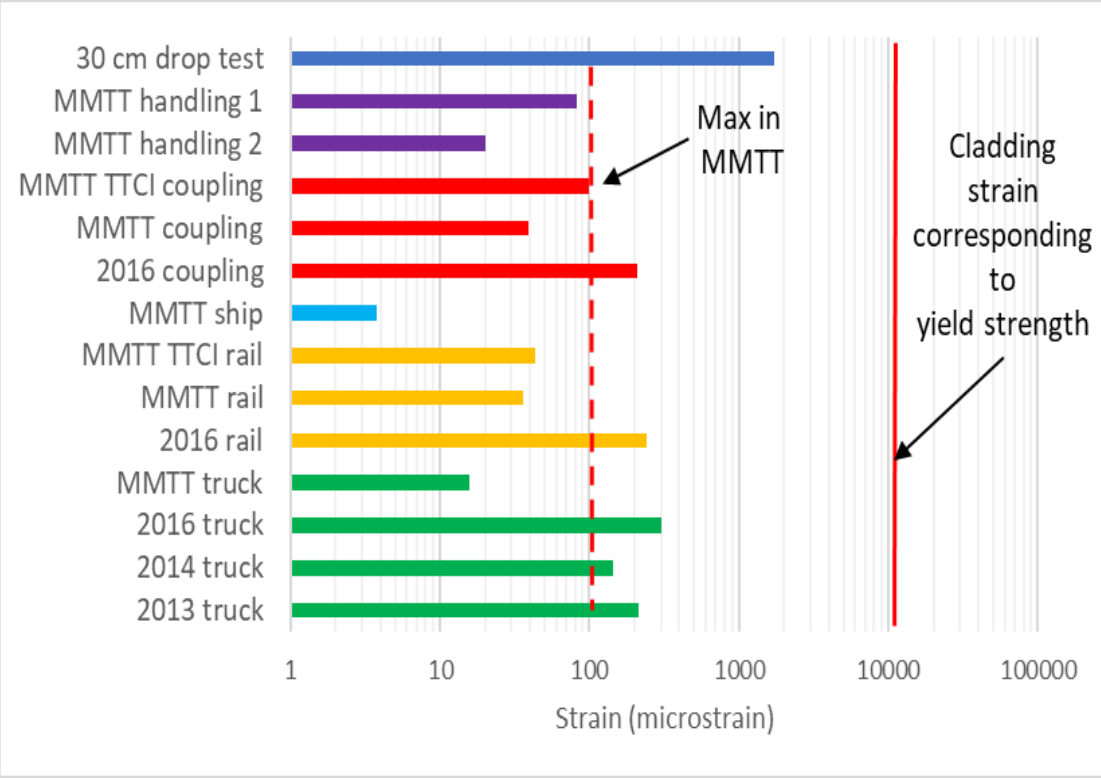
## Stress-Strain Curve for Low Burnup Cladding




## Closeup of the Stress-Strain Curve




## Maximum Strain Observed on the Assembly Rods




- The fuel rods will maintain their integrity during NCT - handling and loading operations, different modes of transport, and 30 cm drop.
- Tests with single surrogate assembly over estimate the stress on the assembly cladding.