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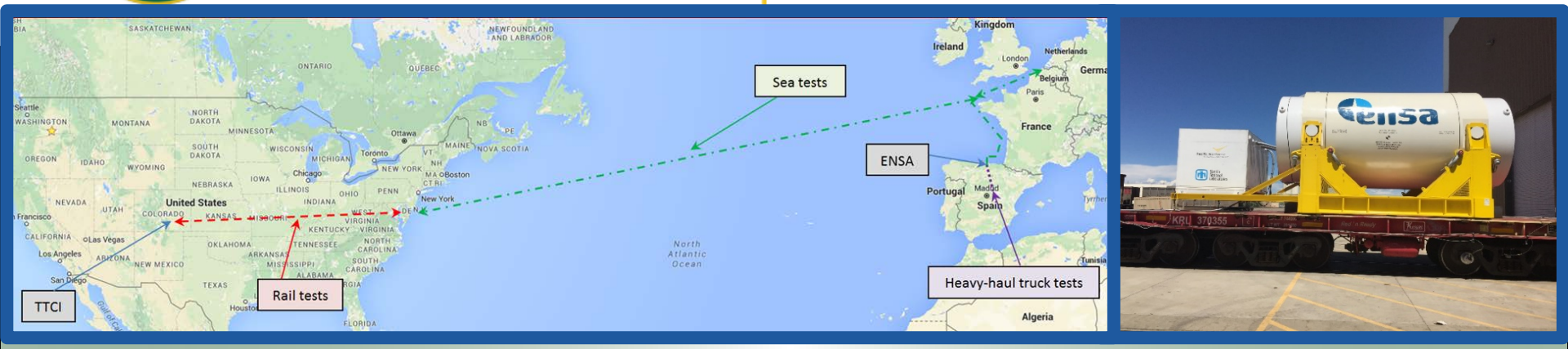

DOE:NE SPENT FUEL & WASTE SCIENCE & TECHNOLOGY

ENSA / DOE Multi Modal Transportation Dry Storage Cask Tests

INMM 2018, January 24, 2018, Alexandria, VA

Sylvia Saltzstein , Paul McConnel, Steve Ross, Elena Kalinina, et al.

Sandia National Laboratories,

Equipos Nucleares S.A.,

Pacific Northwest National Laboratory, & Transportation Technology Center, Inc.

Korea Radioactive Waste Agency (KORAD) & KAERI

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- 54 Days Data Collection (101,857 ASCII Files)
- 6 Terabytes of Data
- 9458 Miles • 7 Countries • 12 States

The ENSA/DOE Multi-Modal Transportation Test using the ENSA ENUN 32P Cask

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Why These Tests?
Measure Strains/Accelerations on Cask System Transporting Fuel Assemblies

- **Data will provide technical basis for asserting safety inherent in transporting spent fuel under normal conditions of transport.**
- **Could vibrations or shocks result in fatigue failure?**
  - ✓ ***Based on previous SNL tests, strains fuel rods experience due to vibration and shock during normal conditions of transport are far below yield strength and fatigue limits for cladding.***
  - ✓ ***Previous tests only simulations of configuration of actual SNF transport modes.***

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Cask Test Participants

- U.S. Department of Energy
- 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.
- Korea Radioactive Waste Agency (KORAD)
- Korea Atomic Energy Research Institute (KAERI)
- Korea Nuclear Fuel Company Ltd. (KNFC)
- Argonne National Laboratory (ANL)

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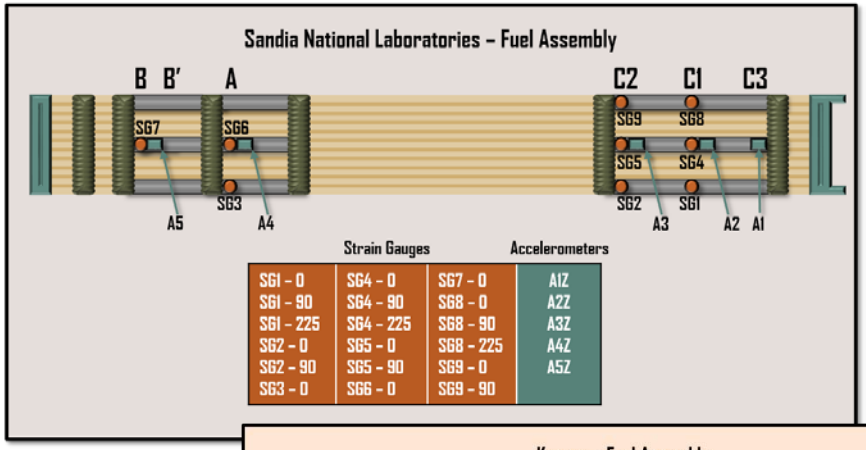
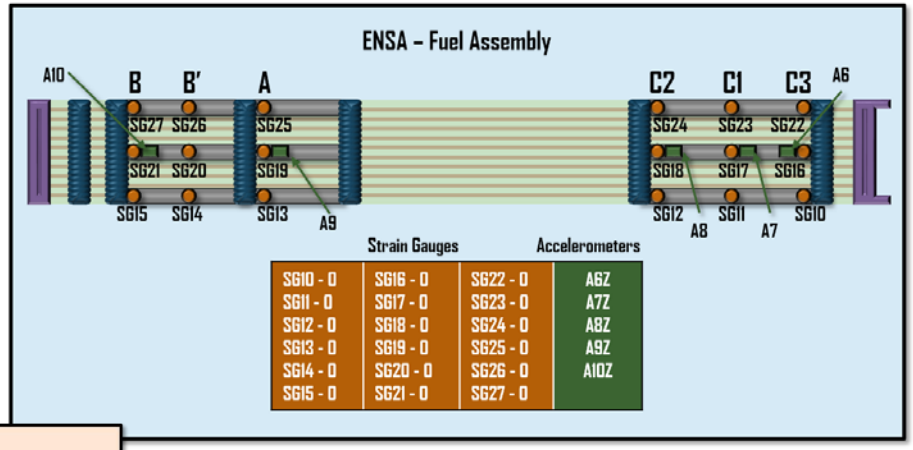
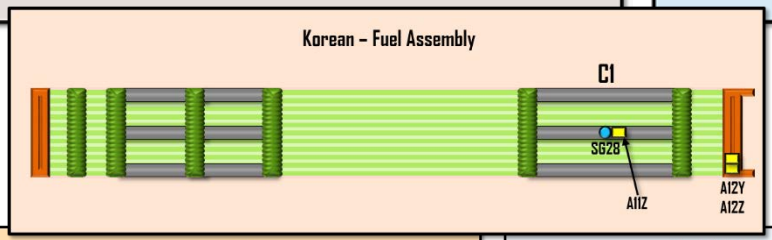
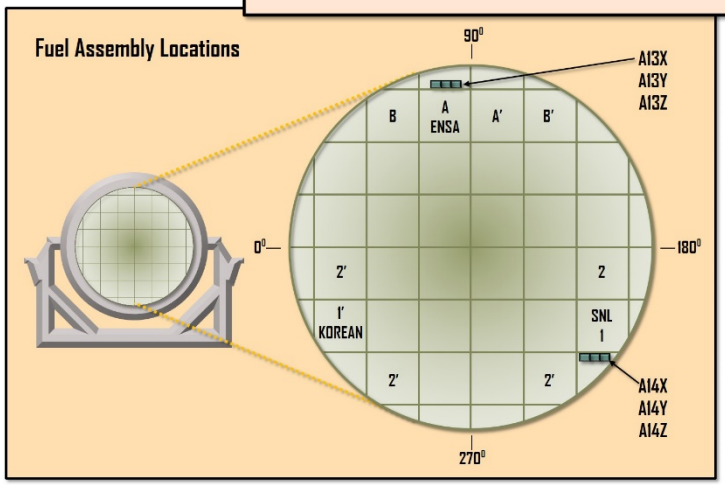
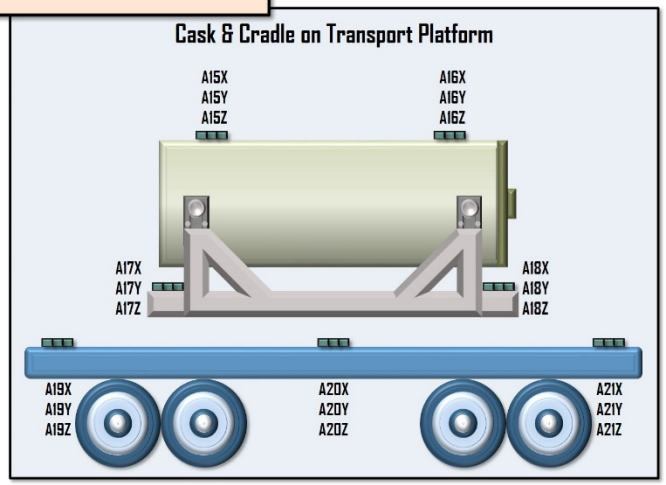
Accelerometer and Strain Gauge Locations











Assemblies & Cask System Instrumented with 77 Accelerometers & Strain Gauges

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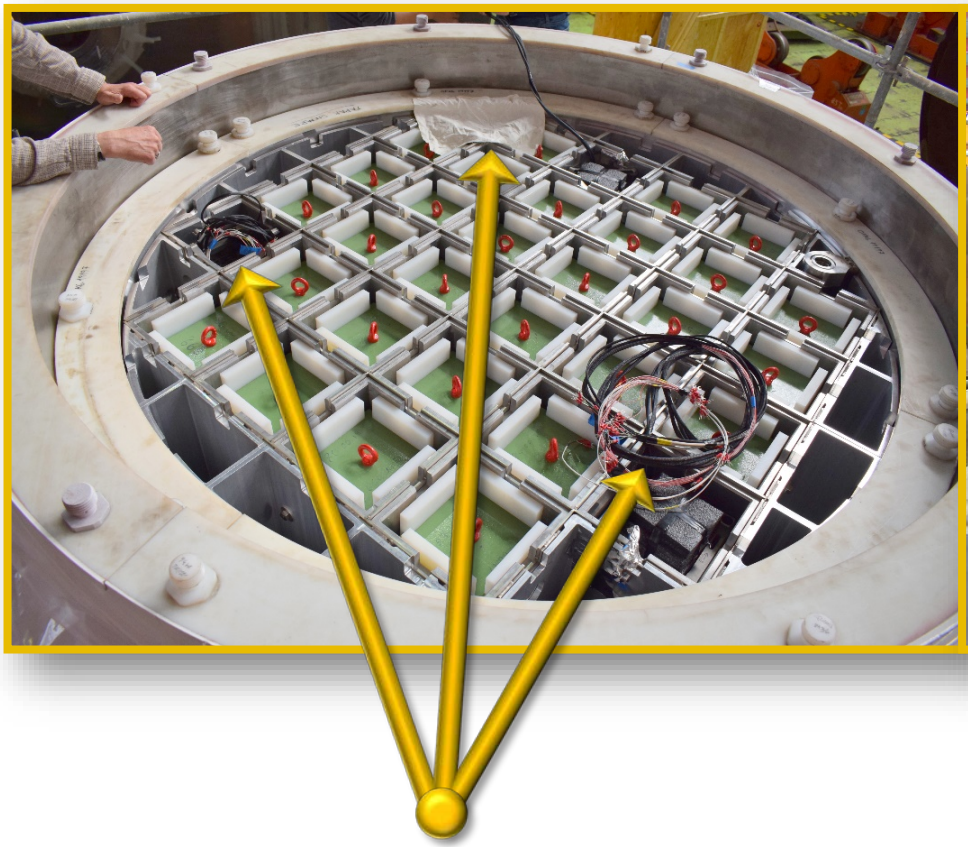
Cask Basket



Locations of the 3 PWR assemblies plus 29 dummy assemblies

Lid being placed on cask

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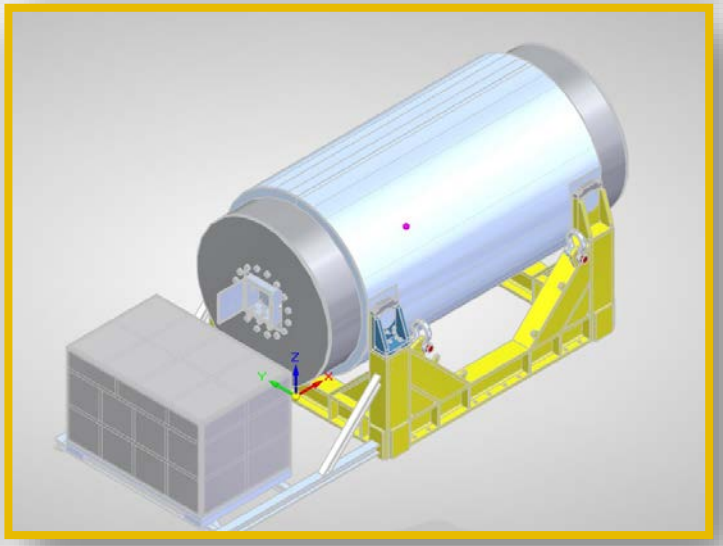
Instrumentation & Battery Box

Two 40-channel Data Acquisition Systems, 4000 lbs. of Batteries, 1.17 Miles of Cable



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Cask Test Route

Cask handling tests at ENSA, Santander/Spain (JUN 2017, 1 day)

Heavy-haul truck tests in northern Spain (JUN 2017, 2 days, 245 miles)

Ocean transport from Spain to Belgium (JUN 2017, 4 days, 939 miles)

Ocean transport from Belgium to Baltimore (JUL 2017, 14 days, 4222 miles, 6 days, 2000 miles)

Rail shipment from Baltimore to Pueblo (AUG 2017)

Testing at Transportation Technology Center, Inc., Pueblo (AUG 2017, 9 test days; 8 types of tests; 125 tests)

Rail shipment from Pueblo to Baltimore (OCT 2017, 18 test days, 1125 test miles)

Ocean transport from Baltimore to Spain (DEC 2017)

Cask handling tests performed in Spain by three different crane operators experienced in dry cask movement.

Each operator performed three tests.

Cask placed onto concrete pad with varying degrees of force.

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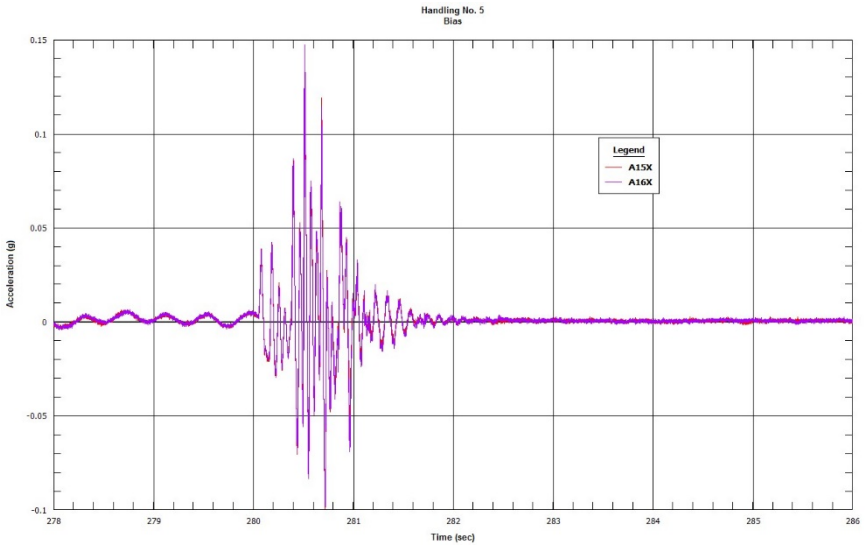
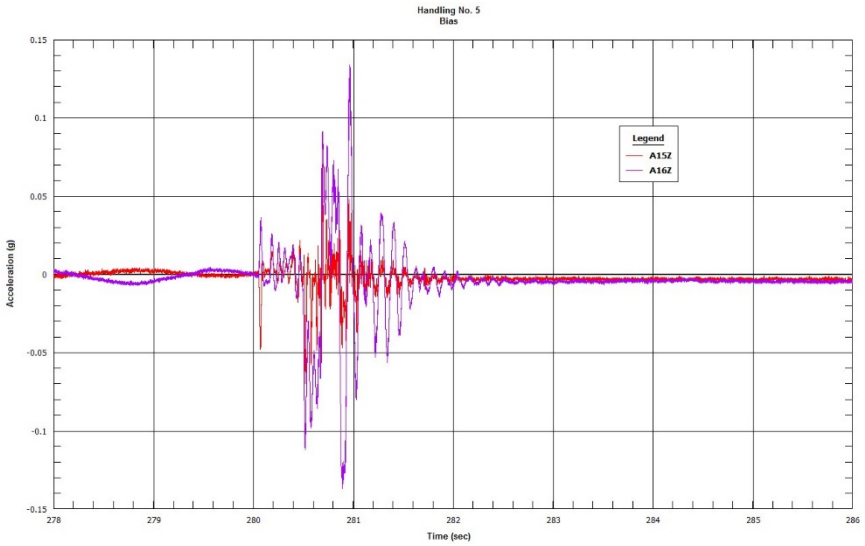
Preliminary Cask Handling Test Accelerometer & Strain Gauge Data

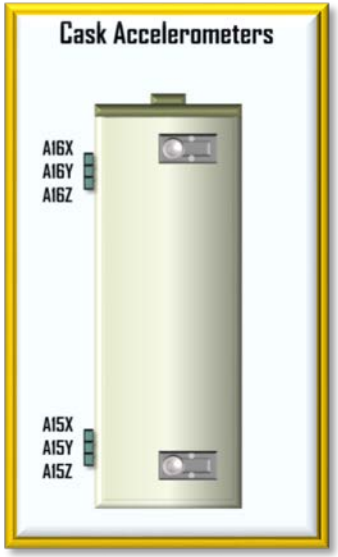
Maximum Cask Acceleration = 0.15 g

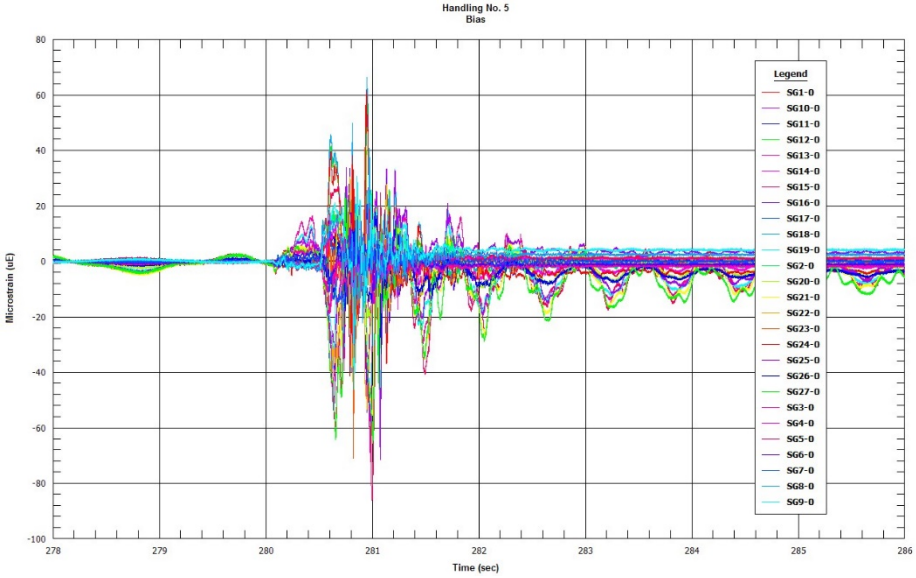
Maximum Assembly Strain = 87 µm/m





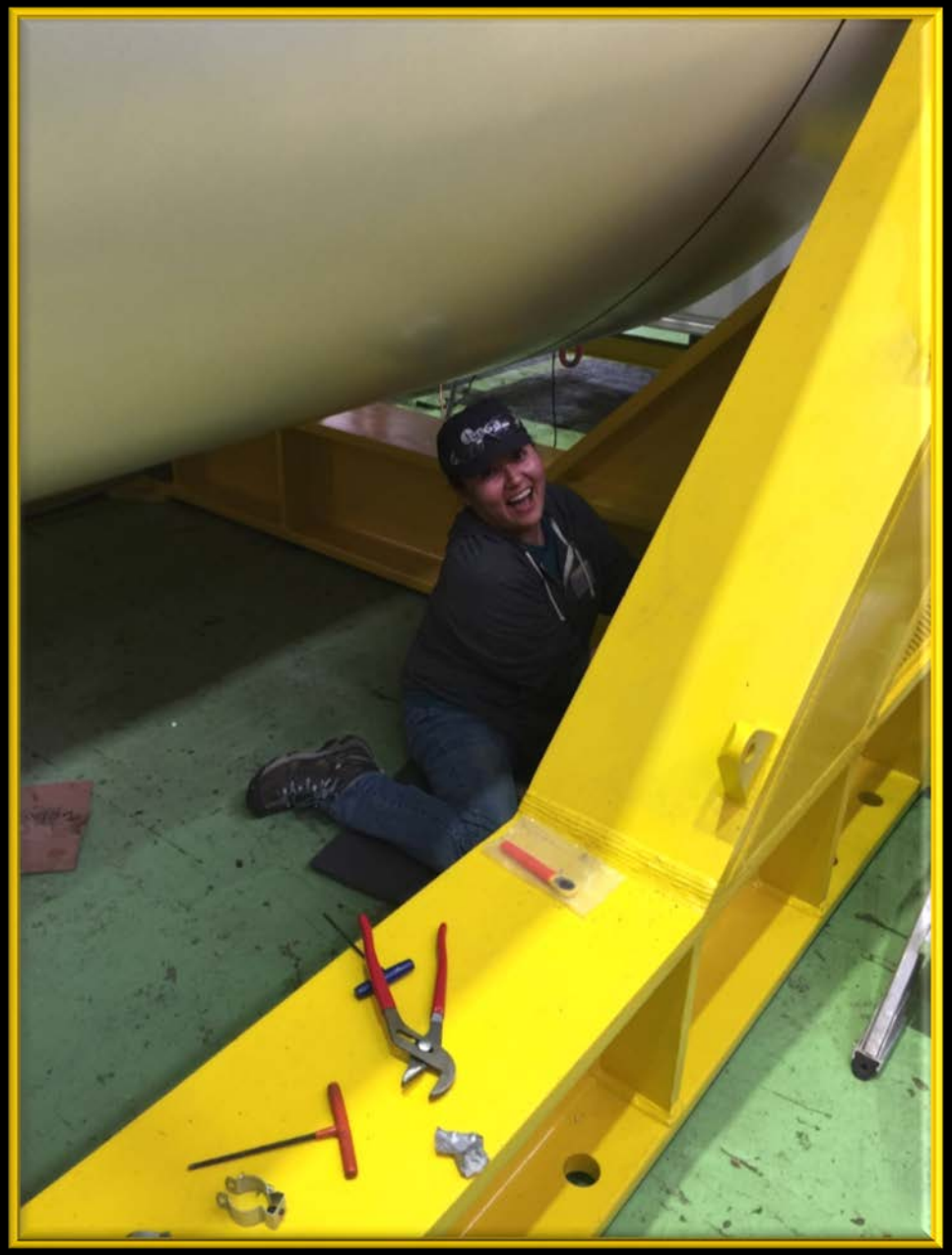
FY18 will examine frequency transmission, instantaneous loading v. gross loading, etc.





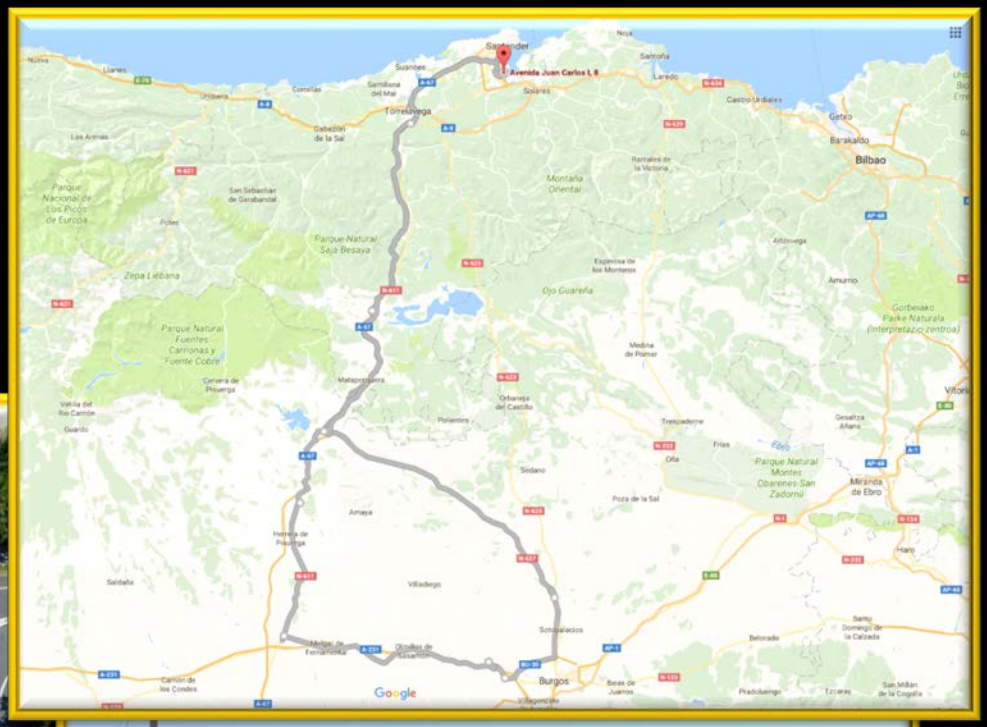
Placement of battery and data acquisition box onto cradle extension (after placing cask onto cradle).

Accelerometers placed on basket, cask, cradle, and transport platforms as well as on surrogate fuel assemblies



Loading on 16-axle, 110 foot-long truck.
Truck trailer had 3 sets of triaxial accelerometers on bed.

Heavy-haul truck route through northern Spain – Burgos to Maliaño.
(Round Trip)



Many *rotondas…*

… and tiny villages negotiated.

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Preliminary Heavy-Haul Truck Test Data

Maximum Cask Acceleration = ≤0.2

Maximum Assembly Strain = 86 µm/m

Maximum Assembly Strain, µm/m	Maximum Platform Acceleration, g	Maximum Cask Acceleration, g	Maximum Cradle Acceleration, g	Maximum Basket Acceleration, g	Maximum Assembly Acceleration, g
86	4.2	≤0.2	≤0.2	≤0.2	0.74

After heavy-haul truck test, cask loaded onto “Autosky” at Port of Santander.

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Intercoastal Ship Test Data

Maximum Cask Acceleration = ≤0.3

Maximum Assembly Strain = 86 µm/m

Maximum Assembly Strain, µm/m	Maximum Platform Acceleration, g	Maximum Cask Acceleration, g	Maximum Cradle Acceleration, g	Maximum Basket Acceleration, g	Maximum Assembly Acceleration, g
≤0.2	0.86	≤0.3	≤0.3	≤0.3	≤0.3

Cask system then loaded onto "Tarago" at Port of Zeebrugge for transport to USA.

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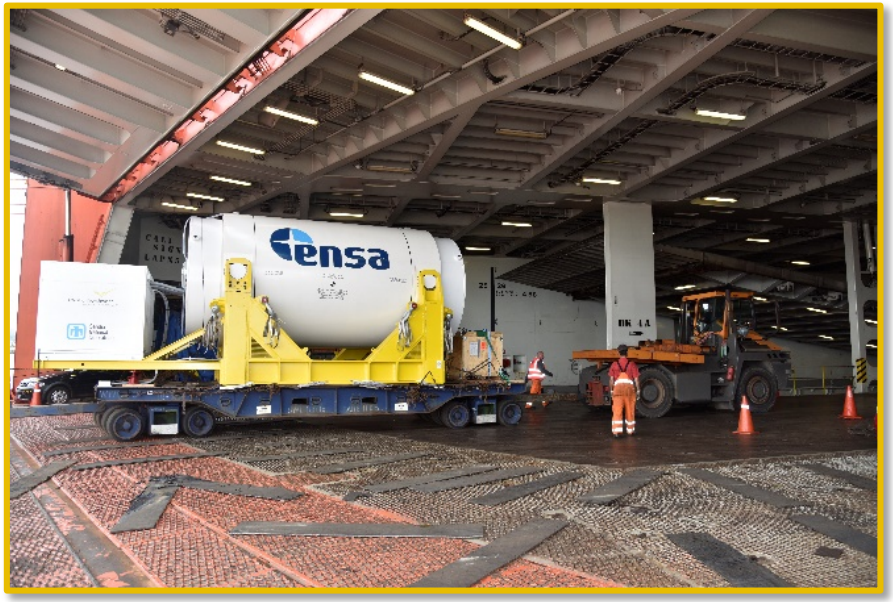
Preliminary Transoceanic Ship Test Data

Maximum Cask Acceleration = ≤0.2

Maximum Assembly Strain = ≤ 20 µm/m



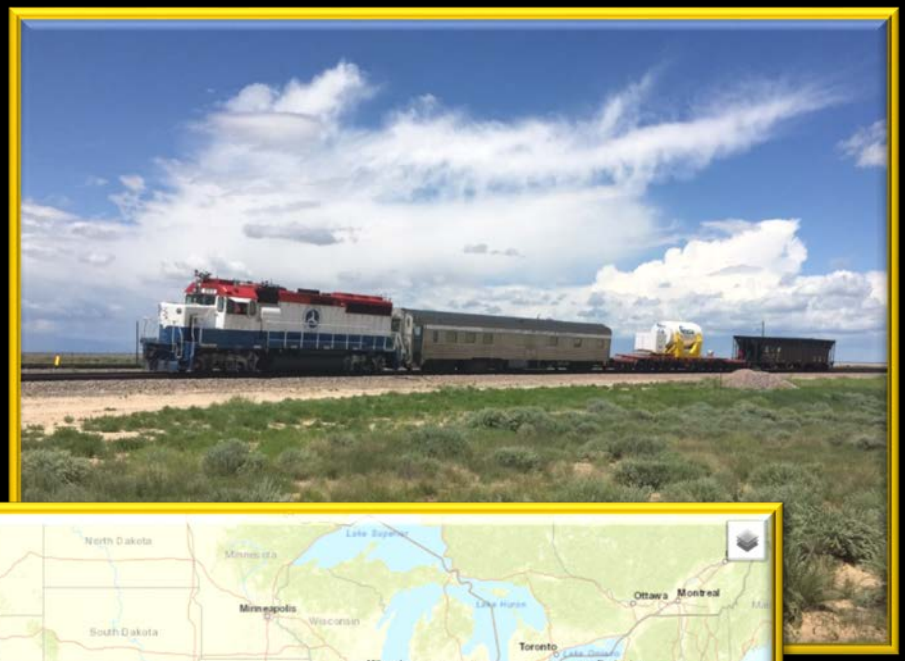
Maximum Assembly Strain, µm/m	Maximum Platform Acceleration, g	Maximum Cask Acceleration, g	Maximum Cradle Acceleration, g	Maximum Basket Acceleration, g	Maximum Assembly Acceleration, g
≤20	0.38	≤0.2	≤0.2	≤0.2	≤0.2

Cask then transferred onto 12-axle Kasgro railcar at Mid-Atlantic Terminal, Baltimore.

Witnessed by DOE, NRC, USCG

While not a 2043 railcar, the 12-axle Kasgro railcar is expected to bound the strains and accelerations seen in a 2043.

Cask transported by rail to TTCI for series of rail tests.



Map from ANL Traveler GPS

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Cross-Country Rail Test Data

Maximum Cask Acceleration = 0.42

Maximum Assembly Strain = 47 µm/m

Maximum Assembly Strain, µm/m	Maximum Platform Acceleration, g	Maximum Cask Acceleration, g	Maximum Cradle acceleration, g	Maximum Basket Acceleration, g	Maximum Assembly Acceleration, g
47	8.40*	0.42	0.70	0.40	1.30

** This platform acceleration does not appear in other accelerometers. This will be investigated further, but appears to be a local, instantaneous load which does not correspond to significant structural loading.*

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Rail Tests Conducted at TTCI

8 Types of Tests
125 Separate Tests

- **Twist & Roll Tests (18)**
  - Determines car's ability to negotiate oscillatory cross-level perturbations.
- **Pitch & Bounce Tests (9)**
  - Determines car's ability to negotiate parallel vertical rail perturbations.
- **Dynamic Curving Tests (25)**
  - Determines car's ability to negotiate curving over jointed track with combination of lateral misalignment at outer rail joints and cross-level due to low joints on staggered rails.
- **Tests at U.S. Army Pueblo Chemical Depot (17)**
  - Determines performance over FRA Class-2 railroad track and tests through No. 8 turnout and No. 8 crossovers.
- **Single Bump Tests (12)**
  - Determines performance at grade crossings.
- **Crossing Diamond Tests (6)**
  - Determines vehicle's behavior when crossing diamonds (or "frogs'), a leading cause of derailments.
- **Loaded Hunting on Railroad Test Track and Transit Test Track (30)**
  - Determines stability at 30, 40, 50-75 mph at 5 mph increments.
- **Coupling Impact Tests (10)**
  - Determines longitudinal inputs from coupling at higher than normal speeds.

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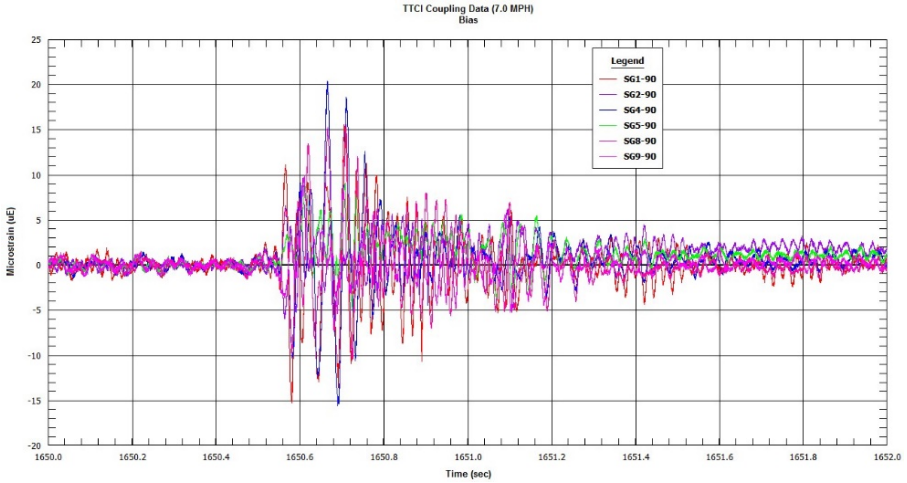
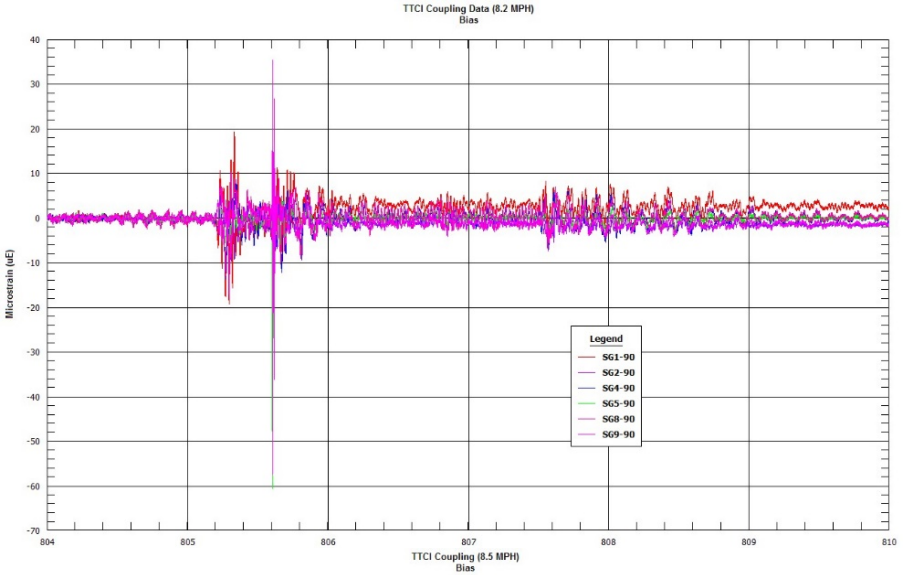
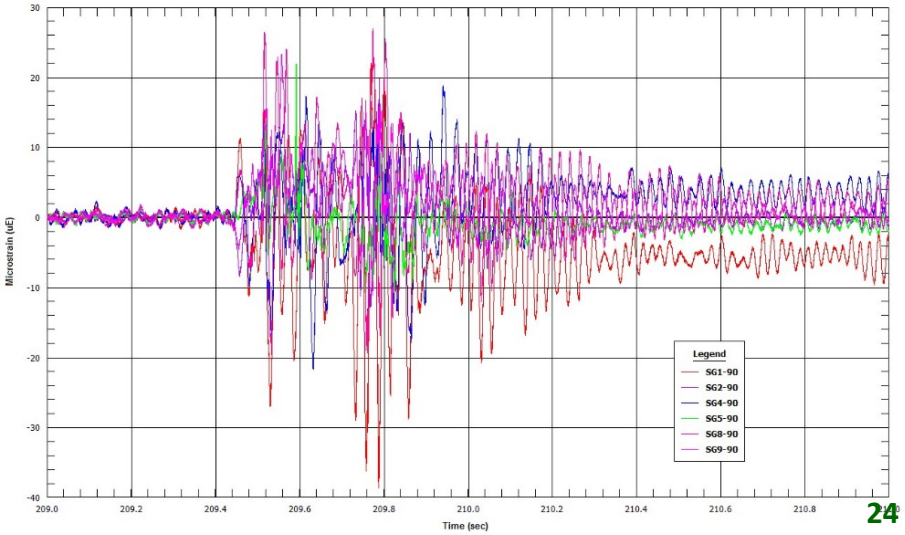
Railcar Coupling at 7.0, 8.2, 8.5 mph

SNL Assembly Strain Gauge Data

Maximum Assembly Strains = 39, 92, 77 µm/m







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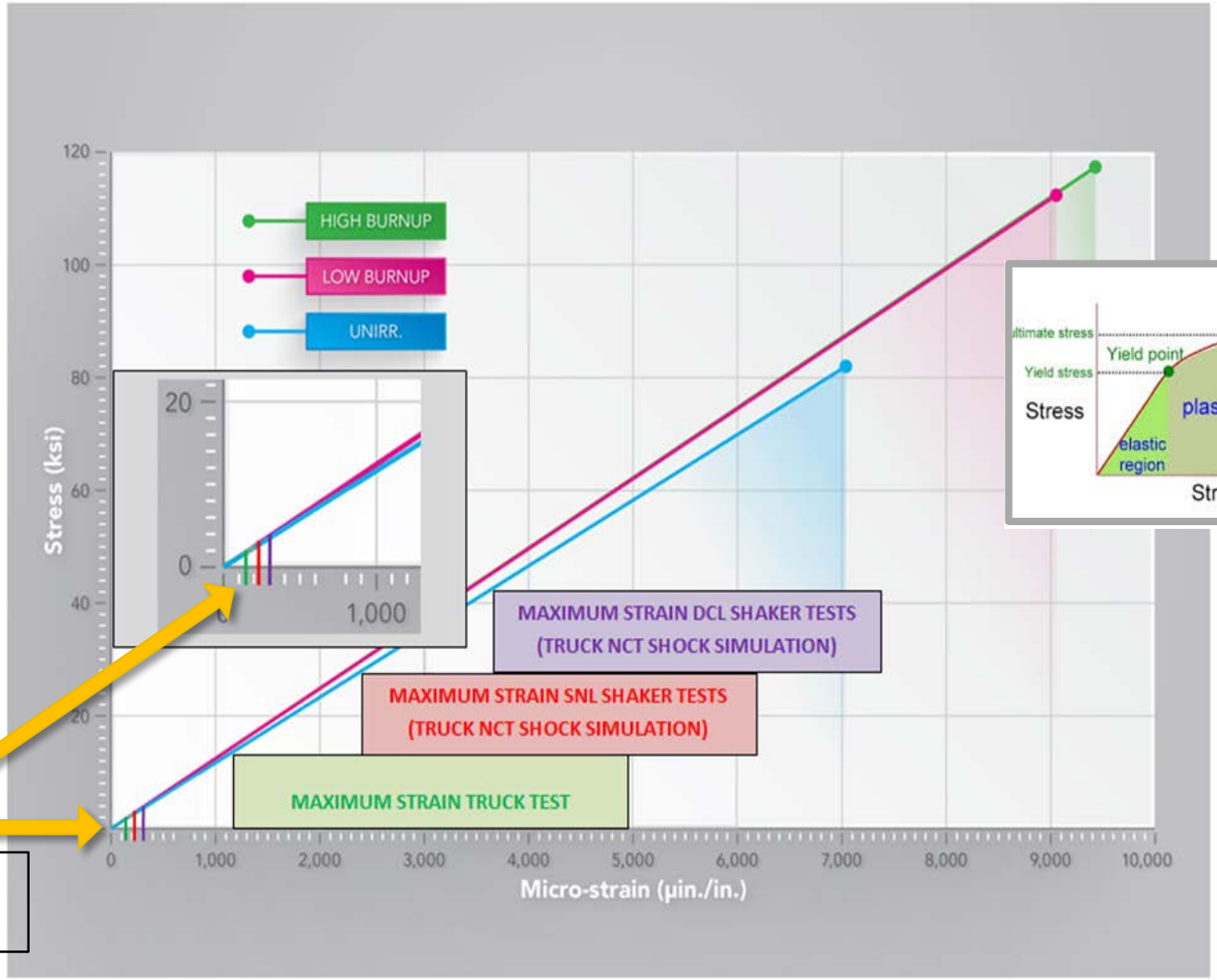
Assembly Strains in Rail-Cask Tests

Sister Rod Tests will confirm post drying high burnup cladding yield points



Cask Tests Max. Strain

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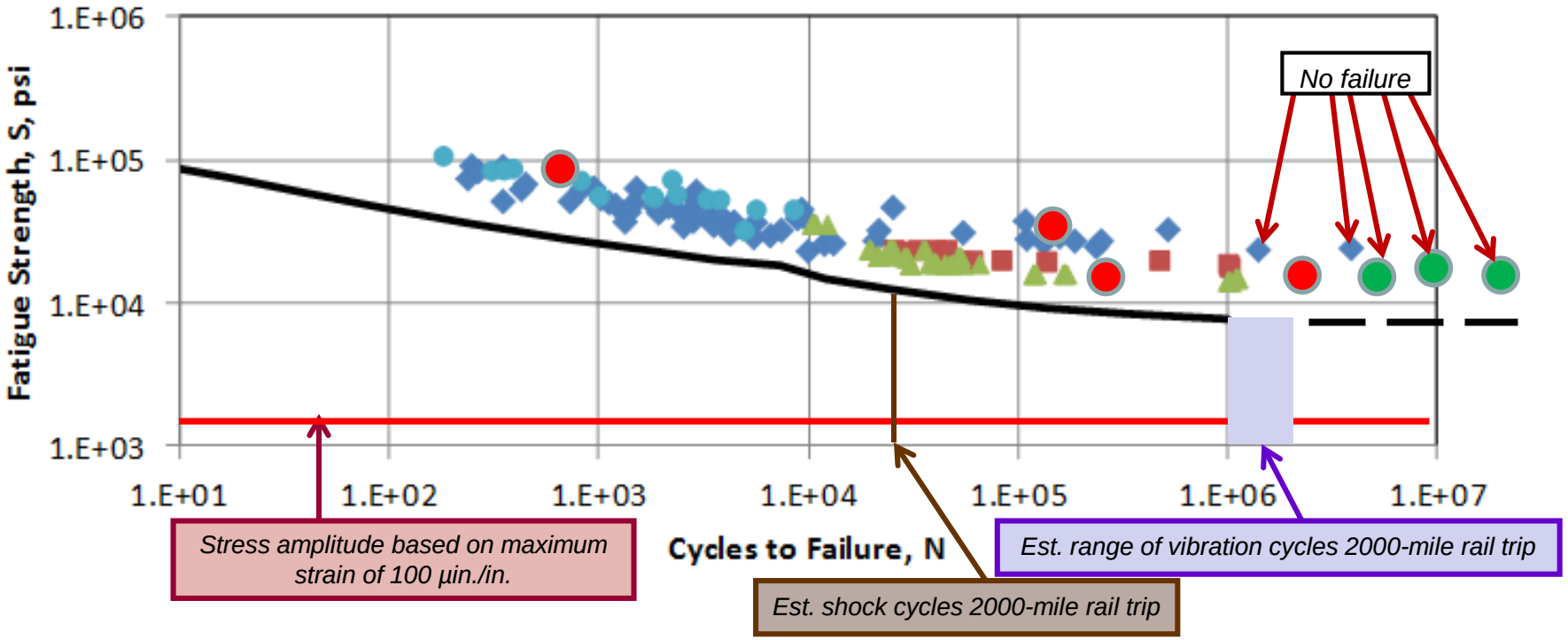
Could Vibrations or Shocks Result in Fatigue Failure?



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)

Data plot courtesy of Ken Geelhood, PNNL
The large circles are ORNL HBR data

Realistic stresses fuel rods experience due to vibration and shock during normal transportation below yield and fatigue limits for cladding.

FY18 to be spent analyzing data and modeling to allow us to relate these results to other casks/transportation systems and other fuel mechanical properties.

Questions?

BACKUP SLIDES

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ENSA Cask US Rail Transportation Experience

- **Dedicated Rail from Baltimore to Pueblo (~7 days)**
  - ***Significant cost increase***
  - ***Known route***
- **Regular Freight from Pueblo to Baltimore (~40 days)**
  - ***~50 stops of an hour or greater***
  - ***No communication about route***

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Analysis Method for Cask Test Data (FY18)

Detailed Analysis of Accelerometer & Strain Gauge Data

- Analyze time history *(corrected for bias)* of each sensor.
- Calculate minimum/maximum values for each time history.
- Perform multiple comparisons of valid time histories and corresponding Shock Response Spectra (SRS) to define relationships between different systems
  - ✓ *Transportation Platform*
  - ✓ *Cradle*
  - ✓ *Basket*
  - ✓ *Cask*
  - ✓ *Assemblies*
- Identify conclusions regarding system behavior.
- Relate this data to fuel mechanical properties.

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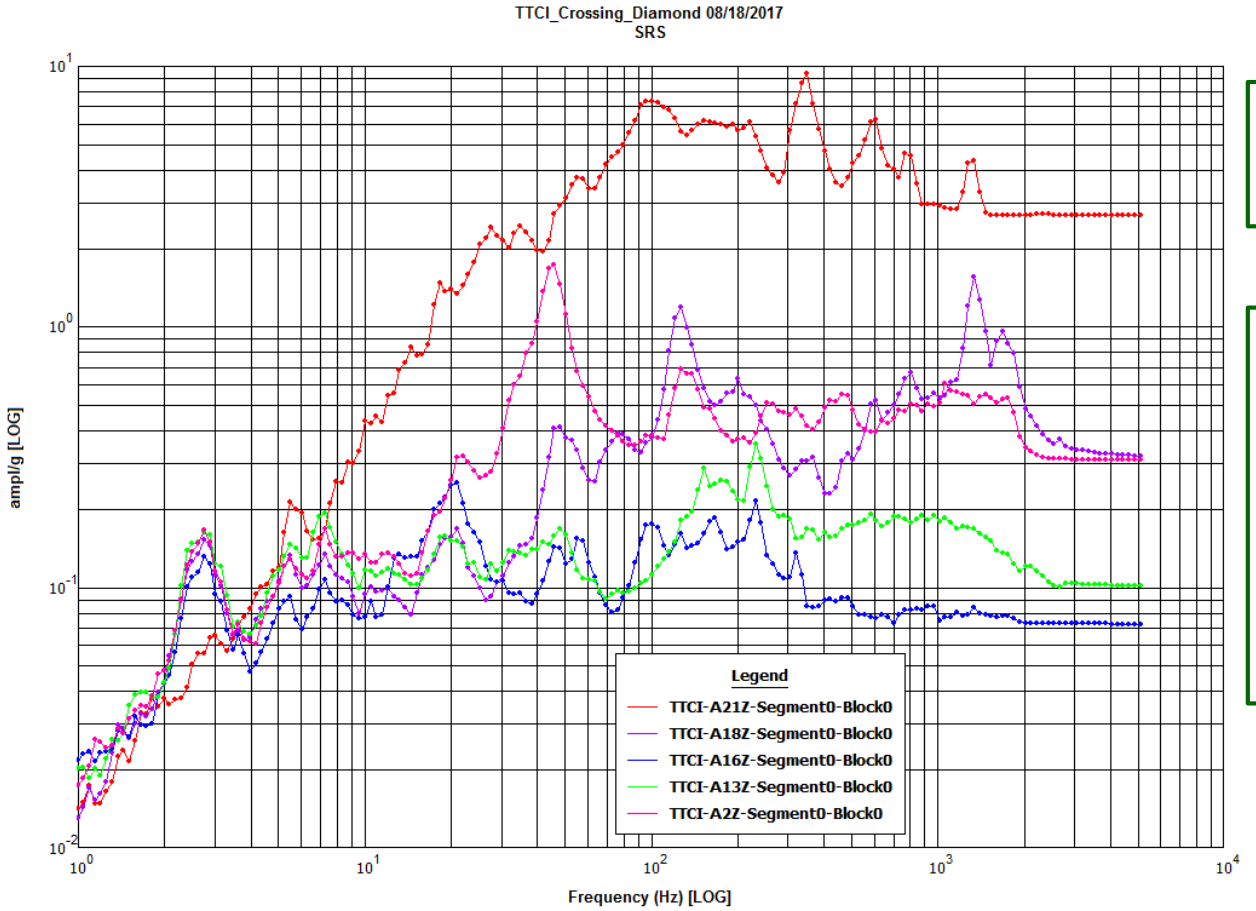
Preliminary Example of Analysis
Shock Response Spectra (SRS) of Cask System Components



TRANSPORTATION PLATFORM

CRADLE ASSEMBLY

BASKET

CASK

SRS of railcar different from other systems.

Assembly and cradle have similar SRSs – Basket and cask have similar SRSs.

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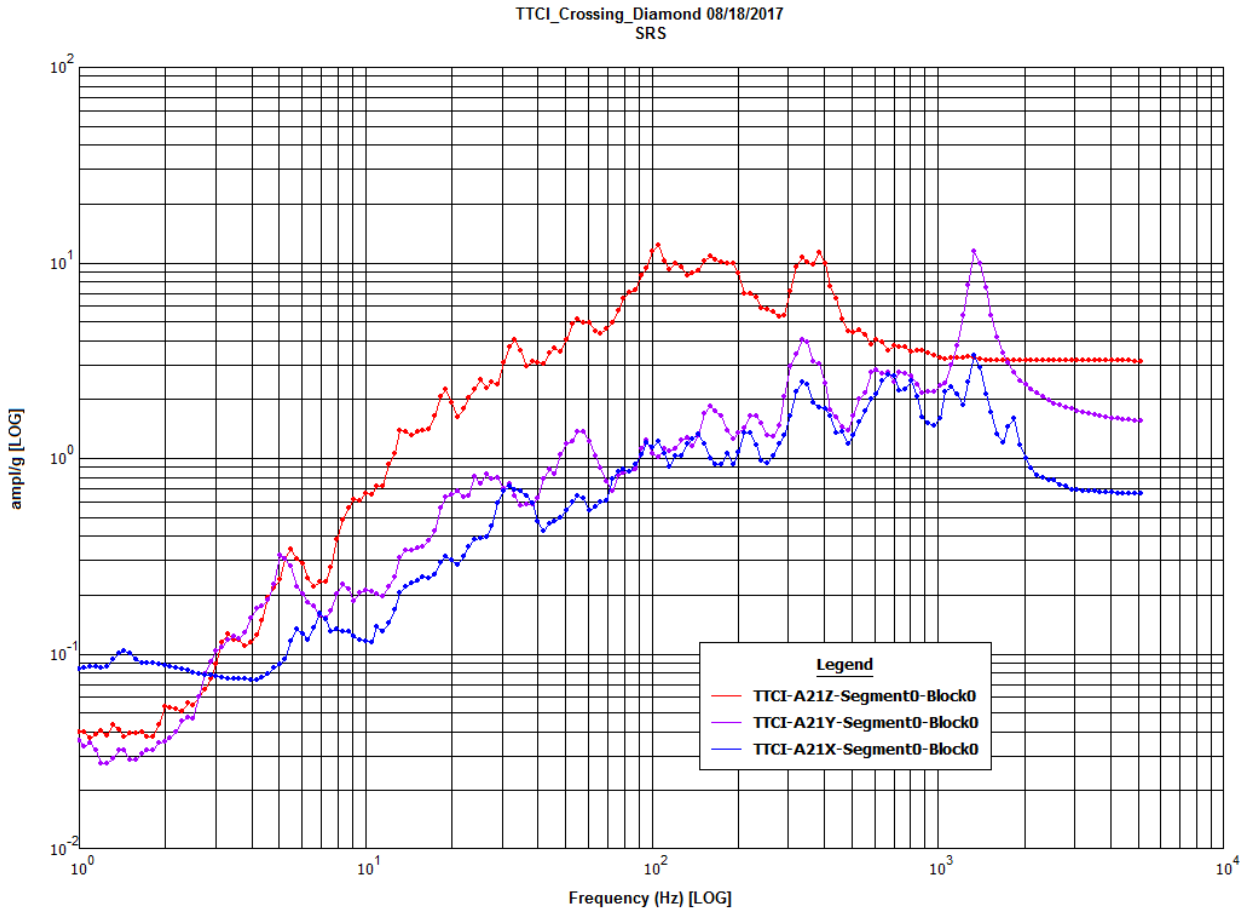
Preliminary Example of Analysis
Railcar SRSs in X, Y, Z



Transportation platform acceleration in Z direction is greater than in X and Y, except at frequencies < 3Hz and one high frequency peak.

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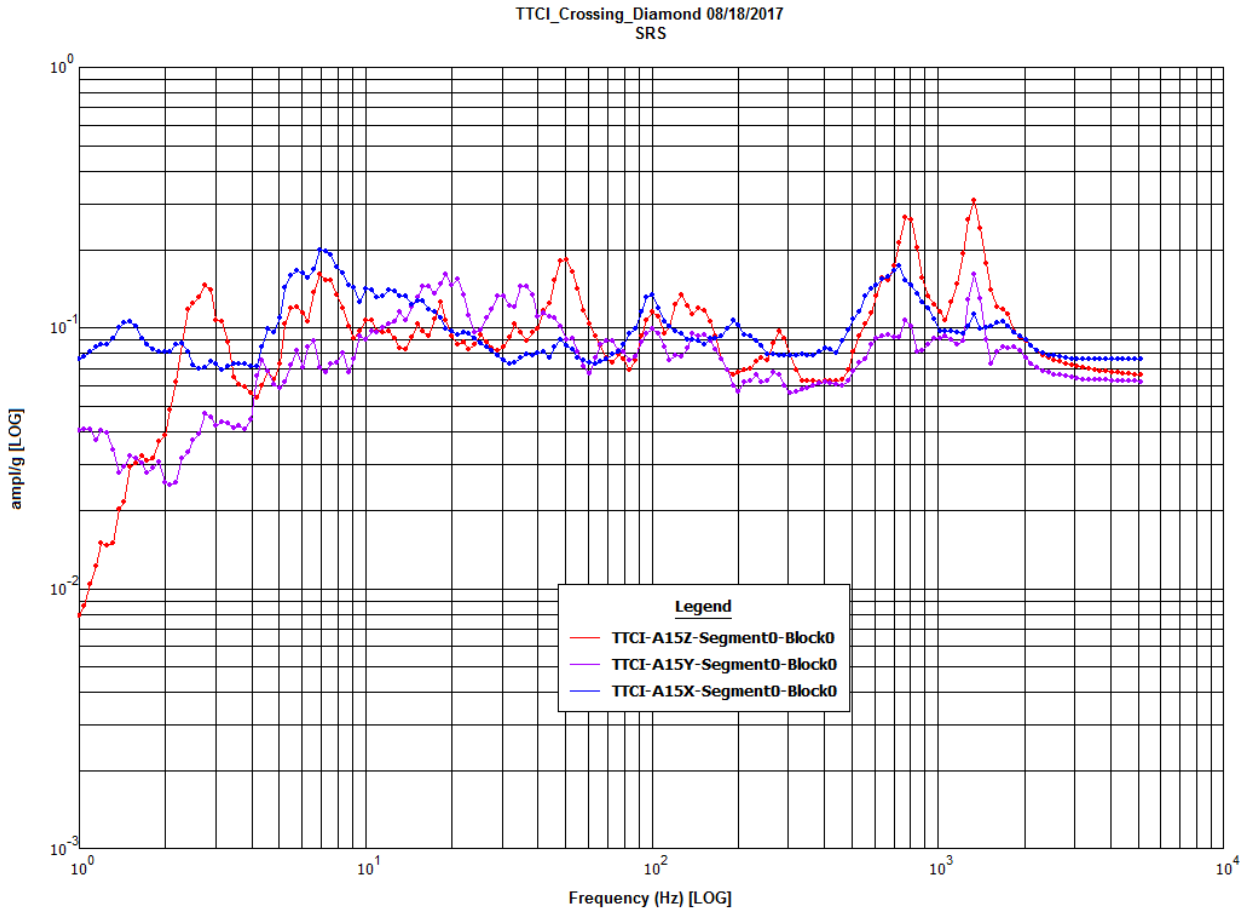
Preliminary Example of Analysis
Cask SRSs in X, Y, Z



Cask acceleration in Z direction is comparable to its acceleration in X and Y.

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Examples of Preliminary Conclusions

Detailed Analyses & Correlations Forthcoming in 2018

- Railcar midsection has lower acceleration than back and front ends.
- Accelerations on railcar significantly higher than accelerations measured on cradle, cask, basket, and assembly.
- Assembly and cradle have similar SRSs.
- Basket and cask have similar SRSs.
- Assemblies have different normalized acceleration amplitudes, but peaks occur at same Hz.
- Railcar acceleration in Z direction is greater than in X and Y, except at frequencies < 3Hz and one high frequency peak.
- Cask acceleration in Z direction comparable to acceleration in X and Y.
- Acceleration of transportation platform in X direction significantly higher than acceleration measured on cradle and cask in X direction.
- Greater strains on assembly back end than on front end, consistent with higher accelerations on back end.