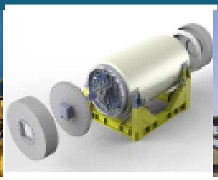
SAND2021-12990PE

Transportation Experiments



PRESENTED BY

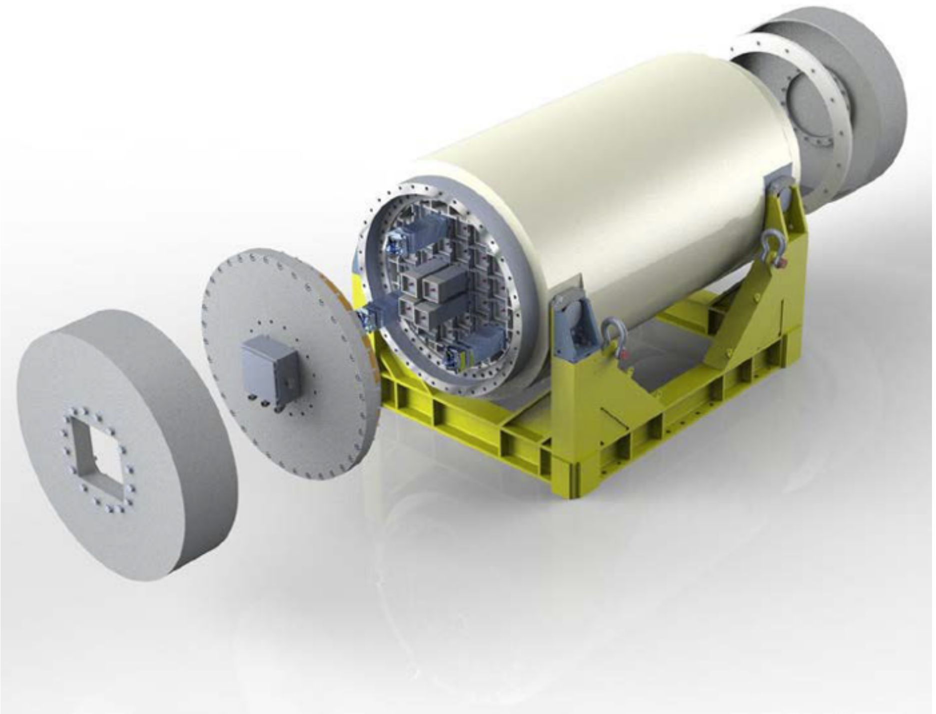
Elena Kalinina

Collaborators

- 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. (TTCI)
- Korea Radioactive Waste Agency (KORAD)
- Korea Atomic Energy Research Institute (KAERI)
- Korea Nuclear Fuel Company Ltd. (KNFC)

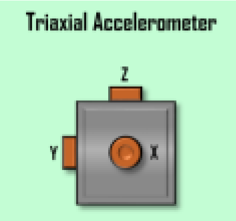
Link to video documenting the major test events:
https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be

Cask Diagram

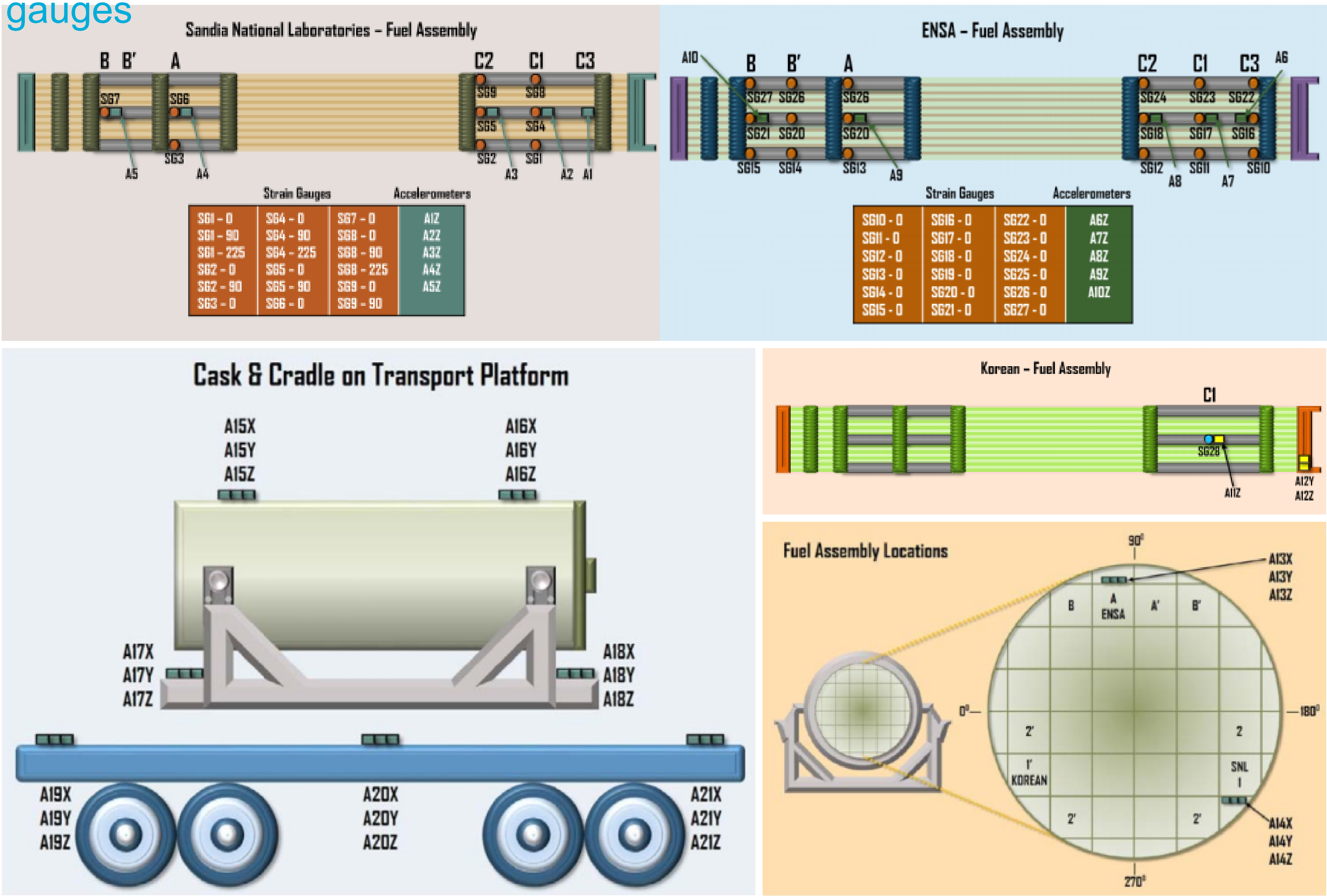


- Length: 5 m
- Body diameter: 2.65 m
- Loaded weight of carbon steel cask: 120 tons
- Loaded weight with surrogate impact limiters: 137 tons

Instrumentation of the Transportation System



40 accelerometers, 37 strain gauges



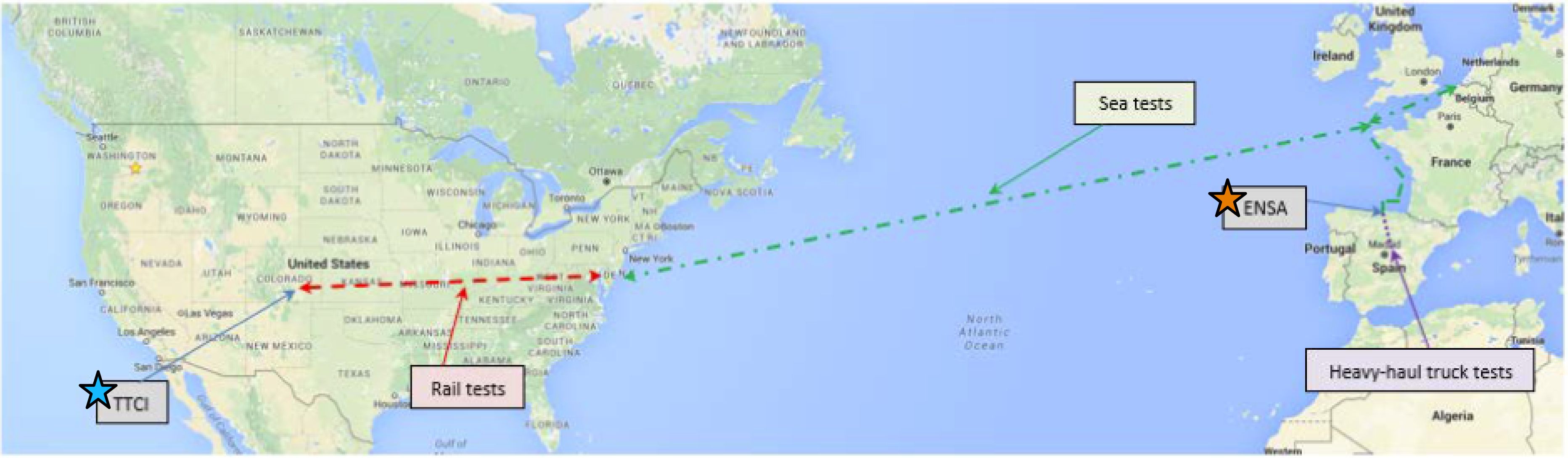
Transportation Configurations

Heavy haul truck transport through Spain

Barge and ocean ship transport

Rail transport and testing – Kasgro 12-axle railcar

Transportation Triathlon Route



- ➢ Cask handling tests at ENSA, Santander/Spain ★
- ➢ Heavy-haul truck tests in Northern Spain (245 miles)
- ➢ Barge 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 (not recorded)

Total distance traveled with data acquisition: 8539 miles

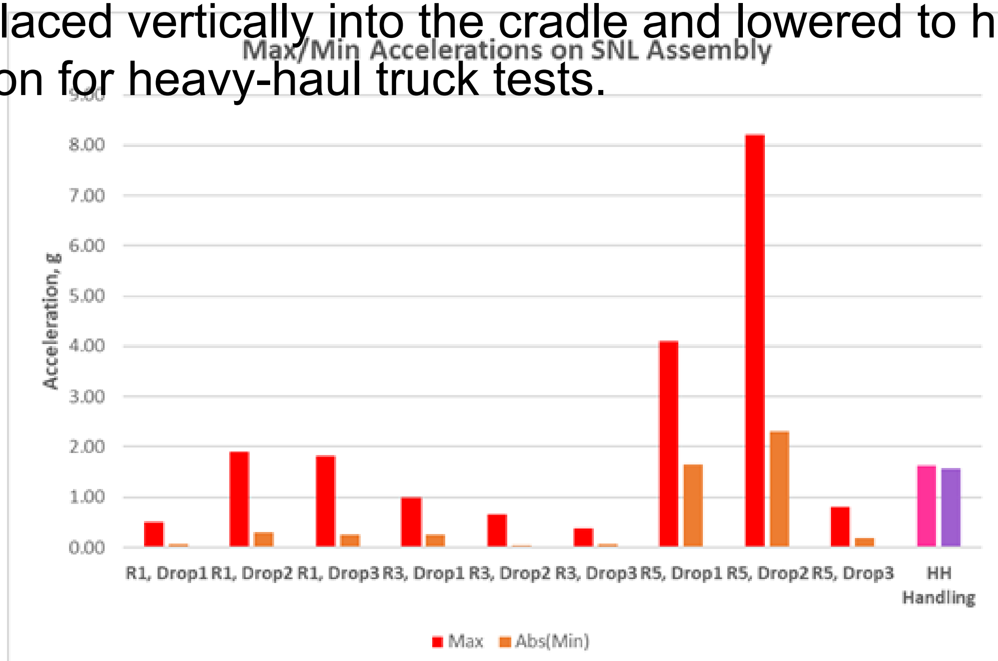
Cask Handling

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

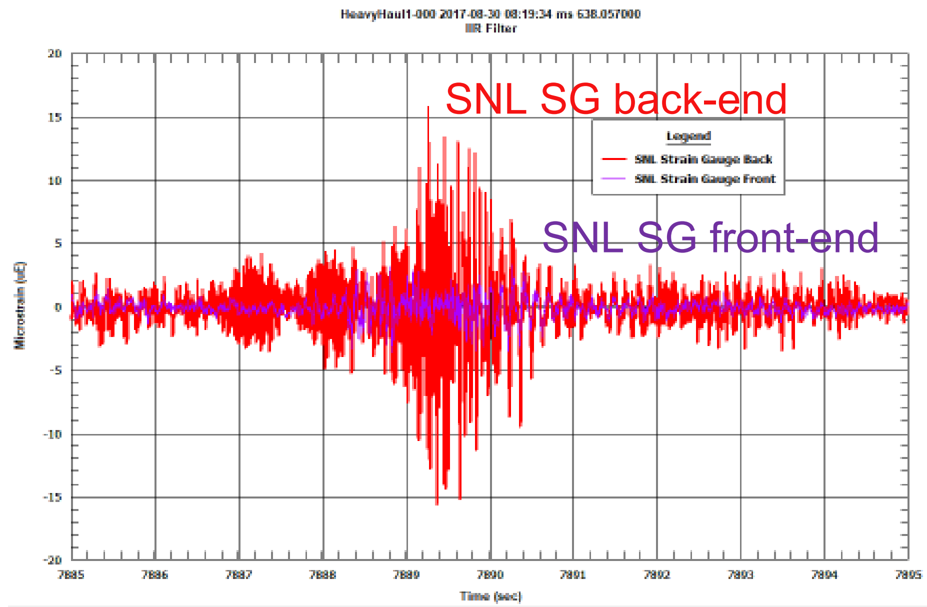
Heavy-Haul Handling Test

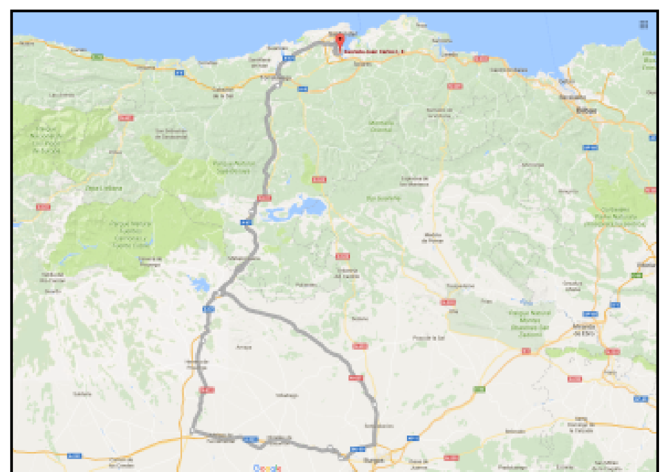
- Cask was placed vertically into the cradle and lowered to horizontal position in preparation for heavy-haul truck tests.



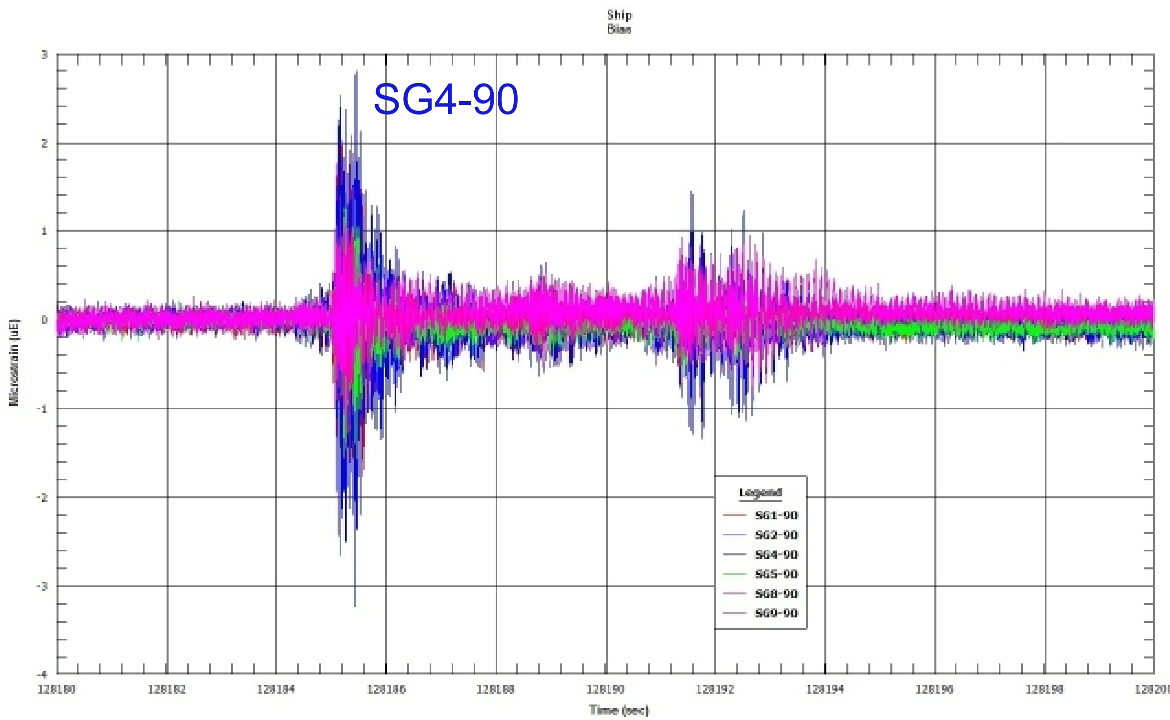
Heavy-Haul Truck Transport

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





Barge and Ocean Ship Transport



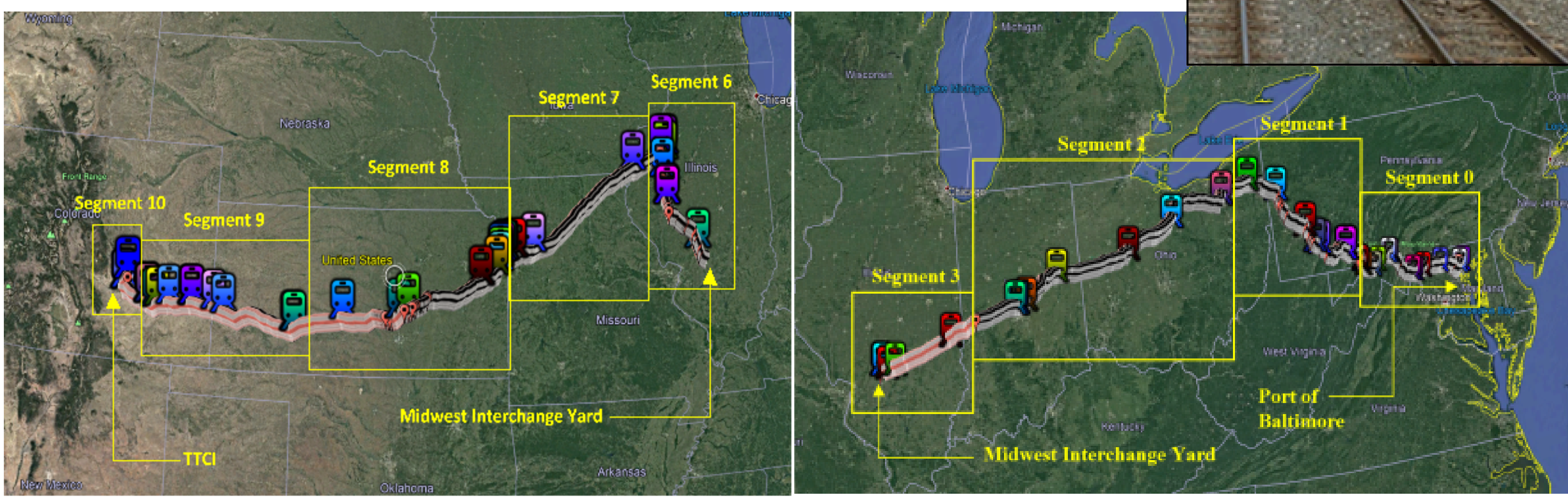
- Observed accelerations and strains were overall very low
- Accelerations (mostly) ≤ 0.3 g, and strains consistently ≤ 4 µE
- Maximum acceleration:
  - Transport platform: 0.38 g
  - Assembly: 0.12 g
- Maximum strain on the SNL assembly: 2.8 µE

Rail 1: Baltimore to TTCI (Pueblo, CO)

- **Total distance:** ***1,950 miles***
- **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 indicated places the train stopped. Rail 1 was recorded over 10 segments of data.

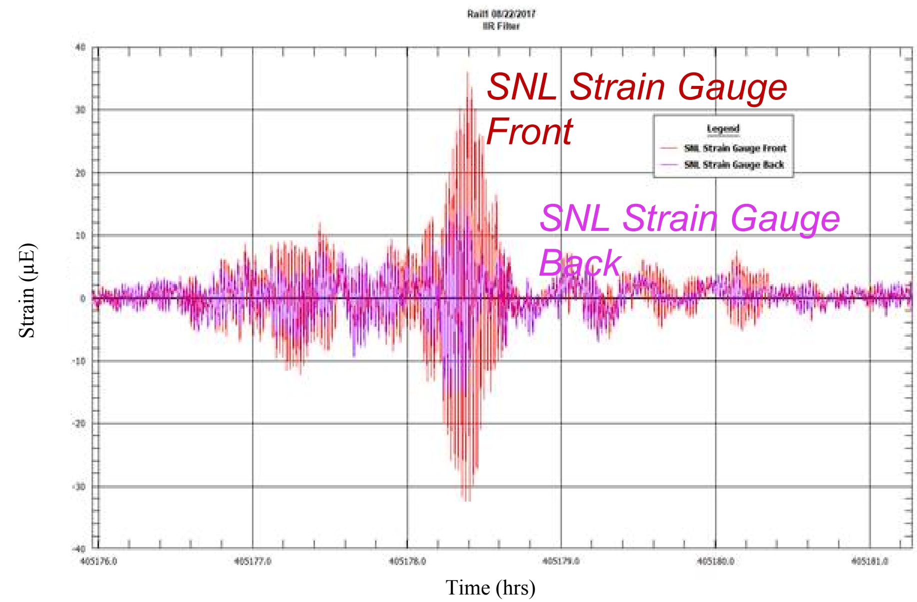
Rail 1: Baltimore to TTCI (Pueblo, CO) - Analysis

<u>Max Acceleration Event</u>

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

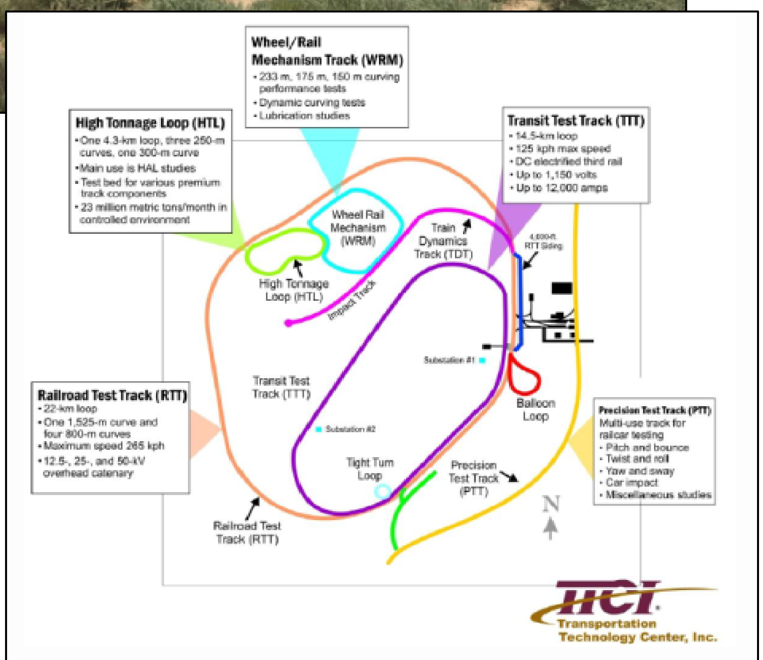
<u>Max Strain Event</u>

- 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



Maximum Strain Event Time History

Rail Tests at the TTCI - Testing

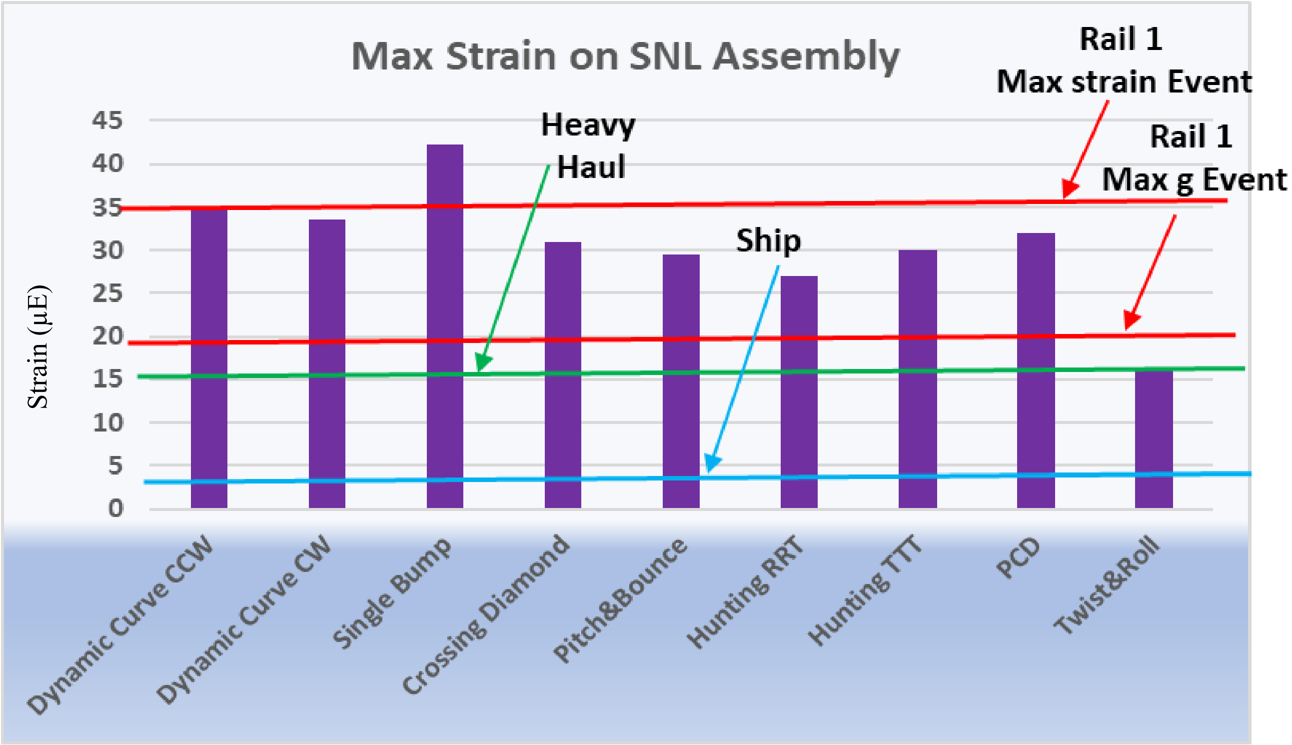


Test Description	Number of Tests
Twist and Roll	19
Pitch and Bounce	9
Dynamic Curve	24
Class 2 Rail Track (PCD)	17
Single Bump	8
Crossing Diamond	6
Hunting	23
Coupling Impact	10

- 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

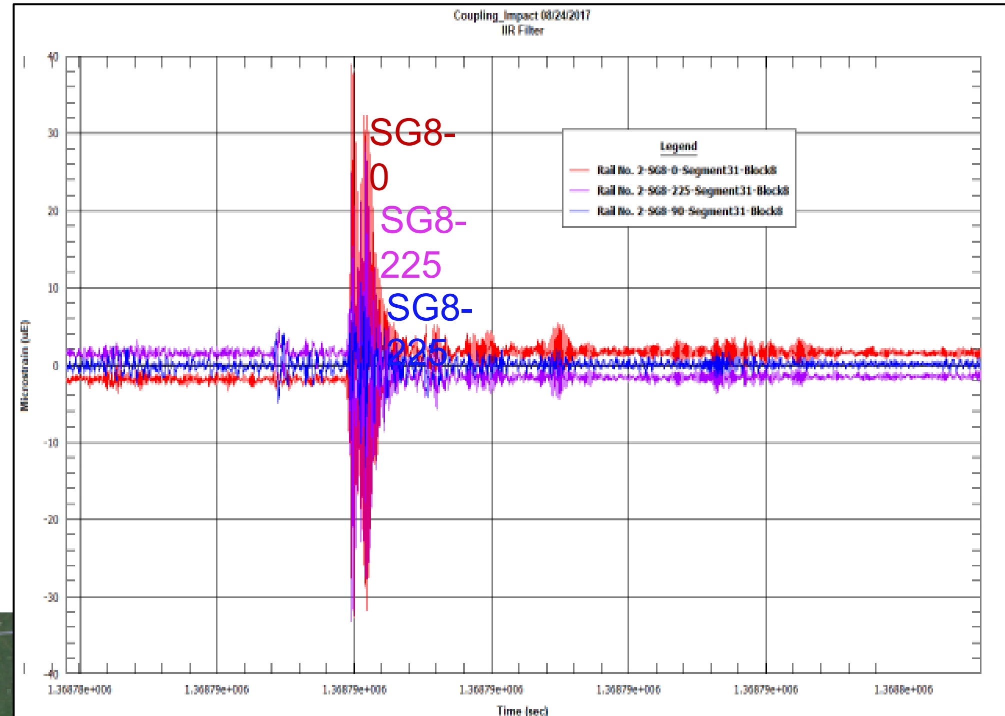
Rail Tests at the TTCI - Results

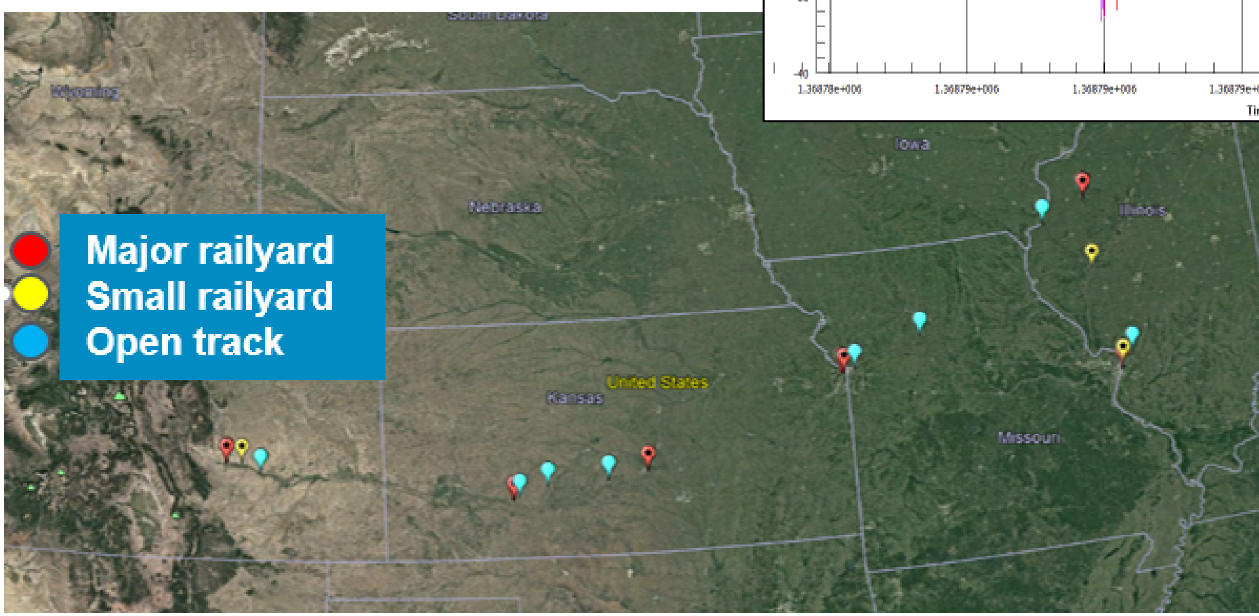
- Testing provided valuable insight of system response to a multitude of transient inputs
- Understanding these inputs made possible the comparison and analysis of rail, heavy-haul, and ship transport data



Rail 2: TTCI (Pueblo, CO) to Baltimore

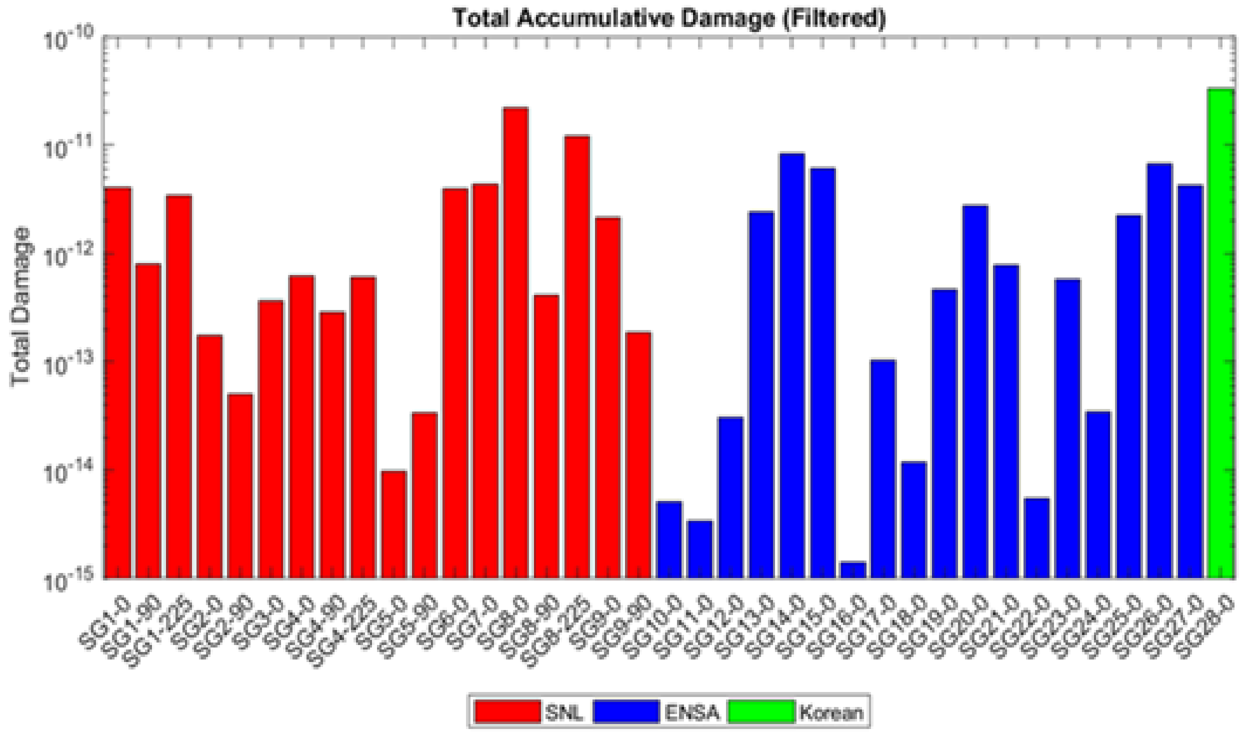
- 18 days (1,125 miles) of data collected from TTCI to near St. Louis, Illinois
- 30 coupling events analyzed at major and minor railyards
- Max SNL acceleration: 1.05 g
- Max SNL strain: 38 µE
- Max TTCI coupling strain: 99 µE at 7.5 mph





Fatigue Analysis

Strain data collected during the multi-modal transportation test were used to perform fatigue analysis on the fuel cladding.



- 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.

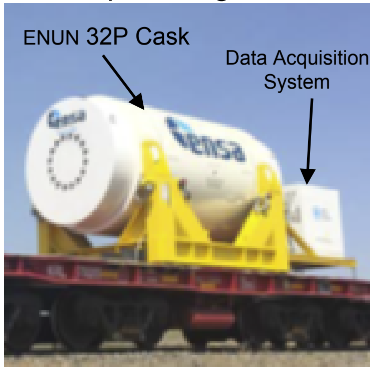
Summary of What We Learned

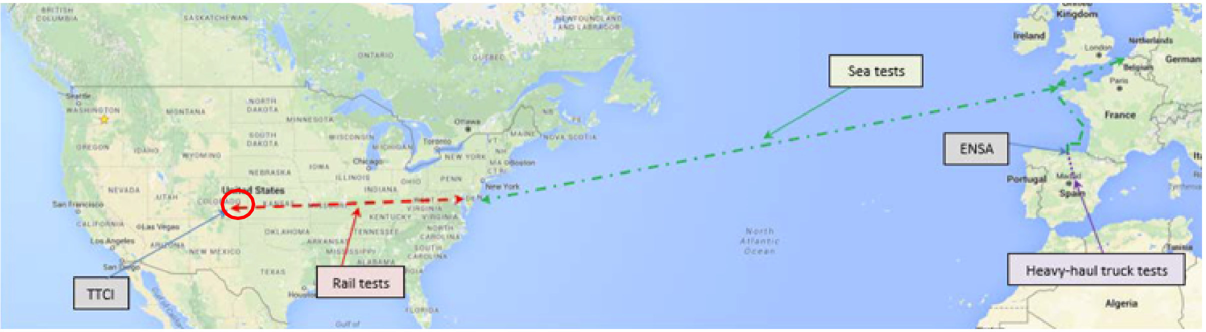
- ❑1. The 137 ton transportation system is a good cushion.
- ❑2. All tested modes of transportation are safe.
- ❑3. Fatigue is not a concern.

Introduction

- The 30 cm drop test was a follow-on to the 2017 US/Spanish/Korean Multi-Modal Transportation Test (MMTT): 8-month, 9,400-mile transportation of spent nuclear fuel (SNF) test.
- The test purpose was to quantify the shocks and vibration environments during heavy-haul, rail, and ship transport and handling.
- For the first time, strains and accelerations were measured on the surrogate assemblies within the ENUN 32P dual purpose rail cask.

Transportation System Setup during MMTT





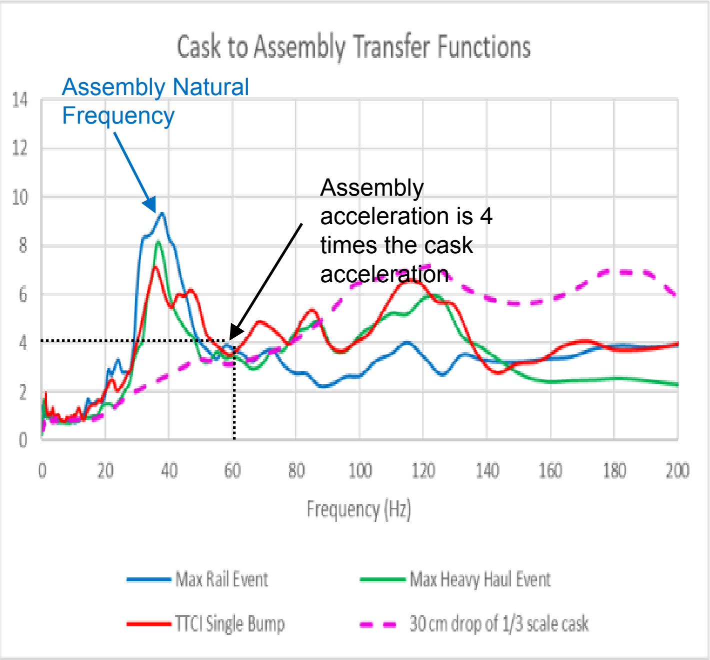
MMTT video is available on YouTube: https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be

MMTT data analysis report is available at: https://www.osti.gov/biblio/1532526-data-analysis-ensa-doe-rail-cask-tests

Motivation for 30 cm Drop Test

- ❑ The common assumption is that the cask content experiences the same accelerations as the cask itself.
- ❑ The data from the MMTT demonstrated that the accelerations were amplified from the cask to the surrogate assemblies during transport.
- ❑ The peaks at 40 Hz were due to assembly natural frequency.

What accelerations and strains will fuel rods experience inside the cask when dropped from a height of 30 cm?



The transfer function is the relationship between accelerometers on the cask and on the fuel assemblies.

NOTE: the accelerations were attenuated from the transportation platform to the cask during MMTT in all transport modes.

30 cm Drop Test: Purpose, Incentive, Goals, and Implementation

Purpose:

Measure accelerations and strains on a surrogate 17x17 PWR fuel assembly

Incentive

- The 30 cm drop is one of the NRC normal conditions of transportation (NCT) regulatory requirements (10 CFR 71.71)
- There are no data on the actual surrogate fuel for the 30 cm drop.
- Obtaining these data is not a direct requirement, but it allows for:

Goals

- Completing the NCT mechanical testing environment
- Better understanding the potential implications of handling incidents
- Quantifying the risk of fuel breakage under the 30 cm drop conditions
- Defining transfer function from the cask to the fuel for more severe impacts

Implementation

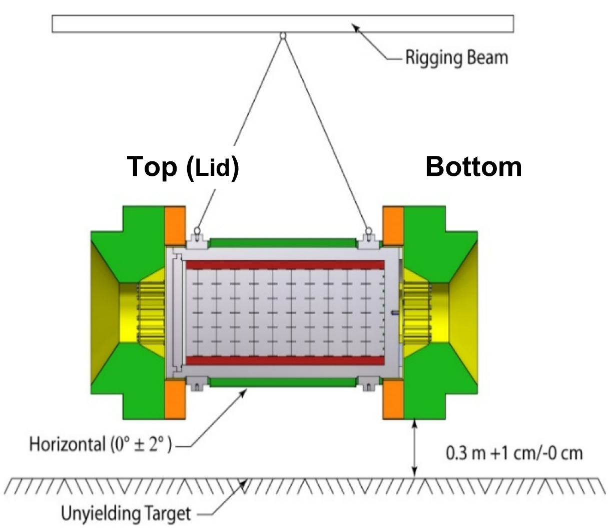
- Ideally, the 30 cm drop test would be conducted with the full-scale cask containing full-scale surrogate assemblies.
- The cost of a full-scale cask and impact limiters make this test impractical.
- The accelerations and strains on a full-scale surrogate fuel assembly were obtained by implementing 3 consecutive steps.
- This presentation describes **Step 3.**

STEP 1 – 30 cm Drop of 1/3 Scale ENUN 32P Cask with Dummv Assemblies

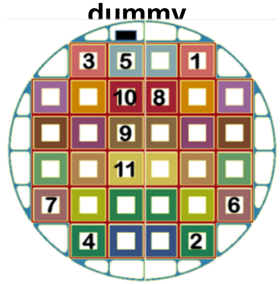
Goal: Obtain maximum acceleration pulses on 1/3 scale dummy assemblies (top and bottom)

Details in PATRAM-2019 paper by Kalinina et al.

Drop Test Setup



11 instrumented 1/3 scale dummy

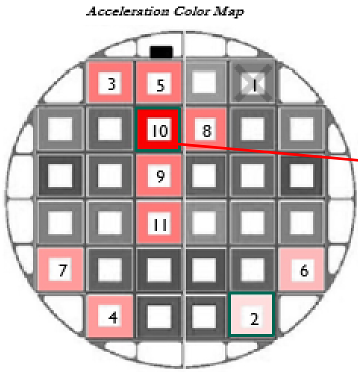


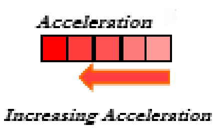
Dummy assembly

BAM Facility in Berlin (Germany), December 2018

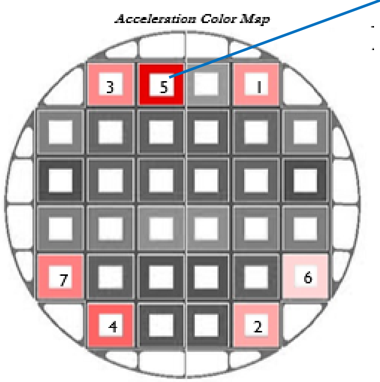
STEP 1 Maximum Acceleration Pulses on 1/3 Scale Dummy Assemblies in 30 cm Drop of 1/3 Scale Cask

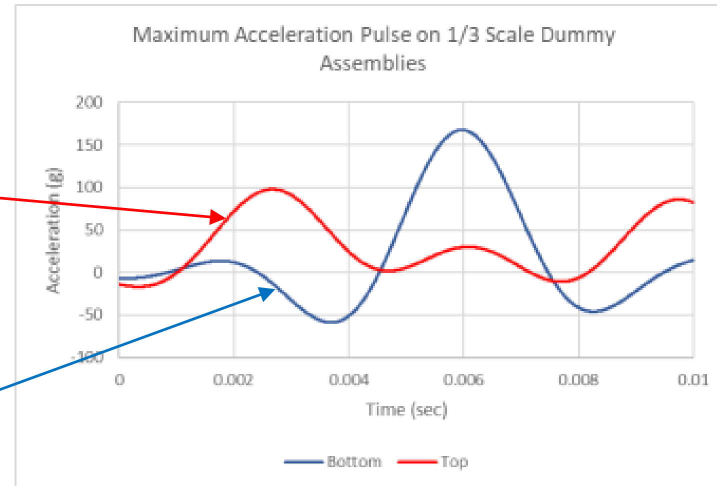
Top (Lid)





Bottom



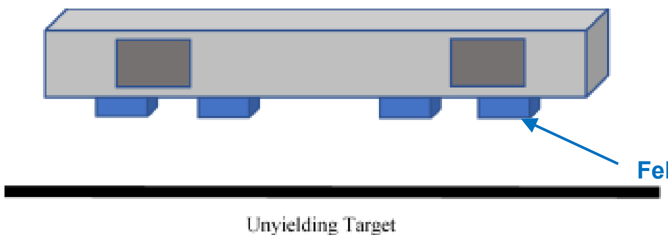


- The pulses at the top and bottom locations are different because the horizontal drop is never truly horizontal.
- In this test the cask hit the target with its lid side first.

STEP 2 – 30 cm Drop of the Full-Scale Dummy Assembly

Goal: recreate a full-scale acceleration pulses on the dummy assembly that corresponds to the measured pulses on the 1/3-scale dummies (from STEP 1).

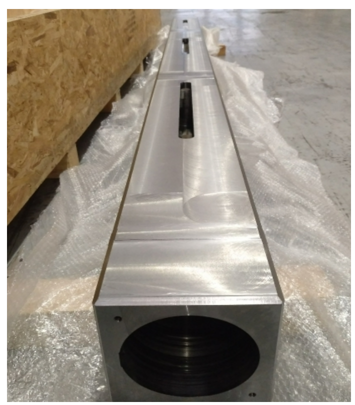
Drop Test Setup



Felt pads to mimic impact limiters and cask

Full-Scale Basket Tube

Full-Scale Dummy Assembly

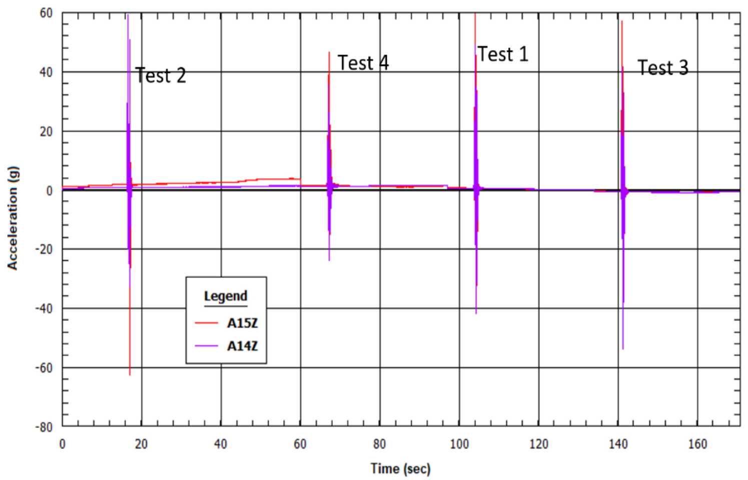


SNL drop tower in Albuquerque (NM) June 2019

Results of the 30 cm Full-Scale Dummy Assembly Drop Tests

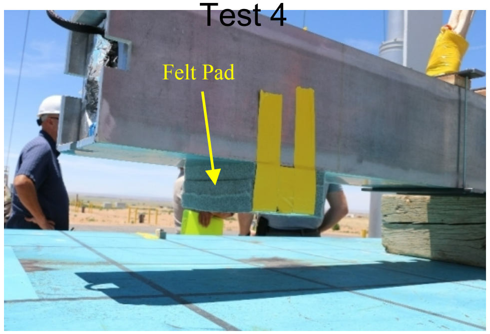
- Multiple tests were performed to get the desired acceleration pulse.
- After each test the pulse amplitude, duration, and shape were examined and the felt programming material was adjusted.

Acceleration Time Histories in Four Drop Tests

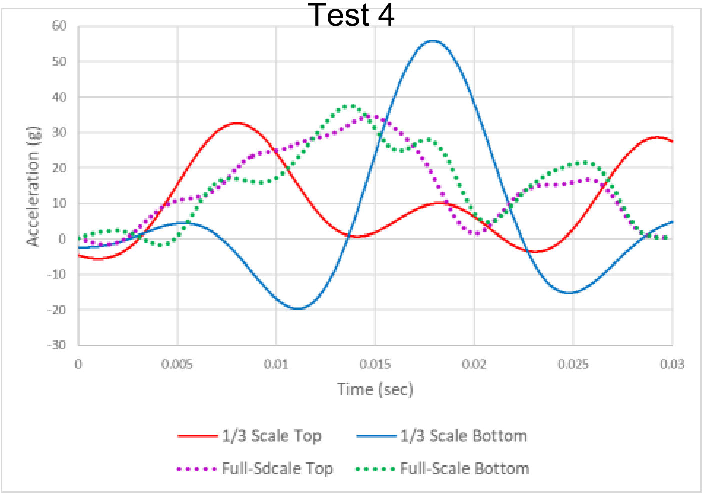


- The full-scale assembly drop was virtually horizontal and the accelerations on the top and bottom were very similar.
- The acceleration pulses in Test 4 showed good agreement with the 1/3 scale acceleration pulses.

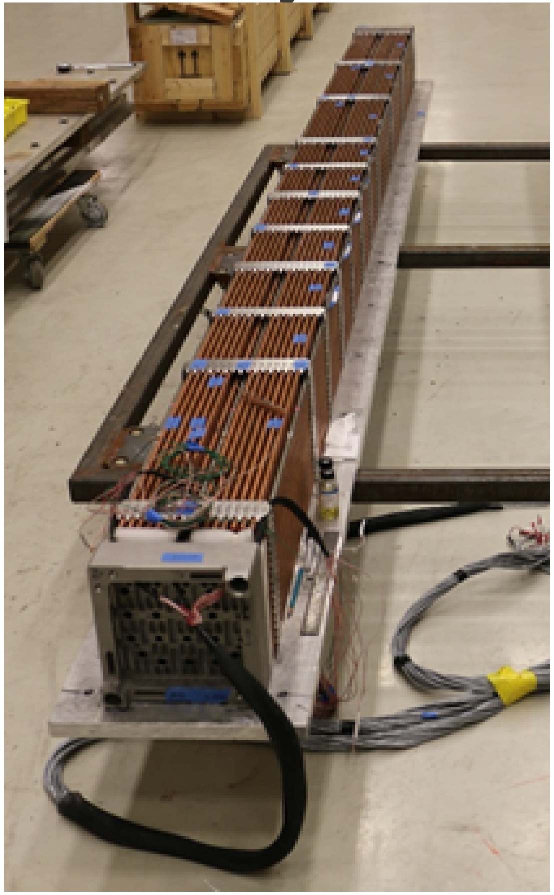
Felt pad configuration in Test 4



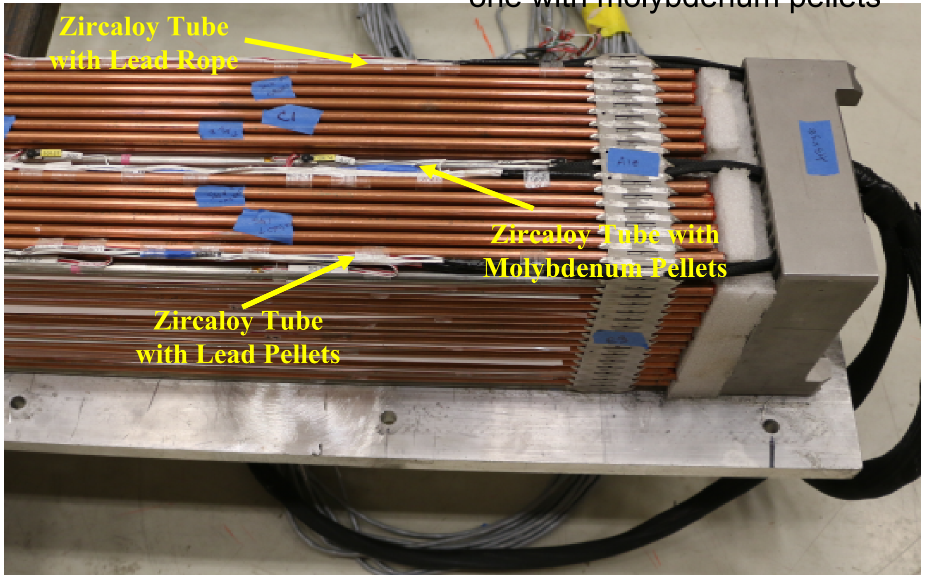
1/3 Scale and Full-Scale Pulses in Test 4



STEP 3 – 30 cm Drop of the Full-Scale Surrogate Assembly



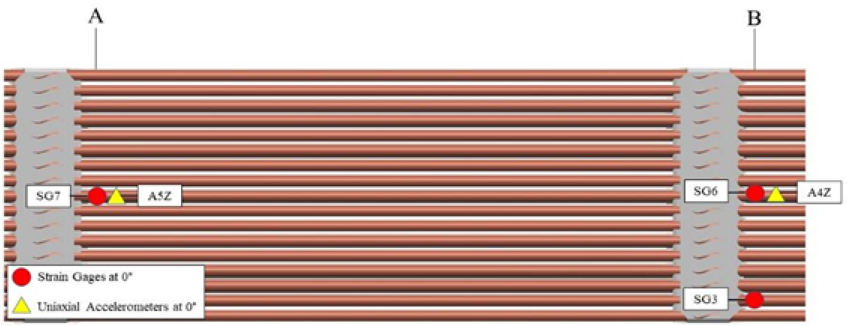
- Surrogate assembly weight was 785 kg
- All rods, except 3, were copper tubes with lead rope.
- 3 rods were zircaloy tubes
  - one with lead rope
  - one with lead pellets
  - one with molybdenum pellets



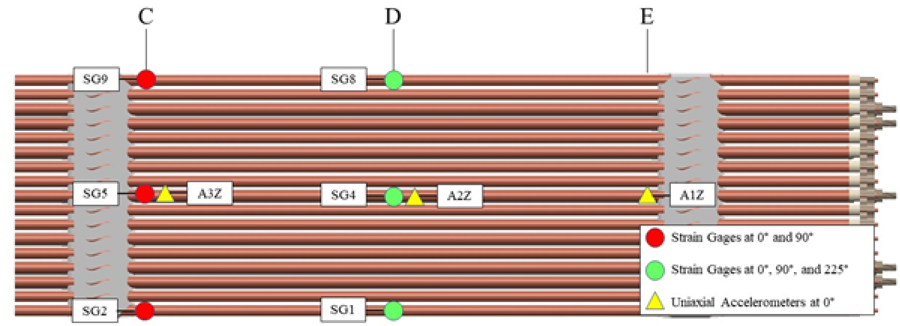
Surrogate Assembly Instrumentation

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

Same Sensors as in MMTT

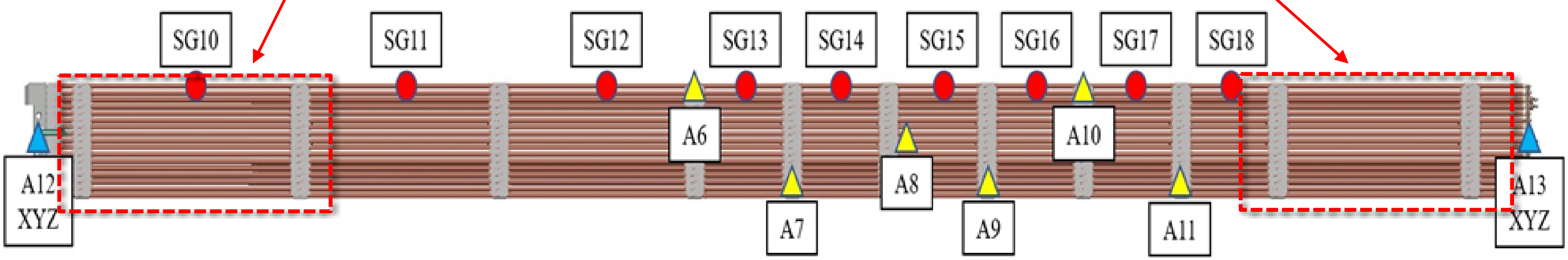


Bottom Nozzle End Instrumentation



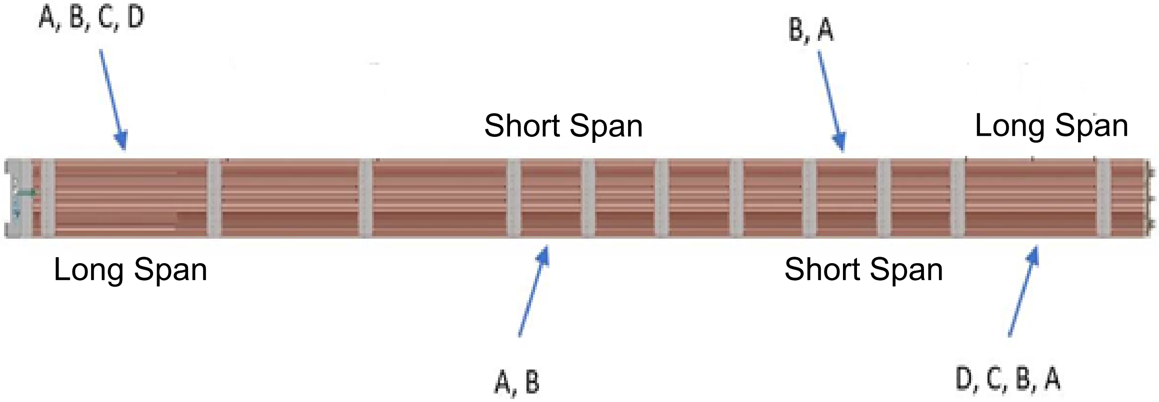
Top Nozzle End Instrumentation

Additional Sensors



Pressure Paper

Pressure Paper Placement



Installation of Pressure Paper

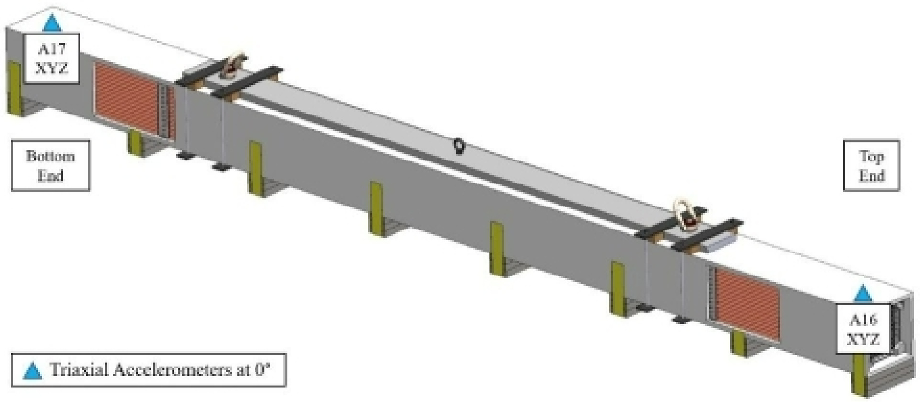
- ➢ The pressure paper sheets were installed between 15 rods in 2 long spans and 2 short spans

Pressure Paper Specifications

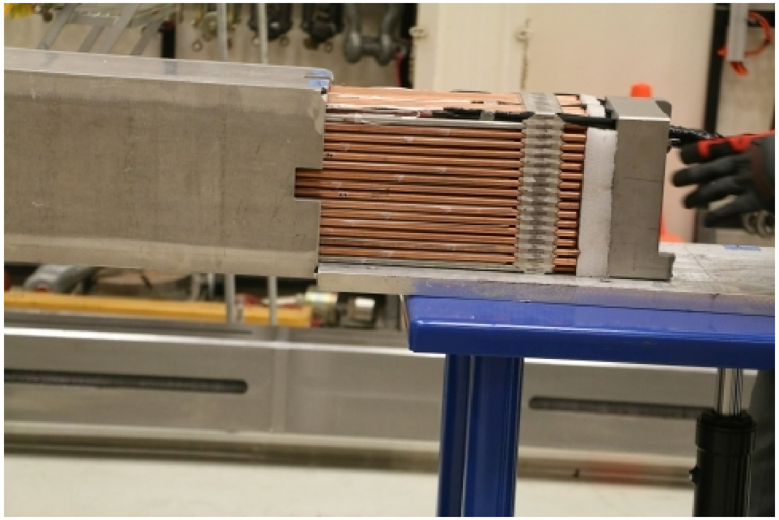
A - Extreme Low – 7.2 – 28 psi
B - Super Low – 70 – 350 psi
C – Low – 350 – 1,400 psi
D - Medium. – 1,400 – 7,100 psi

Basket Tube and Target Surface Instrumentation

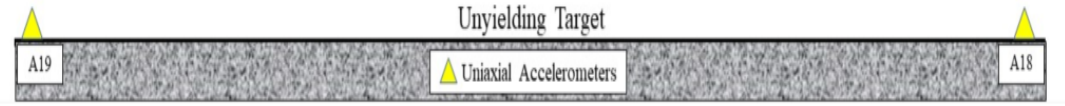
Basket Tube Instrumentation



Surrogate Assembly Placement into the Basket Tu

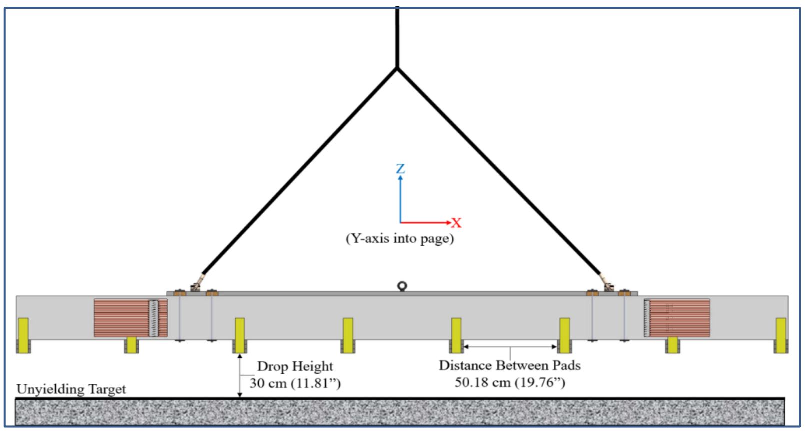


Target Surface Instrumentation



30 cm Drop Test Setup

Test Setup

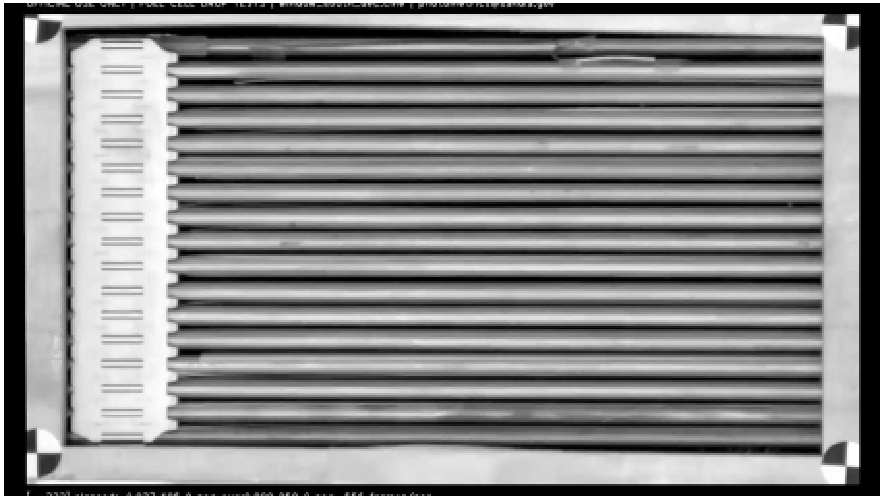


Test Unit Before the Drop

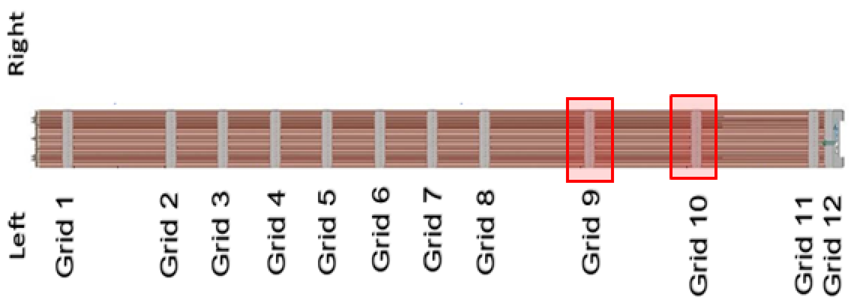
30 cm Drop Videos

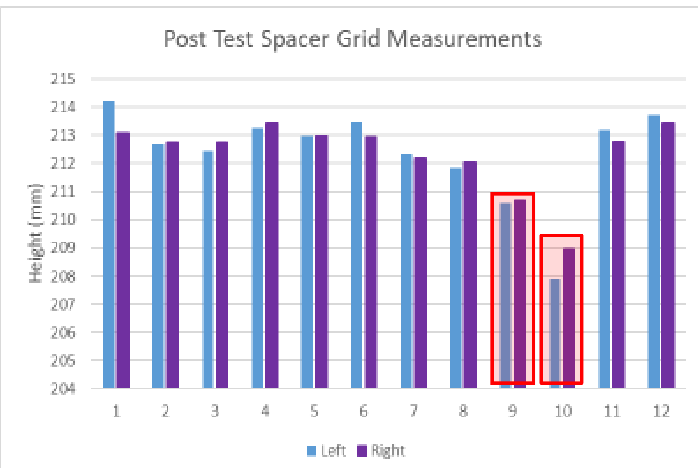
Test Video

High-Speed Video



Post-Test Spacer Grid Conditions



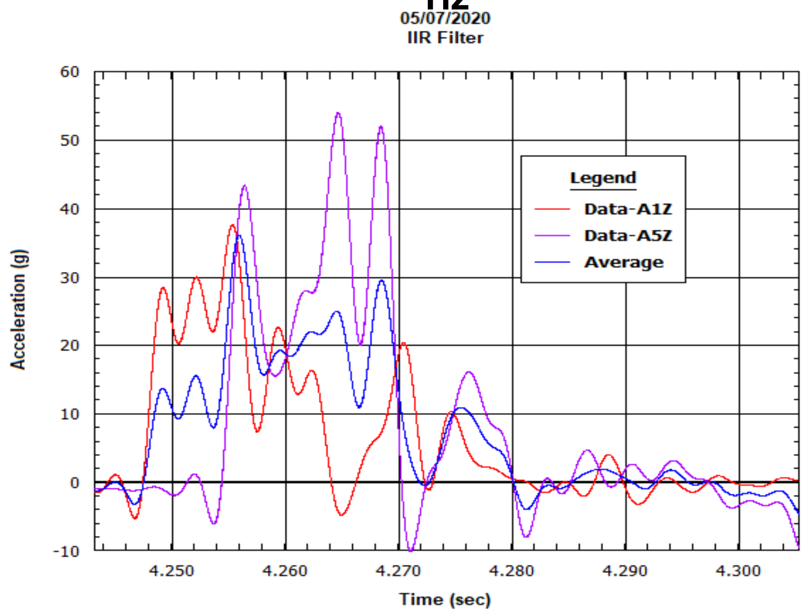


Grid 10 (right)

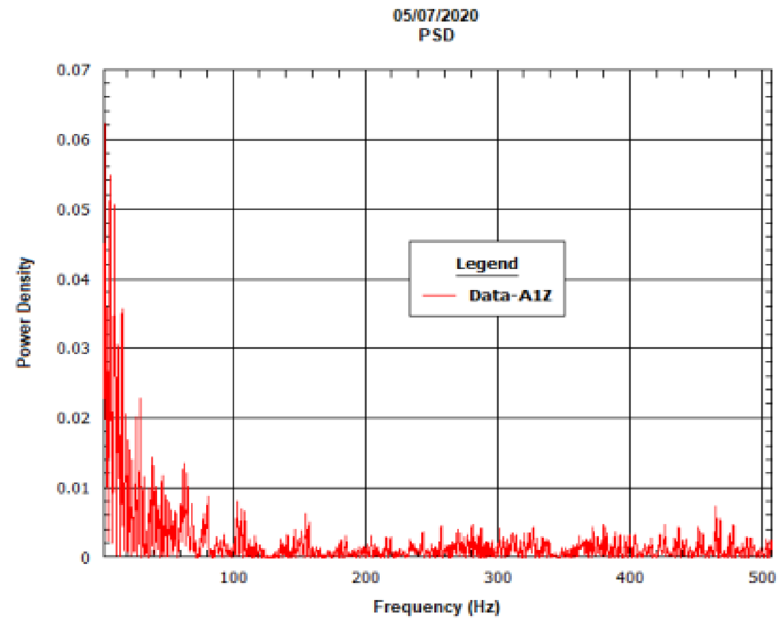
Max Deformation: 6.1 mm

Acceleration Data

Top (A1Z) and Bottom (A5Z) End Acceleration Pulses During the First Impact Filtered to 300 Hz



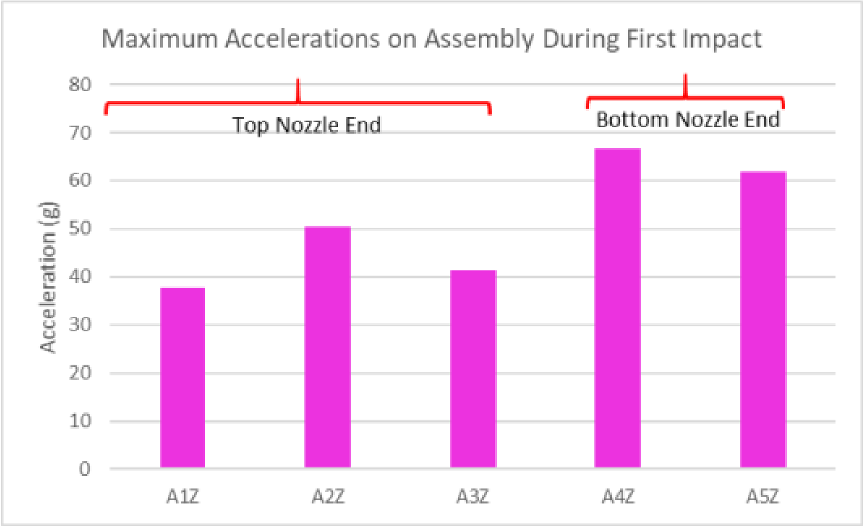
Acceleration Power Spectra Density (PSD)



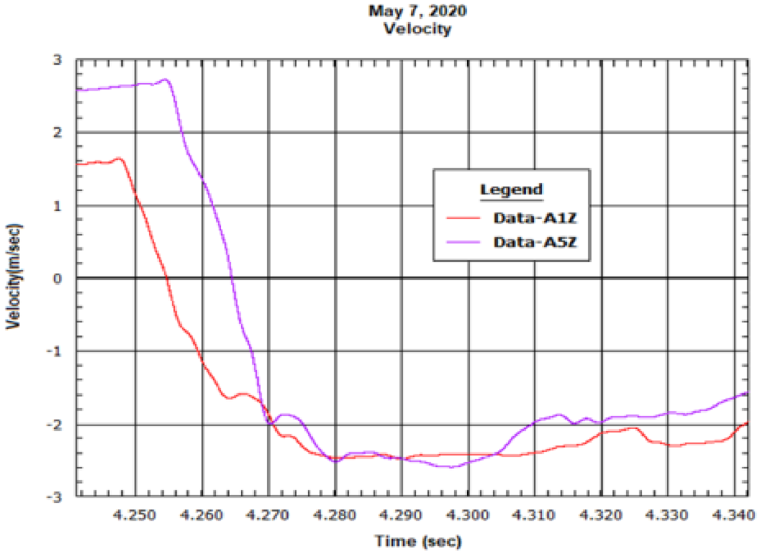
- ❑ The average pulse amplitudes and duration are in good agreement with the expected ones.
- ❑ The greatest acceleration PSD is within the frequency domain up to 150 Hz.

Slap Down Effect

Peak Surrogate Assembly Accelerations During the First Impact

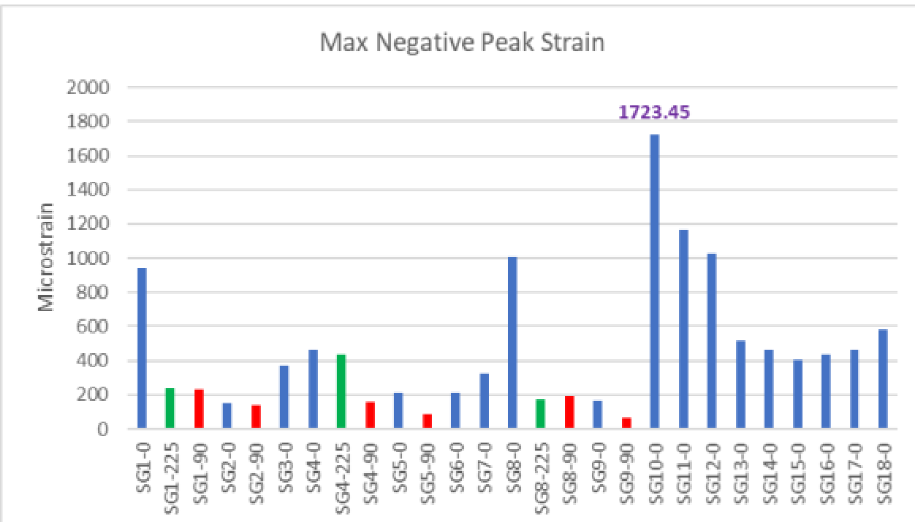


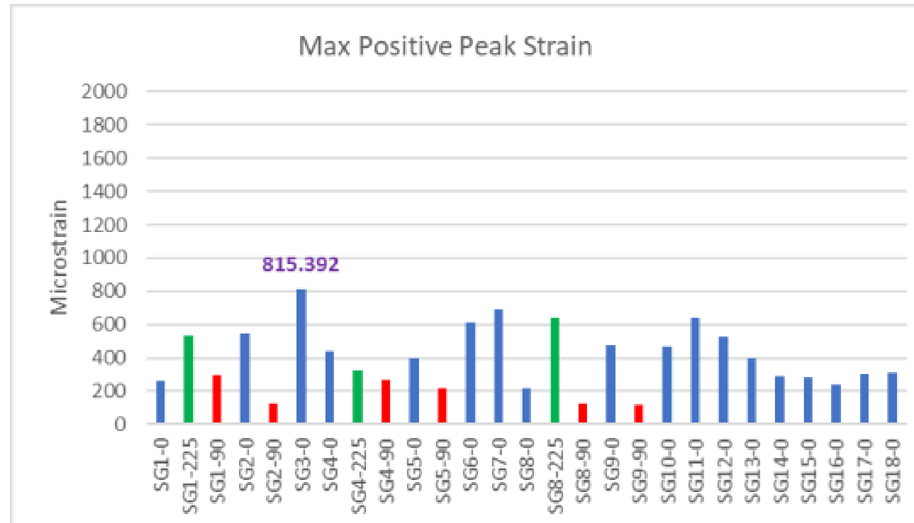
Surrogate Assembly Impact Velocity



- ❑ The top end hit the target first
- ❑ The slap down resulted in the larger accelerations on the bottom end

Maximum Observed Strain on the Surrogate Assembly



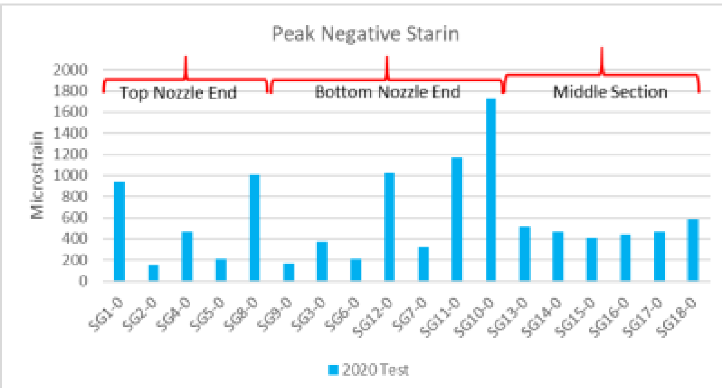


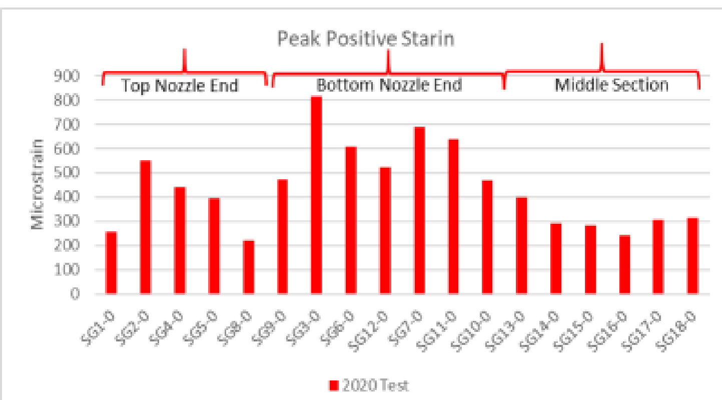
0^0 strain gauges
90^0 strain gauges
225^0 strain gauges

- ❑ Greatest negative strains were observed at the assembly bottom (slap down) end (SG10-0, SG11-0, and SG12-0).
- ❑ Peak strains are all in the long spans.
- ❑ Strains within the short spacer grid spans (SG13-0, SG14-0, SG15-0, SG16-0, SG17-0, and SG18-0) were noticeably lower as expected.
- ❑ The lateral (90^0) and combination (225^0) strain values were generally lower than the vertical ones.

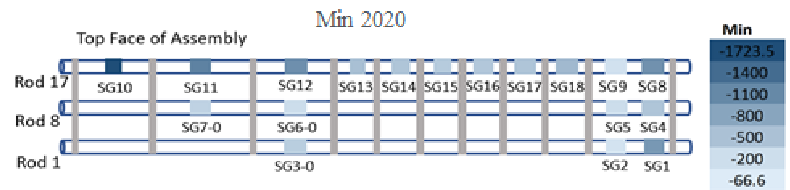
Locations of Peak Axial Strain Values

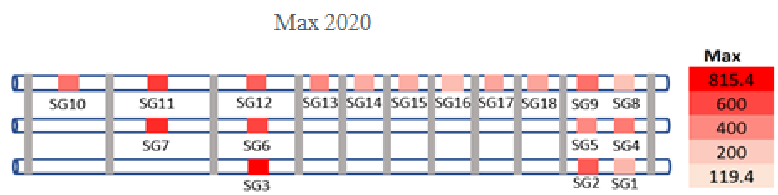
Peak Axial Strain Values





Color Maps of the Peak Strain Values

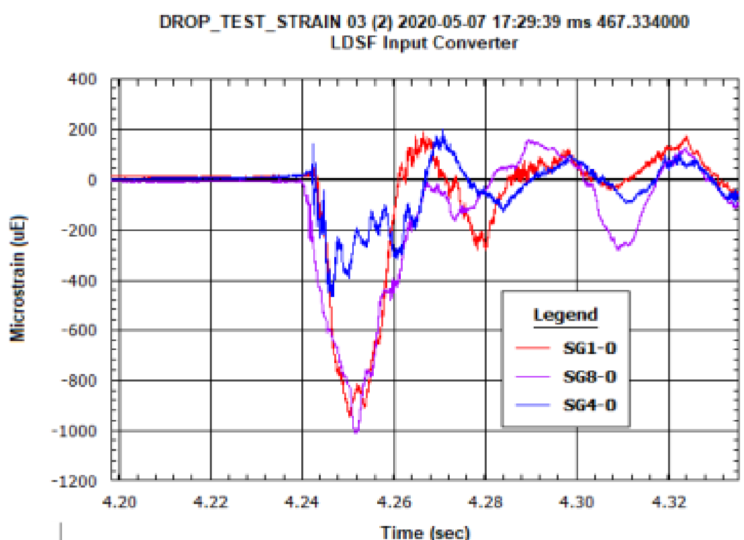


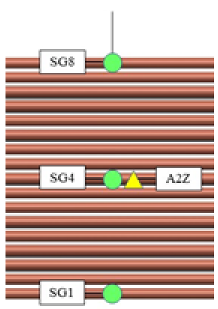


- ❑ Peak negative and peak positive axial strains are greater on the assembly bottom end due to slap down effect.

Strain Time Histories

Assembly Top End

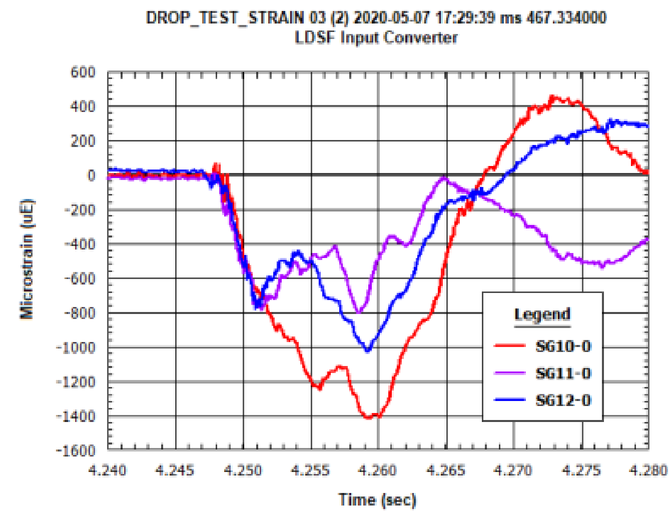


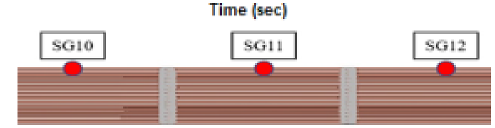


SG1-0 – Zr tube with lead rope; SG8-0 – Zr tube with lead pellets; SG4-0 – Zr tube with Mo pellets

- ❑ Strain gauge on Zr tube with Mo pellets has similar shape, but smaller peak strain, which is consistent with MMTT.

Assembly Bottom End

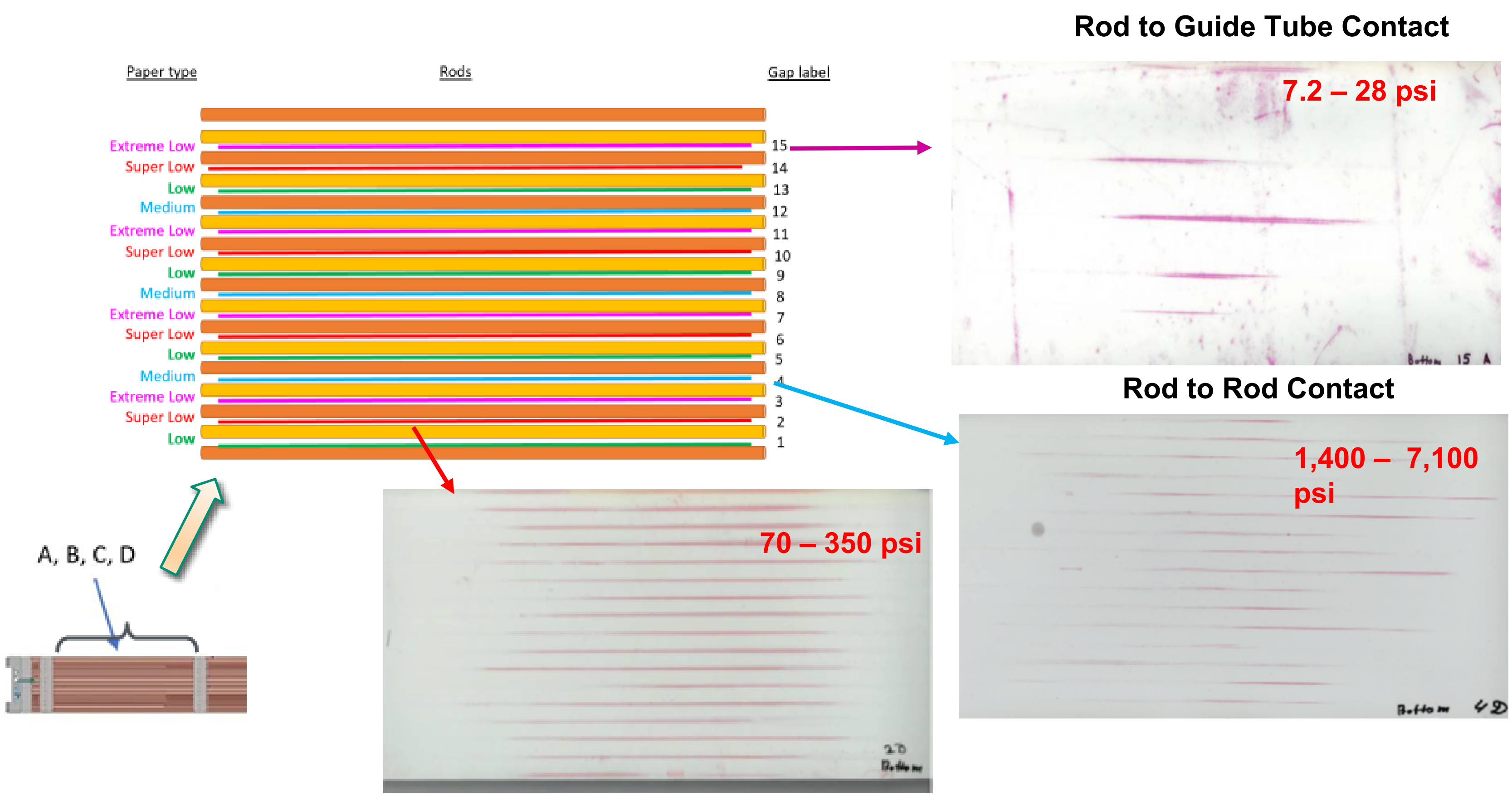




SG10-0, SG11-0, SG12-0 – Zr tube with lead rope

- ❑ Peak strain in long spans is larger in the gauge next to the bottom nozzle.

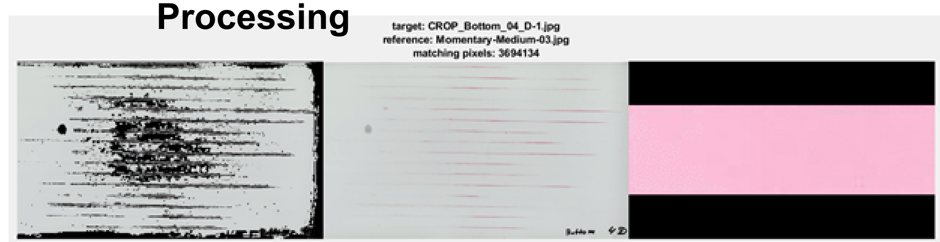
Pressure Paper Examples



Pressure Paper Processing

- ❑ The pressure paper sheets from two short spacer grid spans were blank.
- ❑ A number of the pressure paper sheets from two long spans had the marks indicating rod-to-rod or rod to guide tube contact.
- ❑ The pressure paper scans were processed with Matlab to match the observed color to one of the standard colors and convert it to the corresponding contact pressure.

Example of the Pressure paper Processing

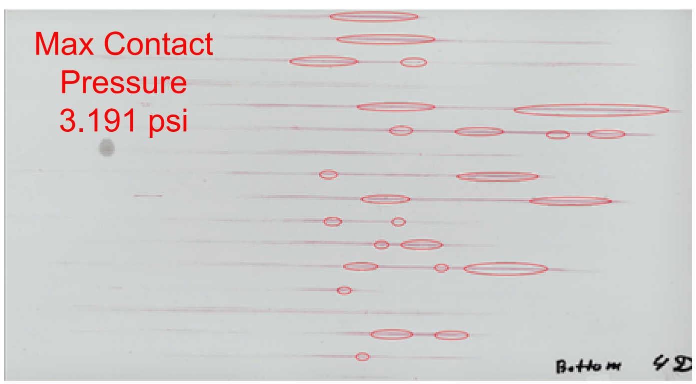


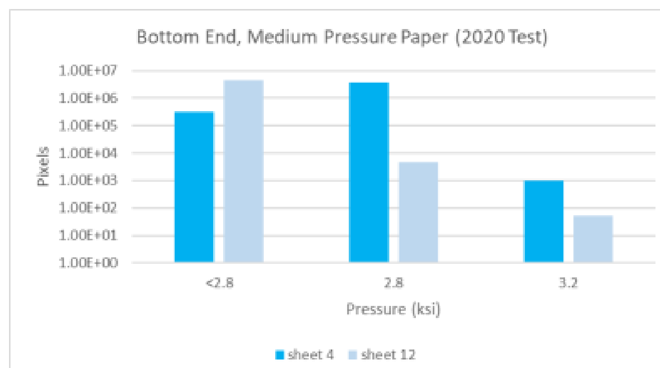
Processed Scan **Original Scan** **Standard Color**

Standard Colors

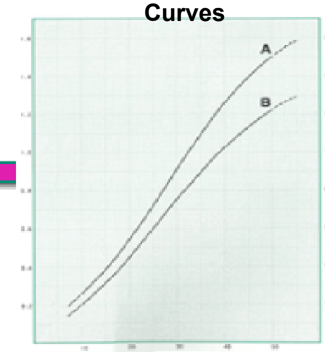
➢ 3,694,134 pixels on the processed scan matched the standard color

Maximum Contact Pressure Locations





Standard Colors-
Contact Pressure
Curves

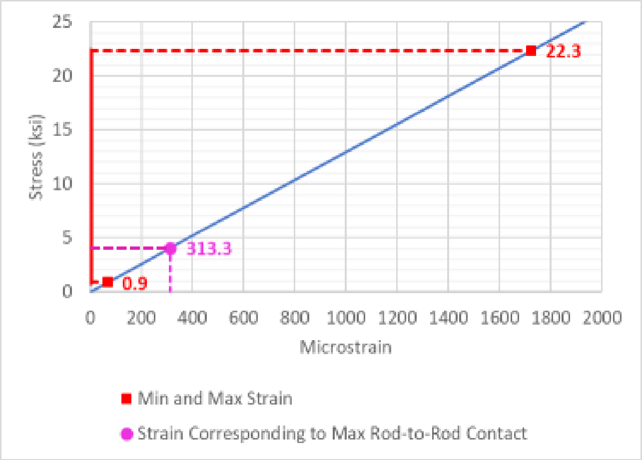


Standard Color

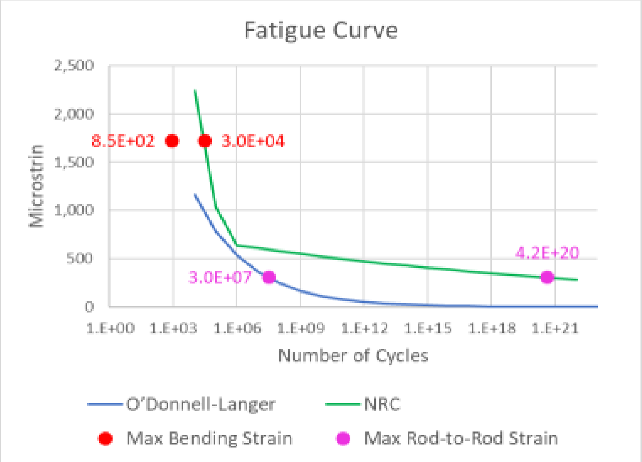
Pressure

Conclusions

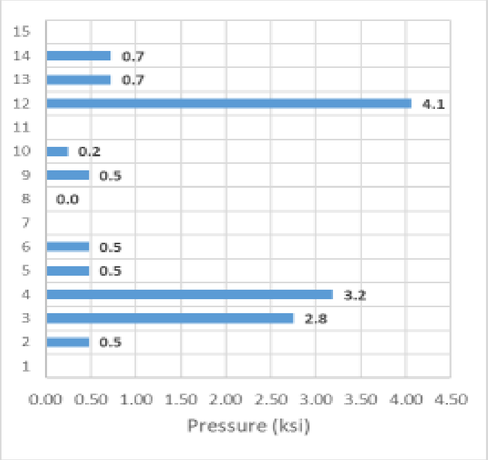
Closeup of the Stress-Strain

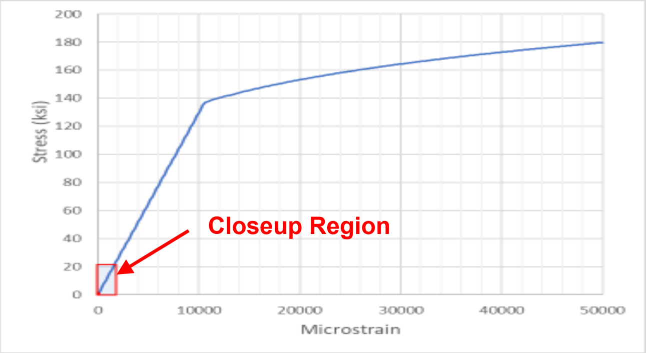


Fatigue Curve



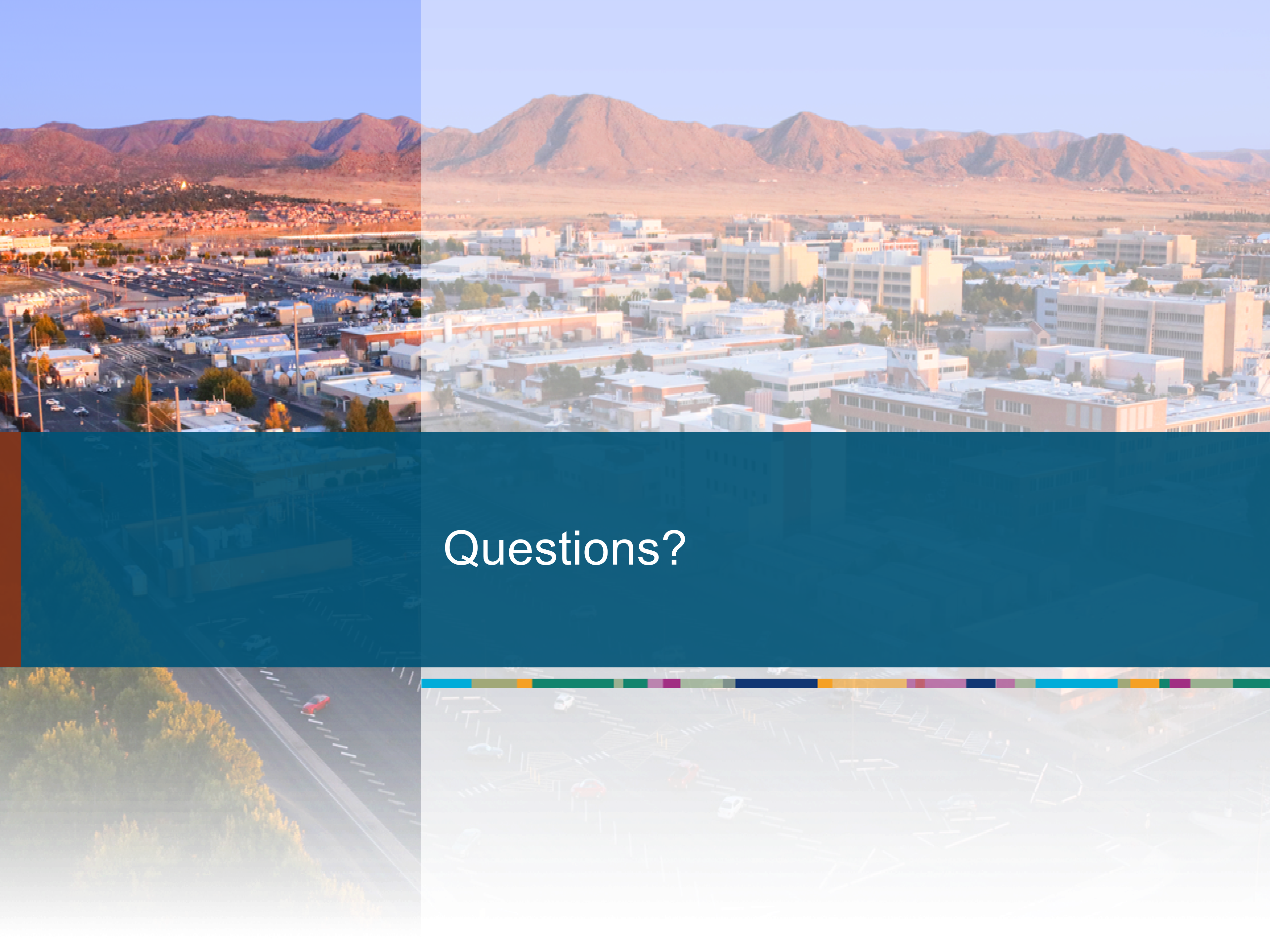
Contact Pressure





➢ **The fuel rods will maintain their integrity after being dropped 30 cm or less more than once.**

- ❑ The maximum rod-to-rod contact pressure was 4.1 ksi
- ❑ The stress corresponding to the maximum strain value was 22.3 ksi.
- ❑ The number of cycles to failure
  - Bending strain: ≥855
  - Rod-to-rod contact strain: ≥ 3.0E07



Questions?