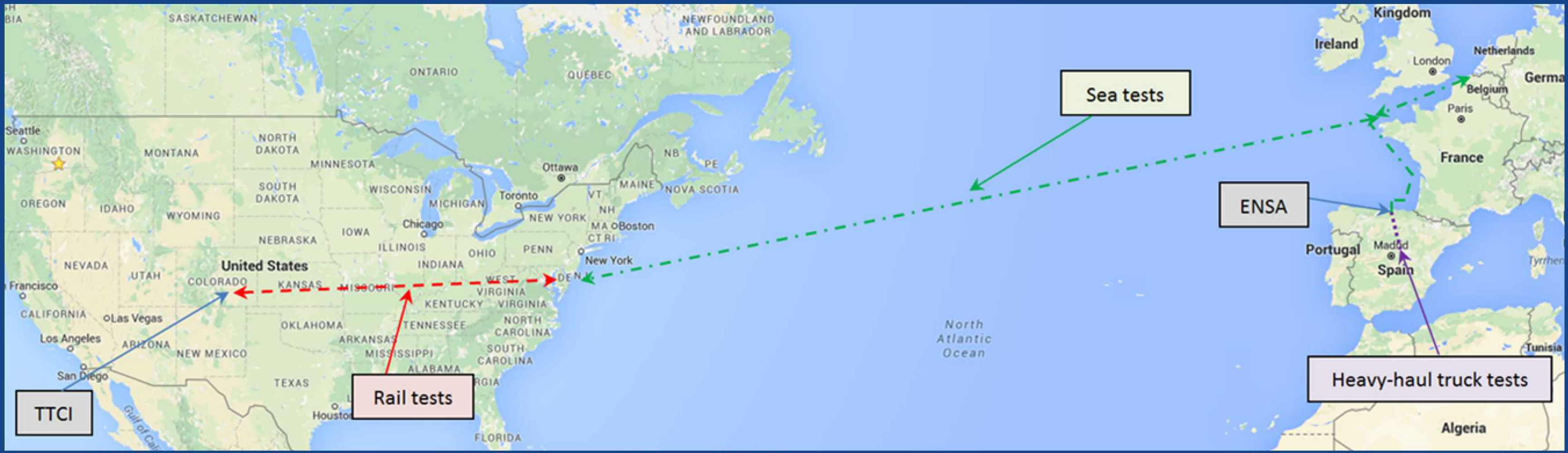


Research on Long-Term Storage and Transportation of Spent Nuclear Fuel

Sylvia Saltzstein, Brady Hanson, John Scaglione, Mike Billone, Steve Ross, Doug Ammerman, Elena Kalinina, Rose Montgomery

Sandia National Laboratories, Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory

National Transportation Stakeholders Forum 2018 Annual Meeting

June 4-7, 2018, Omaha, Nebraska

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

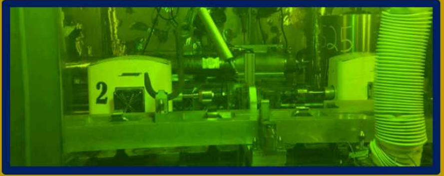
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2018-4192 C

DOE Storage and Transportation Research Projects fit together to answer the question, "Can Spent Nuclear Fuel be Stored and Shipped Safely in the Years to Come?"

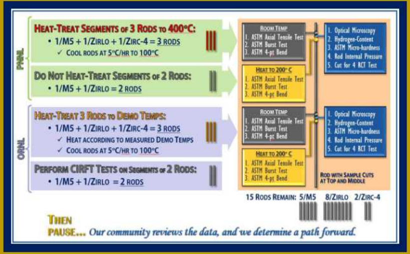
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

We have fuel in hot cells.



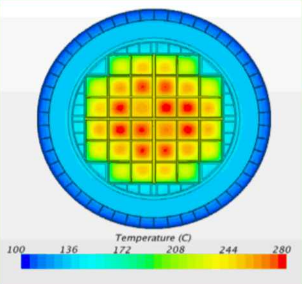
We completed non-destructive tests.



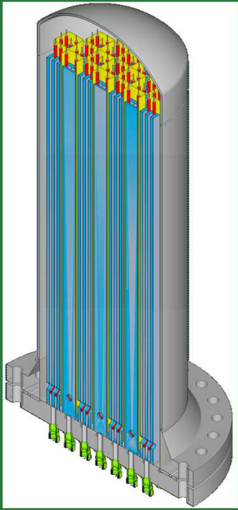
We are starting destructive analysis.

SISTER ROD MECHANICAL TESTING DATA

We have thermal models.



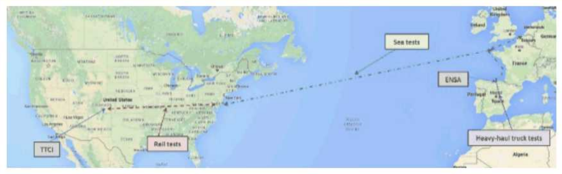
We are getting new thermal data from the Demo.

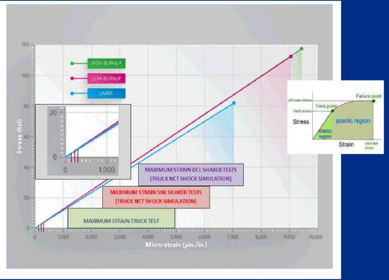


We will build a test apparatus to identify thermal conservatisms & develop more realistic assumptions.

THERMAL BEHAVIOR

PROVIDES KNOWLEDGE ABOUT SPENT FUEL INTEGRITY WHICH IS COMPARED TO DATA FROM THE TRANSPORTATION TESTS





SPENT FUEL TRIATHLON: QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS

- 54 Days Data Collection (101,857 ASCII Files) • 8 Terabytes Data
- 4 Transport Modes • 9458 Miles • 7 Countries • 12 States

The ENSA/DOE Multi-Modal Transportation Test Using Surrogate Fuel Assemblies & the ENSA ENUN 32P Cask

Why These Tests?

Measure Strains/Accelerations on Cask System Transporting Fuel Assemblies

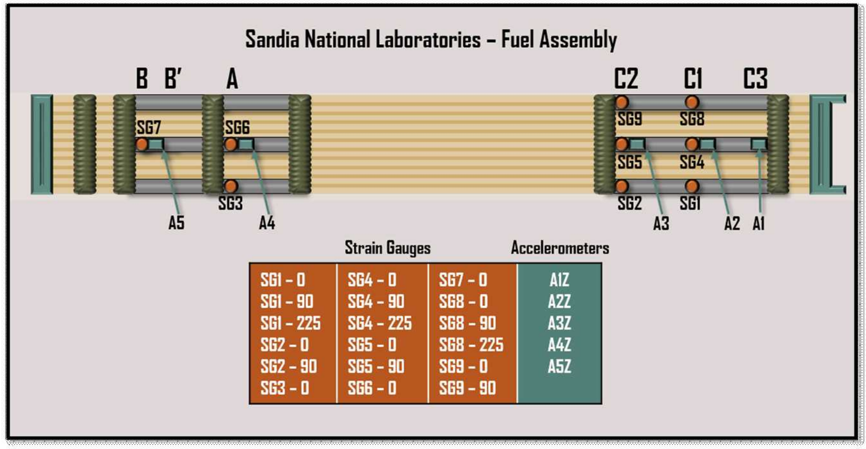
- **Data will provide technical basis for asserting safety inherent in transporting spent fuel under normal conditions of transport.**
- **Could vibrations or shocks result in fatigue failure?**
- **Previous tests only simulations of configuration of actual SNF transport modes.**

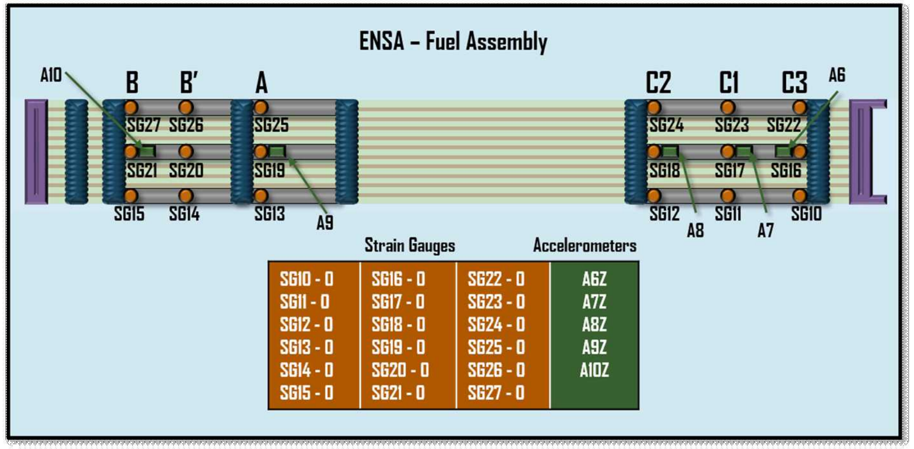
"One accurate measurement is worth a thousand expert opinions."
Admiral Grace Murray Hopper

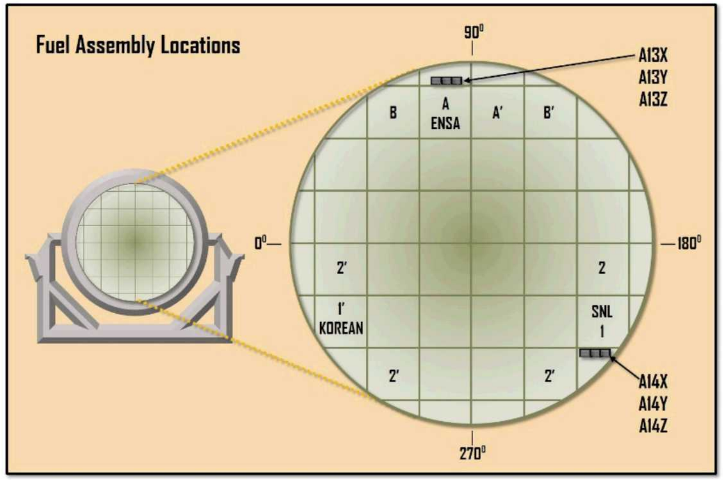
Cask Test Participants

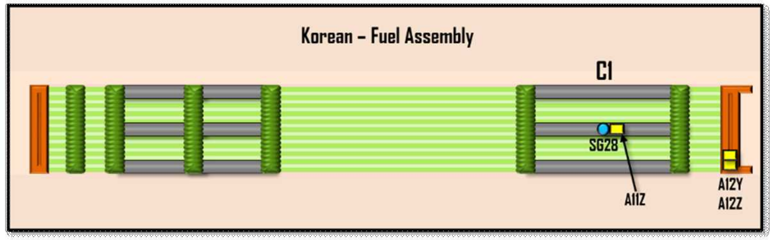
- U.S. Department of Energy
- Equipos Nucleares Sociedad Anónima (ENSA)
- Empresa Nacional de Residuos Radiactivos S.A. (ENRESA)
- ENUSA Industrias Avanzandas S.A.
- Coordinadora Internacional de Cargas, S.A.
- Sandia National Laboratories (SNL)
- Pacific Northwest National Laboratory (PNNL)
- Transportation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

Accelerometer & Strain Gauge Locations

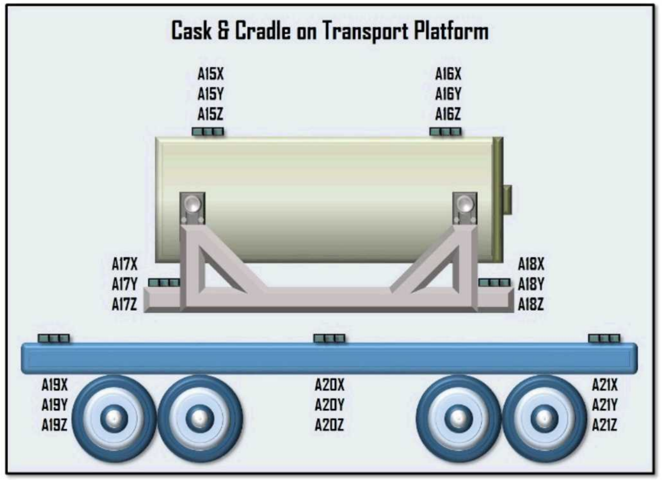








Assemblies & Cask System Instrumented with 77 Accelerometers & Strain Gauges



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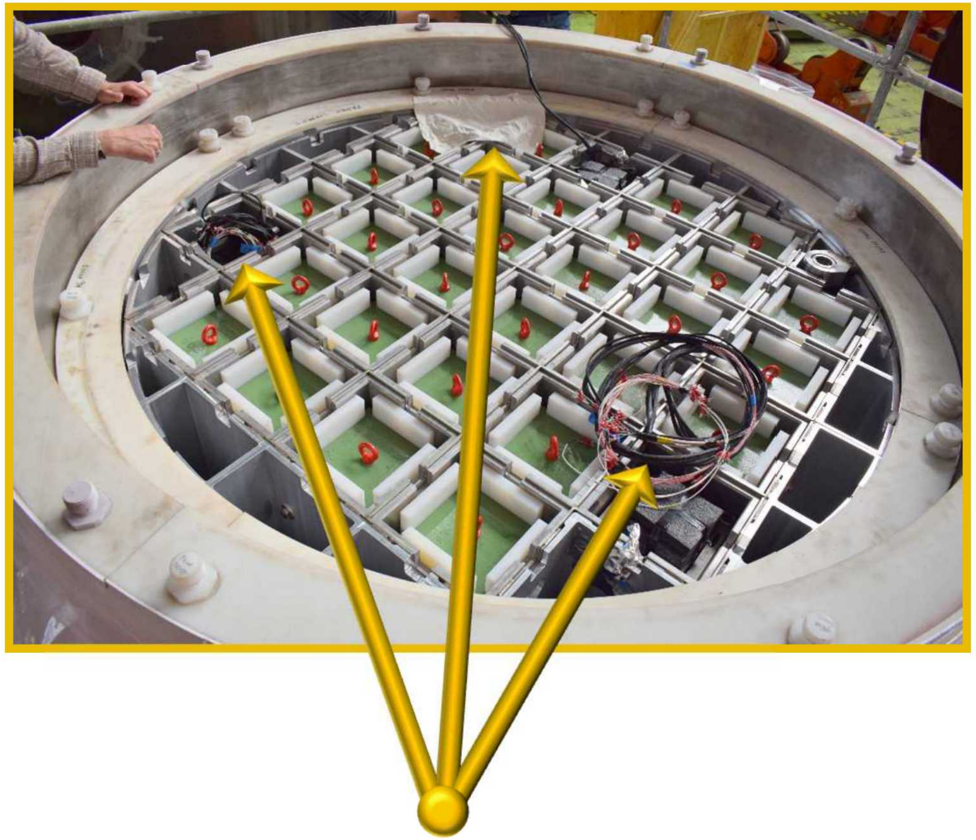
32P Cask Basket

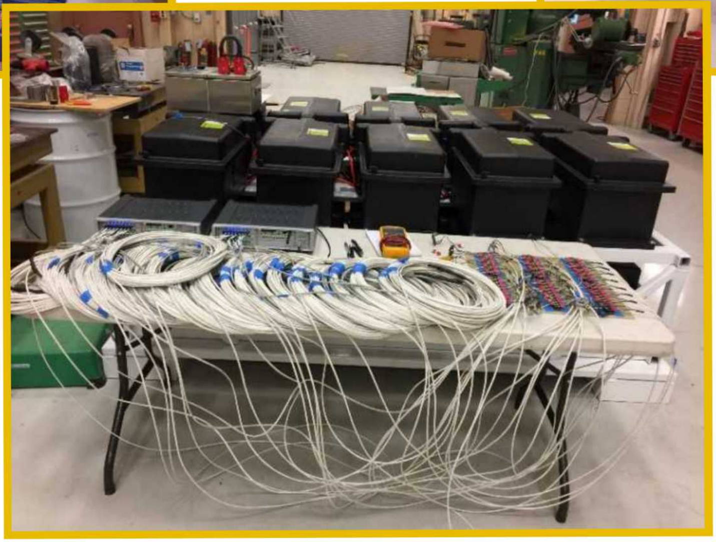


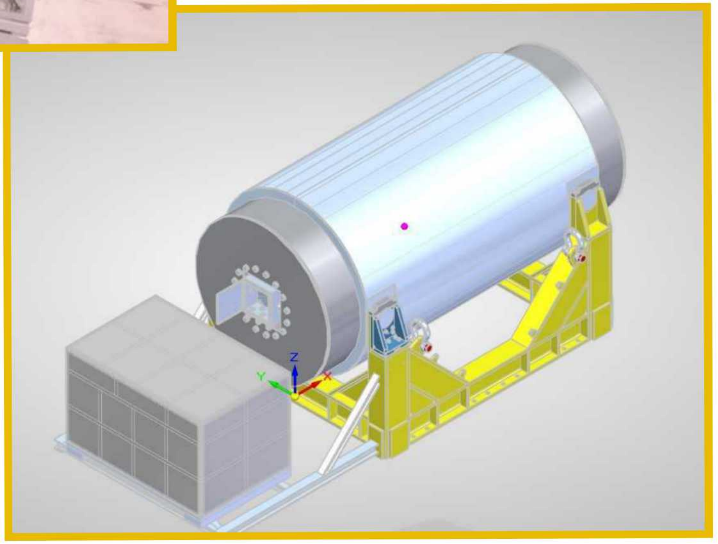
Locations of the 3 surrogate PWR fuel assemblies plus 29 dummy assemblies (Informed by PNNL Modeling)

Lid being placed on cask

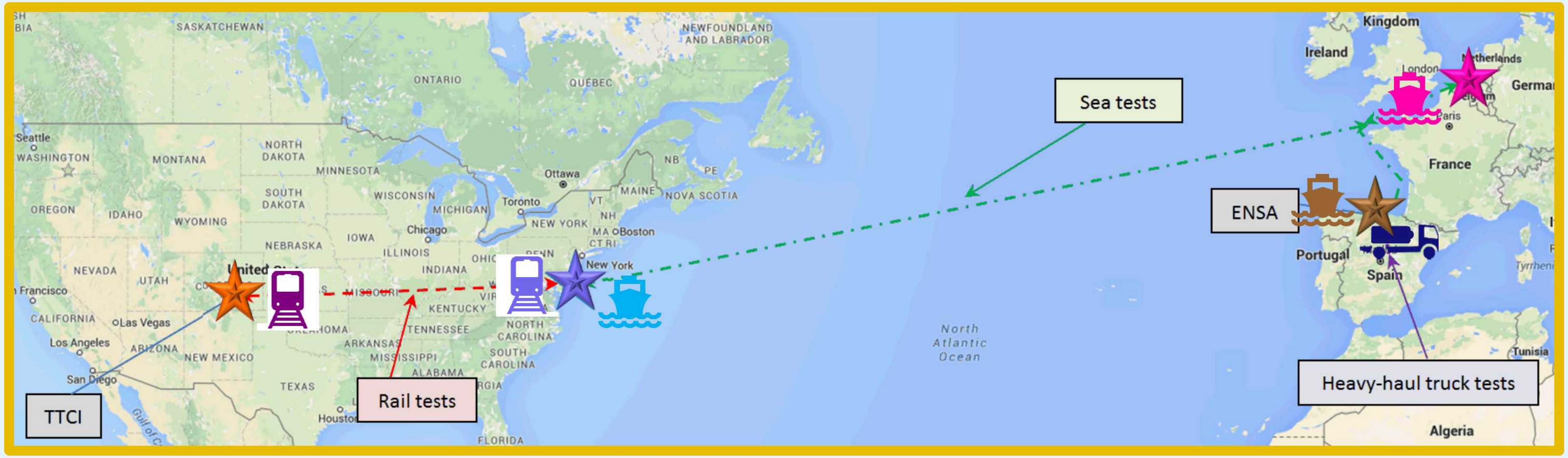
Instrumentation & Battery Box

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





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,)

Rail shipment from Baltimore to Pueblo (AUG 2017, 6 days, 2000 miles)

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, 43 travel days, 18 test days, 1125 test miles)

Ocean transport from Baltimore to Spain (DEC 2017, no data collected)

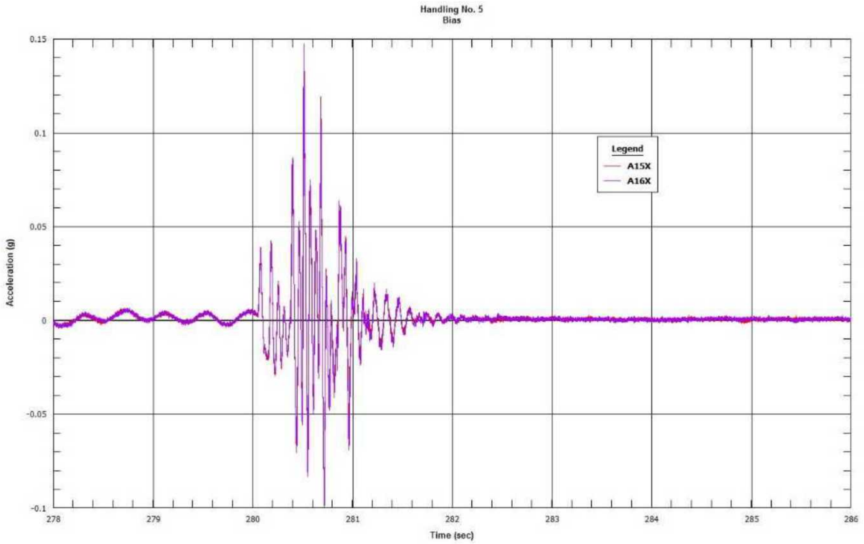
Cask handling tests performed in Spain by three different crane operators experienced in dry cask movement.

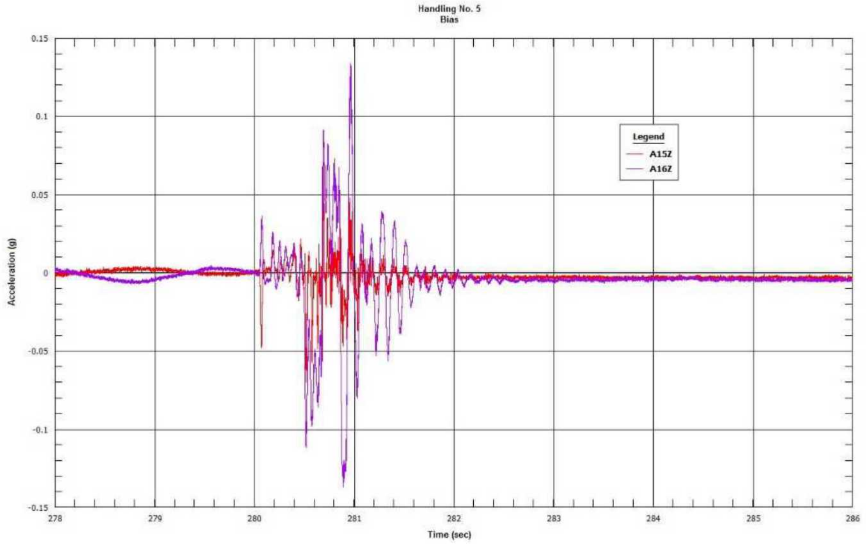
Each operator performed three tests.

Cask placed onto concrete pad with varying degrees of force.

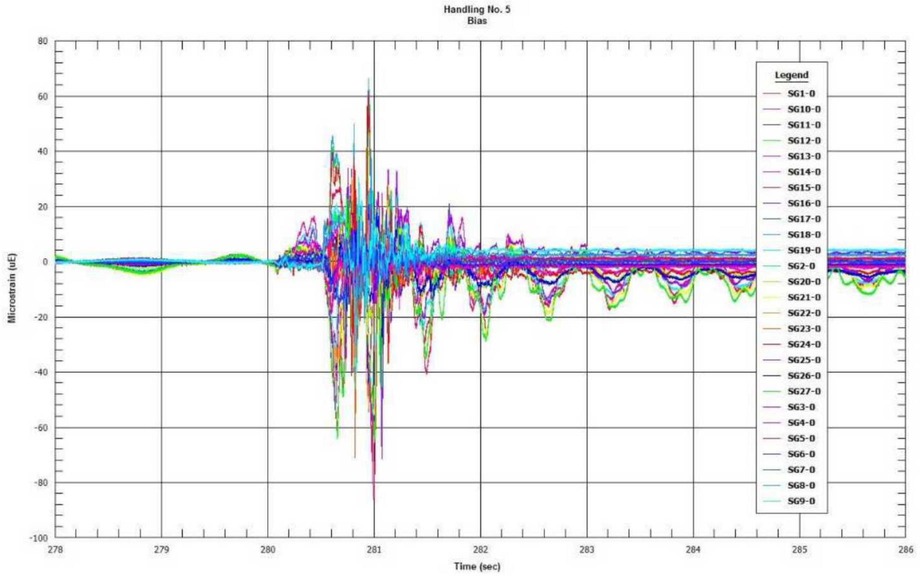
Preliminary Cask Handling Test Accelerometer & Strain Gauge Data

Maximum Cask Acceleration = 0.15 g; Maximum Assembly Strain = 87 µm/m



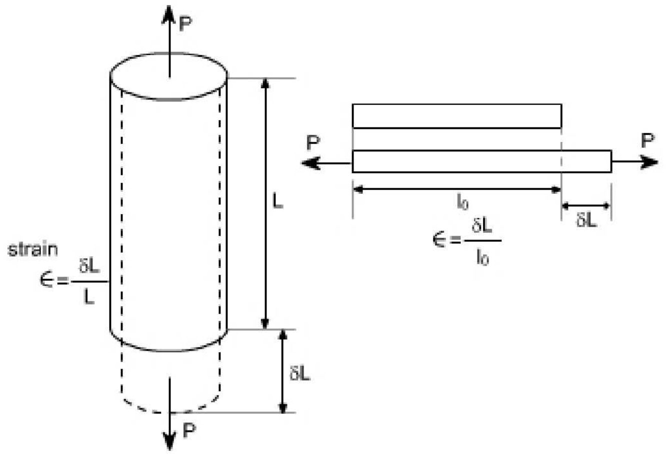


FY18 will examine frequency transmission, instantaneous loading vs. gross loading, etc.



Results Are in Micro Strains

A microstrain is the change in length (ΔL) per unit of the original length L expressed in parts per million.

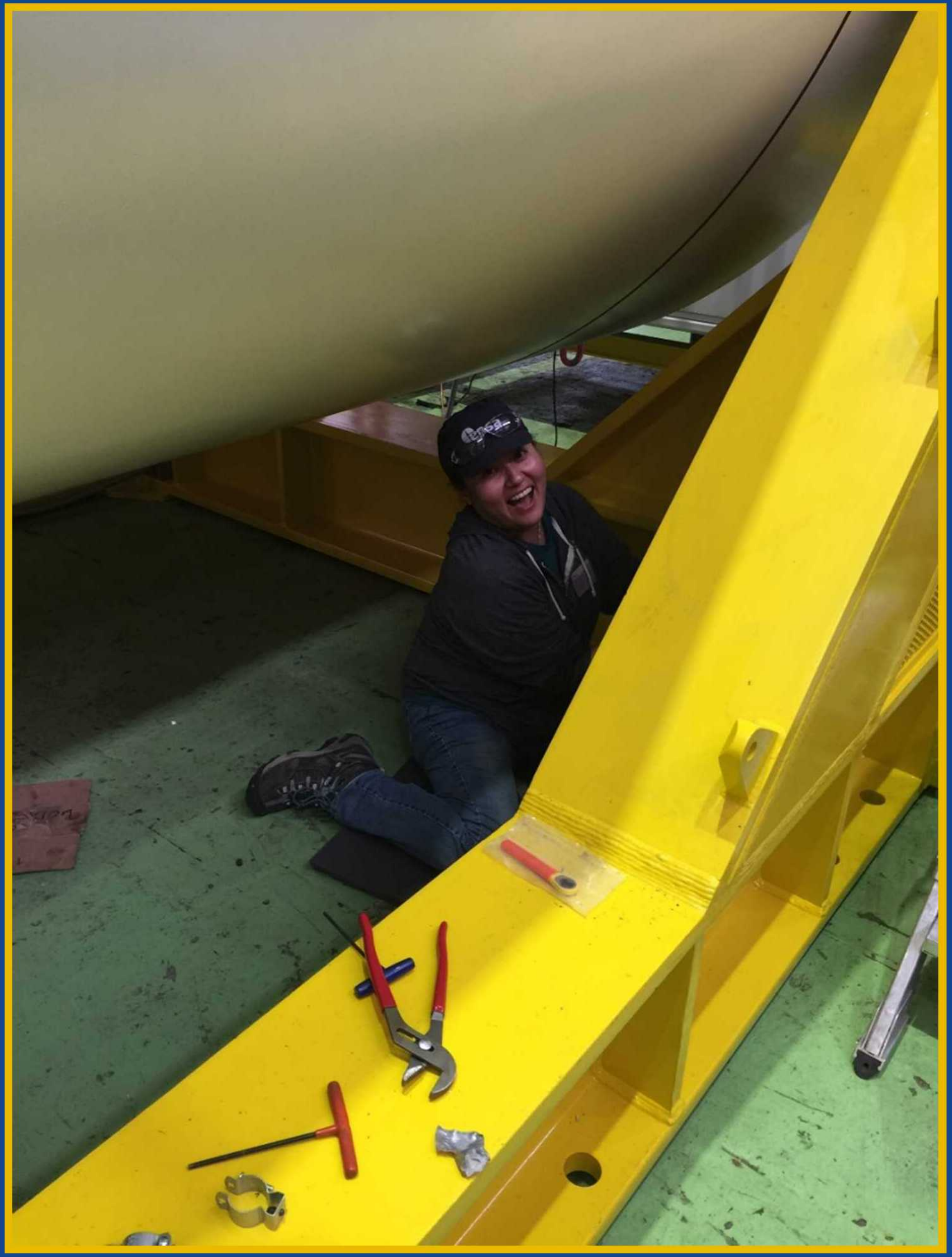


$$\epsilon = \frac{\Delta L}{L} = \frac{\ell - L}{L}$$

This means that a 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

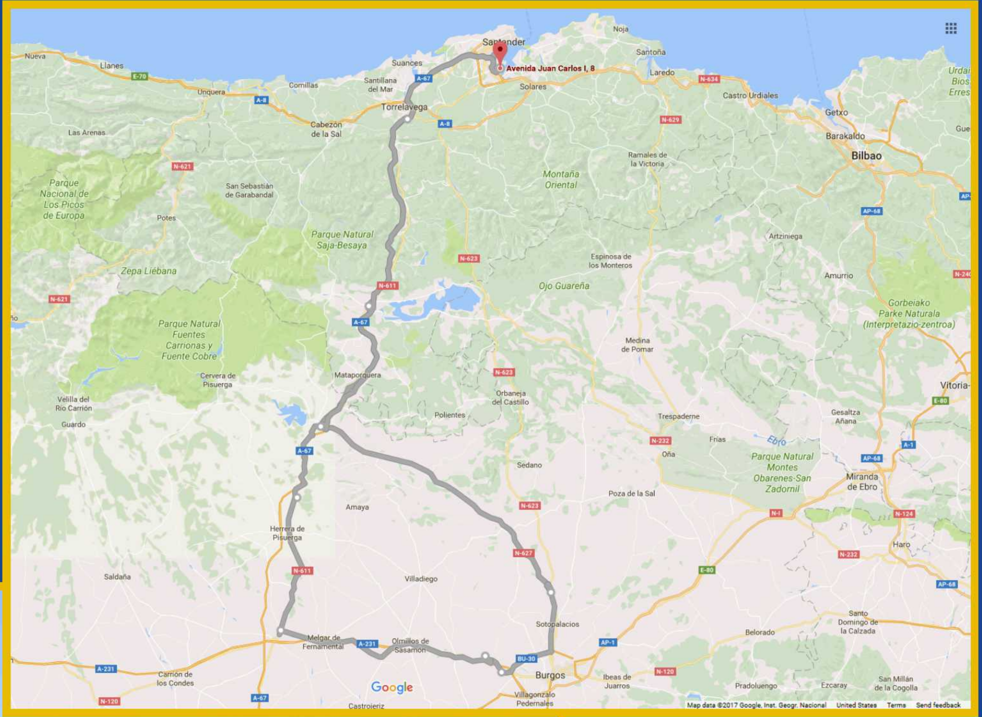
After the handling tests, the cask was connected to the battery and data acquisition box on a cradle extension.

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



Loading on 16-axle, 110 foot-long heavy-haul truck.
The truck trailer had 3 sets of triaxial accelerometers on the bed.

Heavy-haul truck route through northern Spain – Burgos to Maliaño and back.



Many *rotondas*…

… and tiny villages negotiated.

Preliminary Heavy-Haul Truck Test Data

Maximum Assembly Acceleration = 0.74 g

Maximum Assembly Strain = 86 μm/m

A 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

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.

Preliminary Intercoastal Ship Test Data

Maximum Assembly Acceleration = ≤0.3 g

Maximum Assembly Strain = ≤20 μm/m

A 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

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	0.86	≤0.3	≤0.3	≤0.3	≤0.3

Cask system then loaded onto “Tarago” at Port of Zeebrugge for transport to Baltimore, MD, USA.

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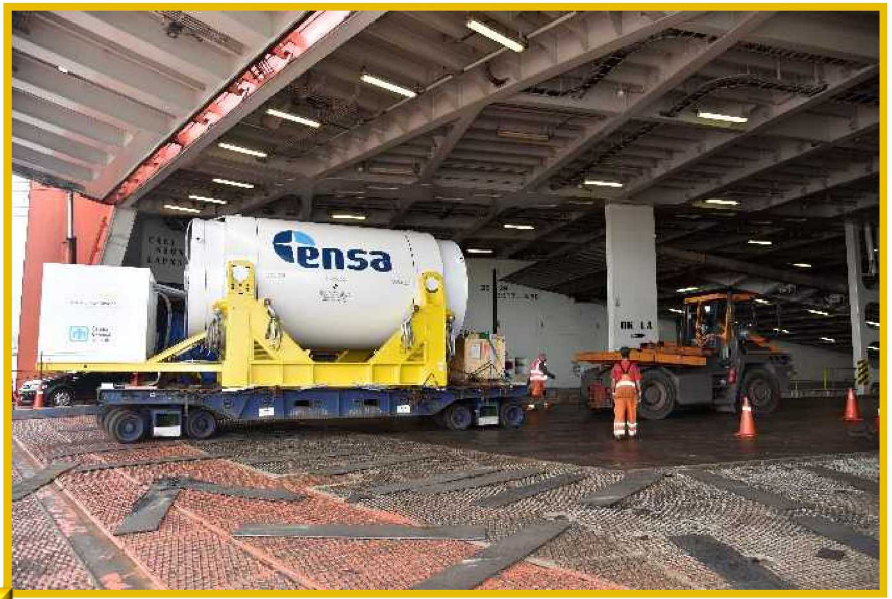
Preliminary Transoceanic Ship Test Data

Maximum Assembly Acceleration = ≤0.2 g

Maximum Assembly Strain = ≤ 20 μm/m



A 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

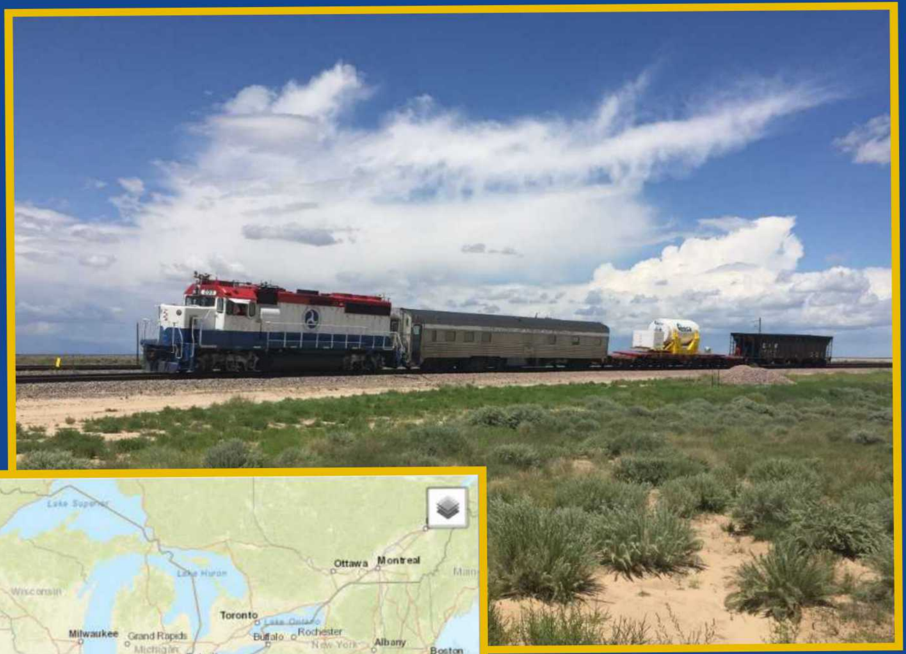
Maximum Assembly Strain, μm/m	Maximum Platform Acceleration, g	Maximum Cask Acceleration, g	Maximum Cradle Acceleration, g	Maximum Basket Acceleration, g	Maximum Assembly Acceleration, g
≤20	0.38	≤0.2	≤0.2	≤0.2	≤0.2

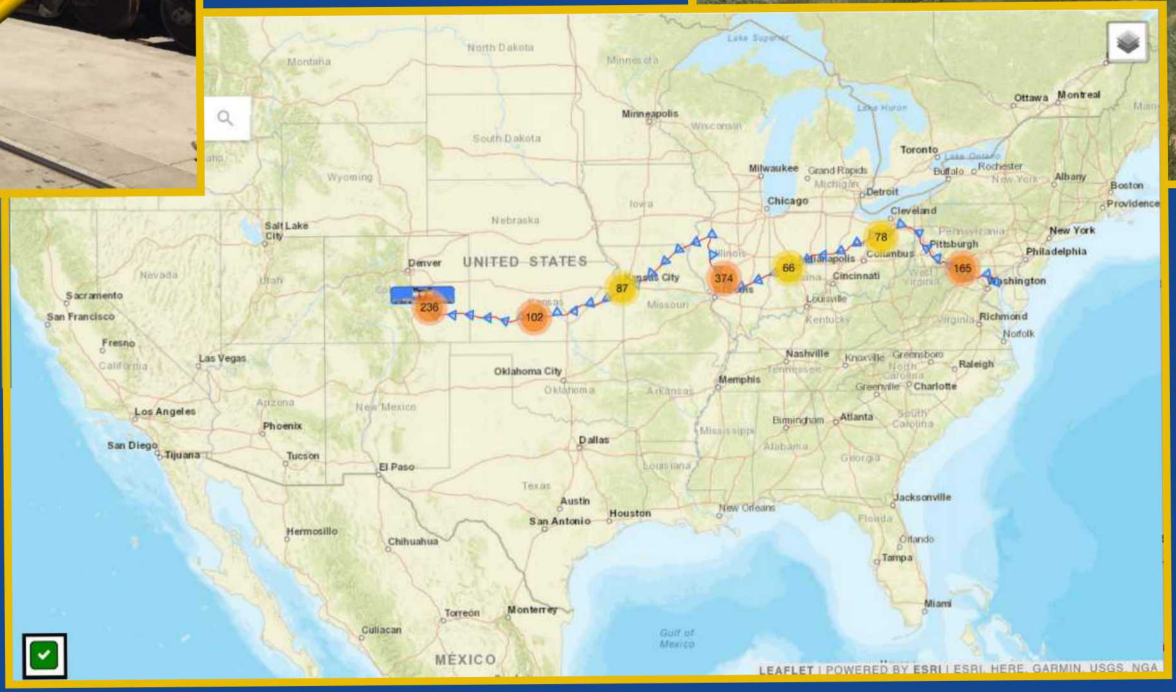
Cask then transferred onto 12-axle Kasgro railcar at Mid-Atlantic Terminal, Baltimore.

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

Preliminary Cross-Country Rail Test Data

Maximum Assembly Acceleration = 1.3 g

Maximum Assembly Strain = 47 μm/m

A 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

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.*

Pushing the Envelope with Tests at TTCI

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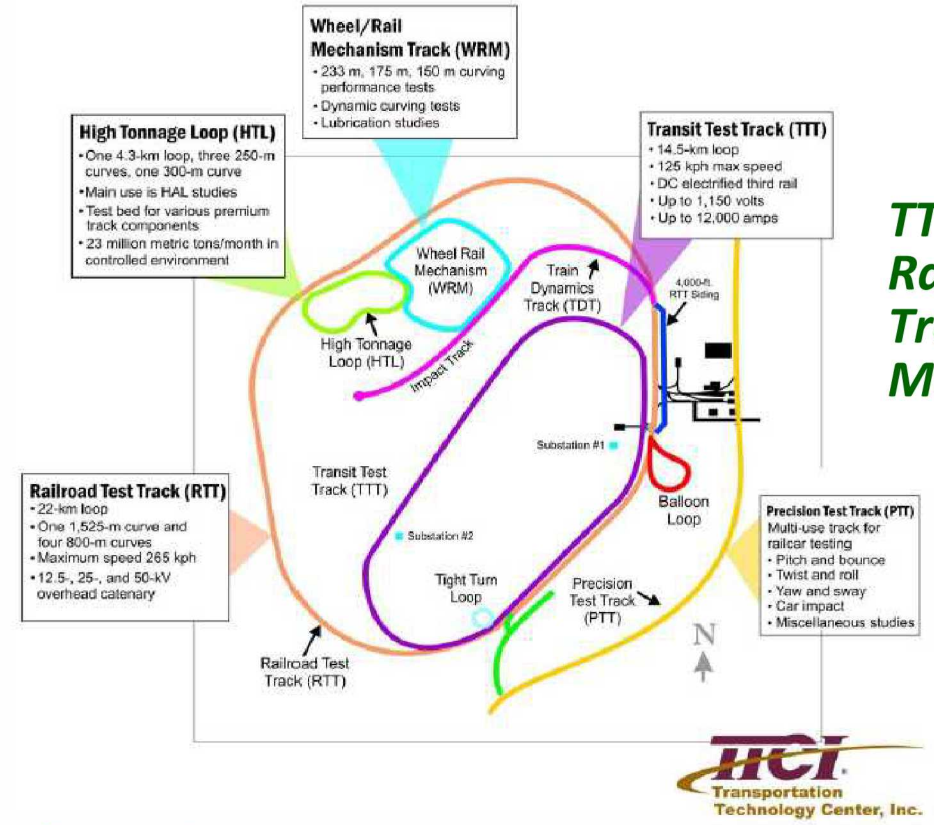
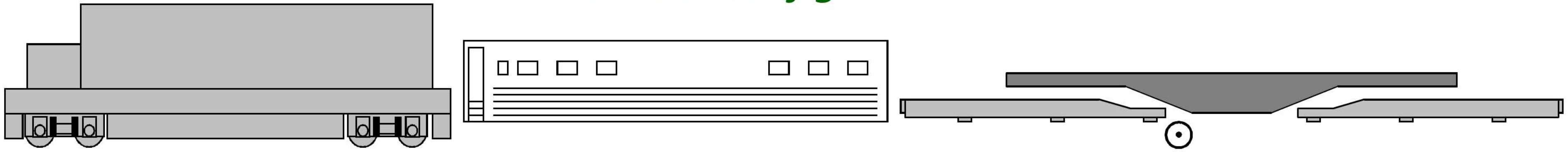
Kasgro 12-Axle Car with Cask at TTCI

TTCI Rail Track Map

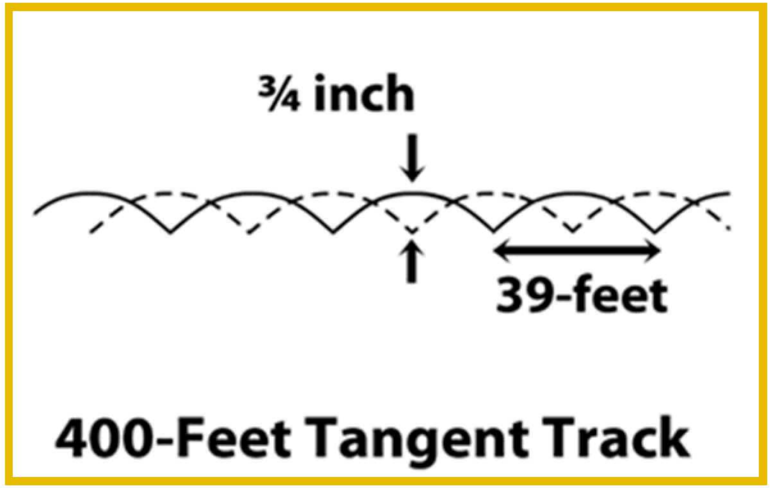


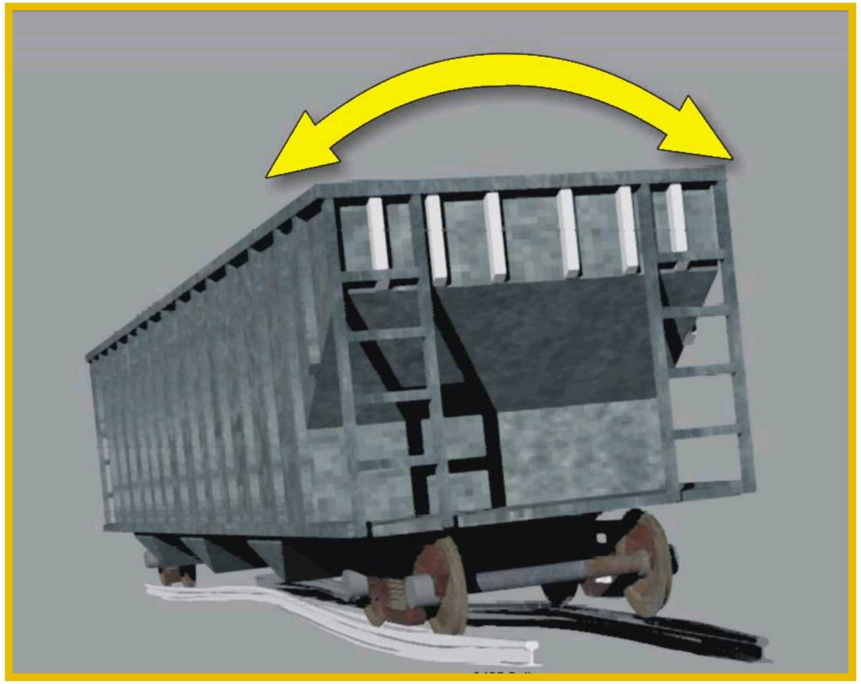
Consist Configuration



Twist & Roll *(18 tests)*

Car's ability to negotiate oscillatory cross-level perturbations





Staggered Joints on a 39-foot Wavelength

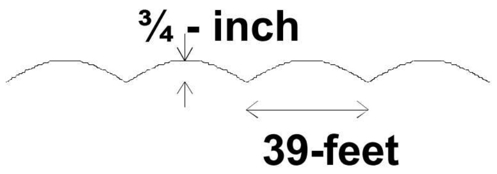
- **39-feet was the typical rail length**
- **"Rock off Derailments" were once a problem**
- **Continuously welded rail has reduced, but not eliminated this kind of behavior**

Pitch & Bounce *(9 tests)*

Car's ability to negotiate parallel vertical rail perturbations

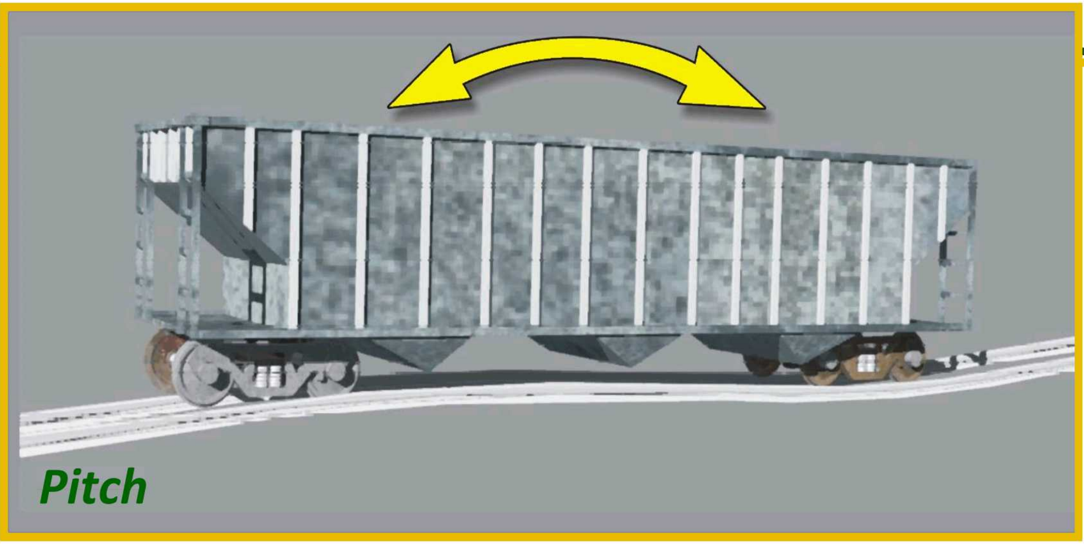
PITCH AND BOUNCE
Parallel Jointed Track

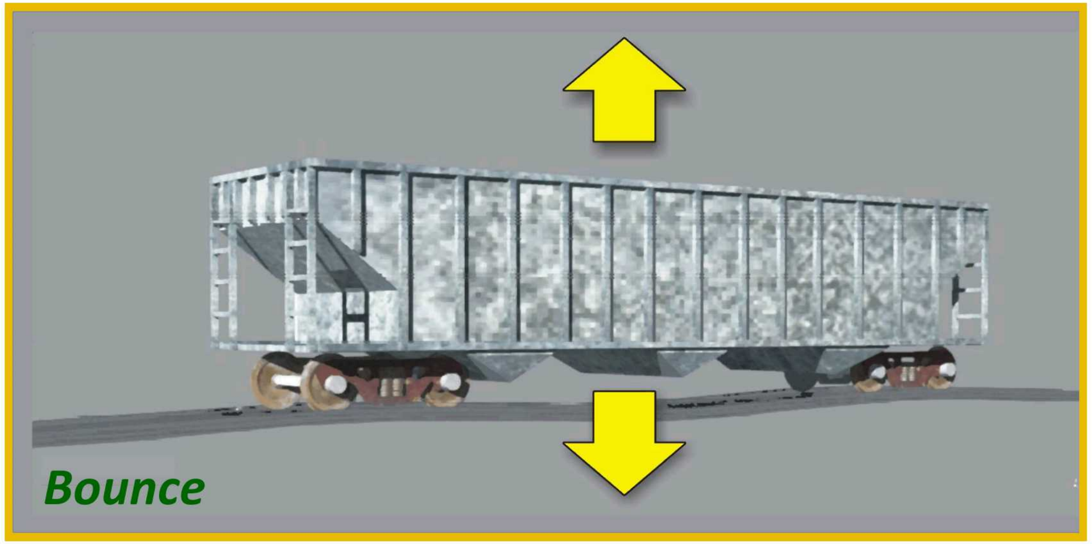
PTT *Track*



400 feet Tangent Track

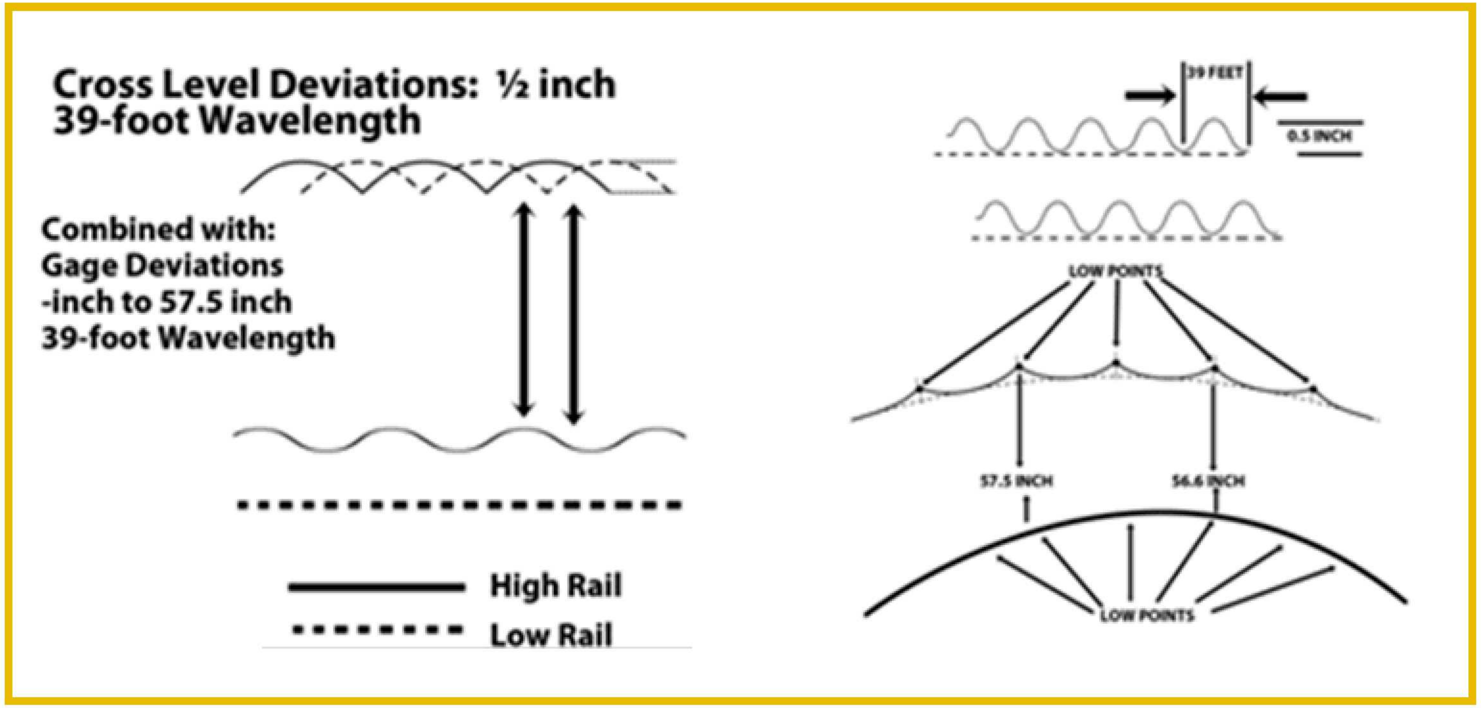
- **39-foot wavelength**
- **Parallel joints**





Dynamic Curving *(25 Tests)*

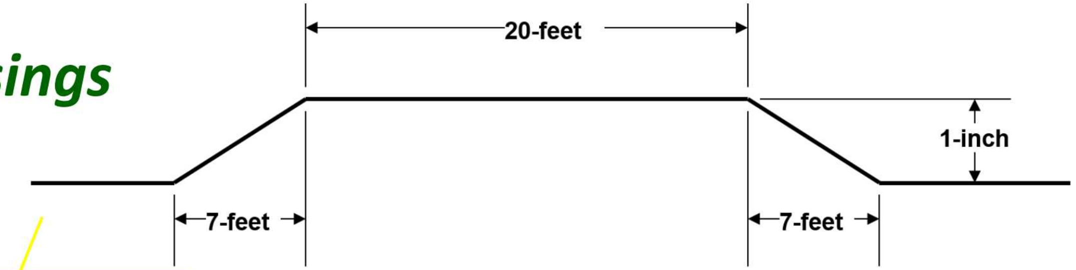
Car's ability to negotiate curving over jointed track with combination of lateral misalignment at outer rail joints and cross-level due to low joints on staggered rails.



- **39-foot wavelength**
- **Cross-level deviations**
- **Gage deviations that create a "down and out" perturbation**
- **10-degree curve with 4-inch super-elevation**

Single Bump *(12 Tests)*

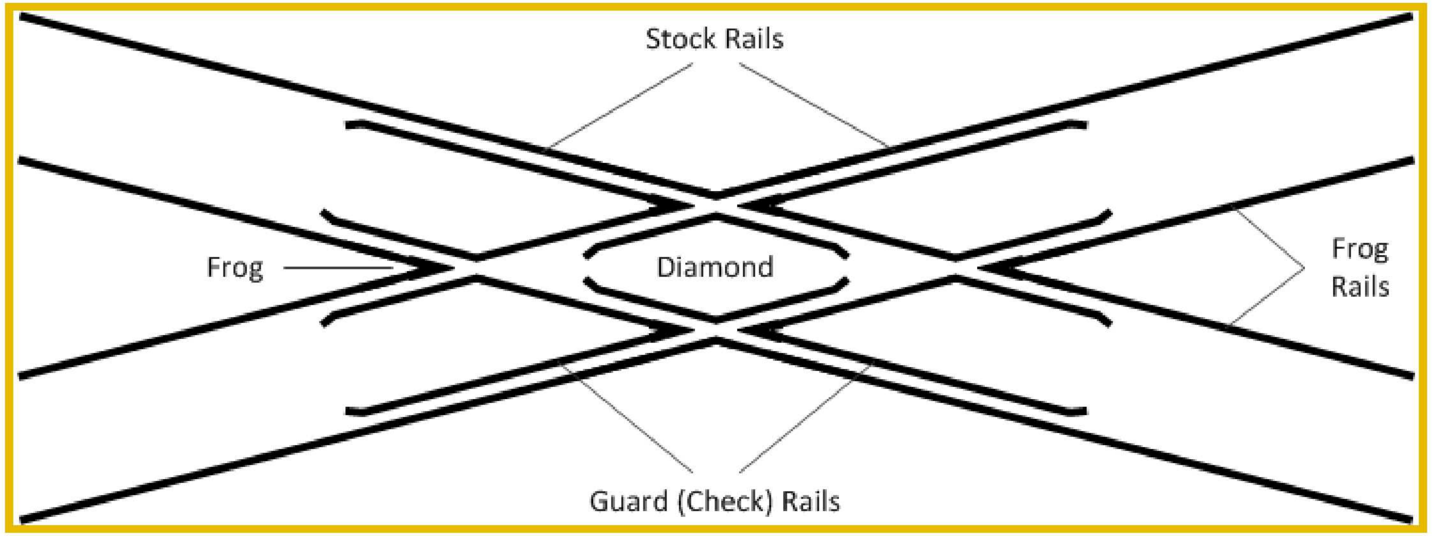
Car's performance at grade crossings



Crossing Diamond *(6 Tests)*

Car's behavior when crossing diamonds or "frogs" is a leading cause of derailments.

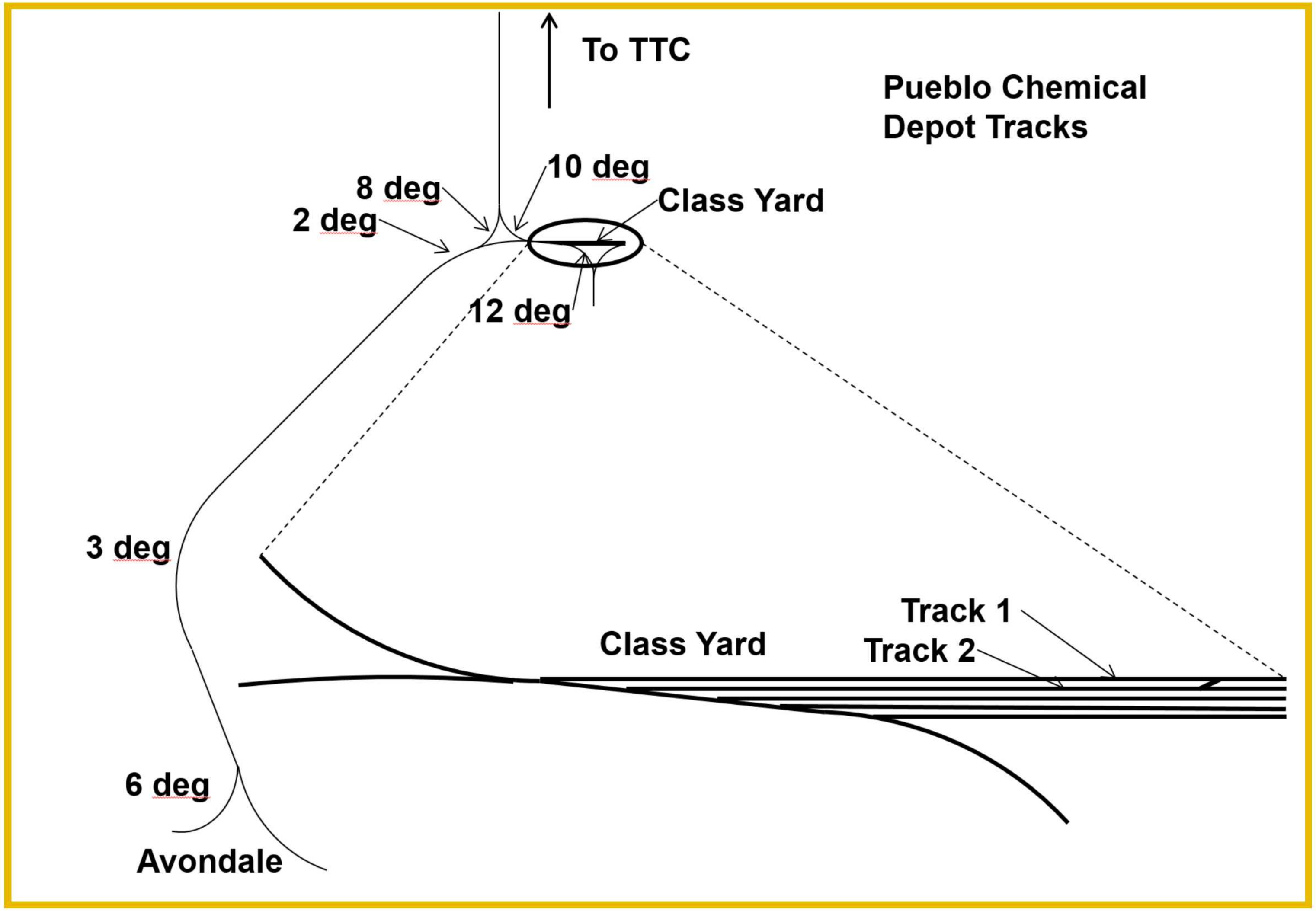
Vertical impacts resulting from the wheels traversing gaps in the rails where tracks intersect.



The crossing diamond was simulated by cutting gaps in the rails matching the dimensions of those that would be present on an actual crossing diamond.

Pueblo Chemical Depot *(17 Tests)*

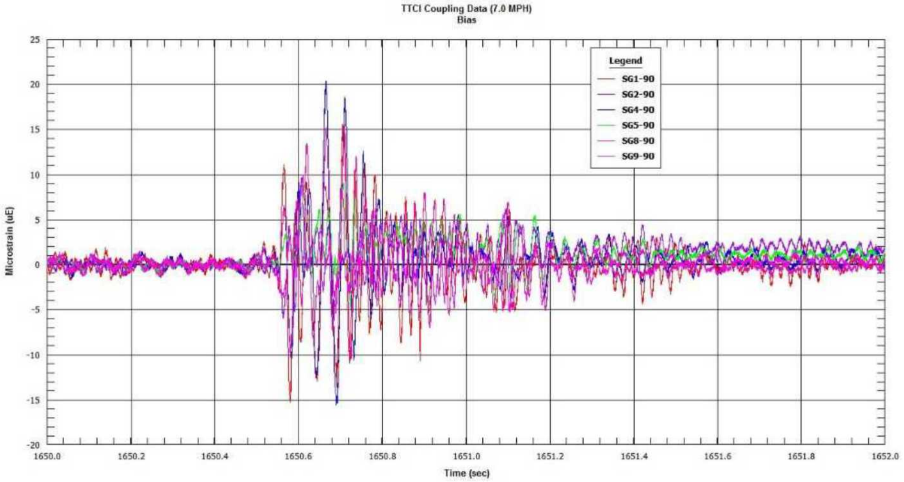
Car's performance over FRA Class-2 railroad track and tests through No. 8 turnout and No. 8 crossovers.

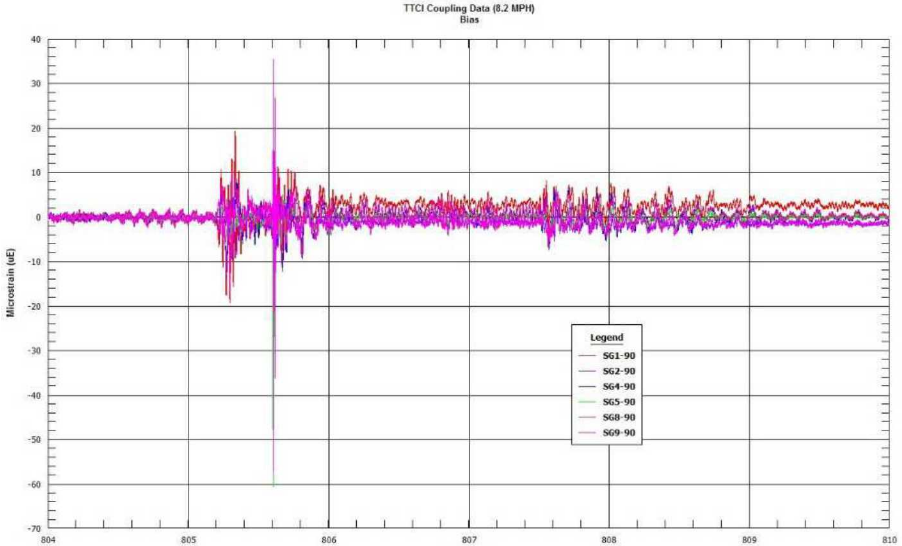


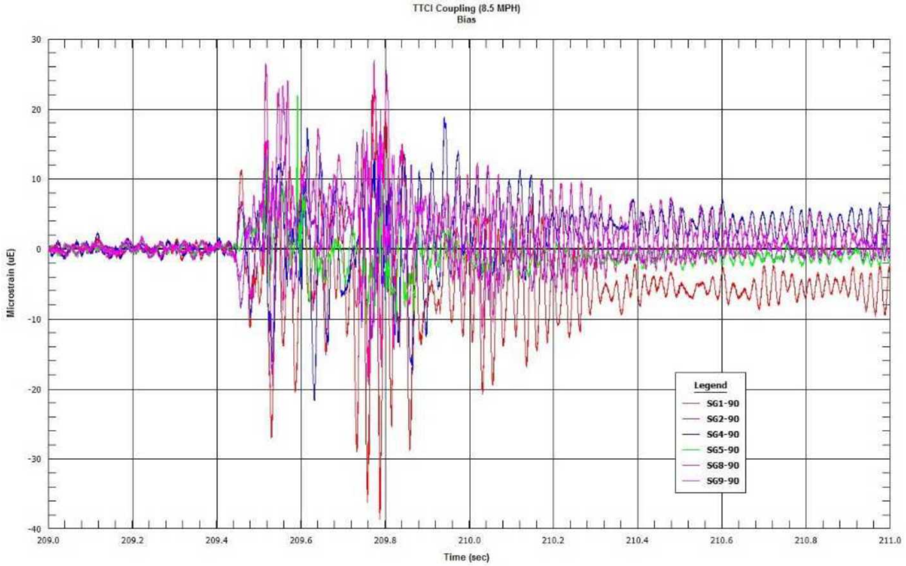
Preliminary Railcar Coupling: 7.0, 8.2, 8.5 mph

SNL Assembly Strain Gauge Data

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







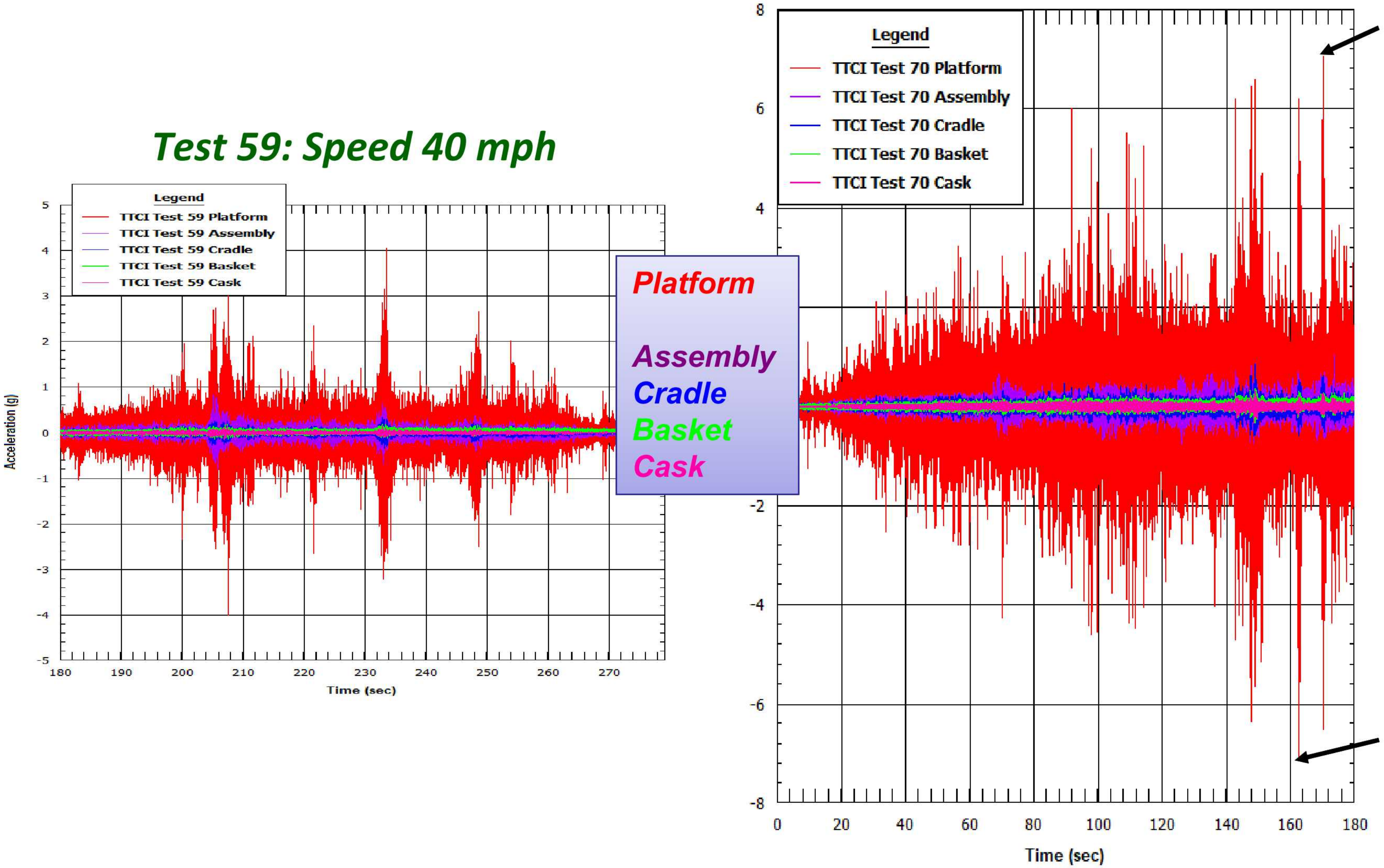
A 13-foot rod subjected to 100 microstrain would experience a change of length of 1/64 in.

How do Accelerations Travel in the Transportation System?

Single Bump Tests

Test 59: Speed 40 mph

Test 70: Speed 75 mph



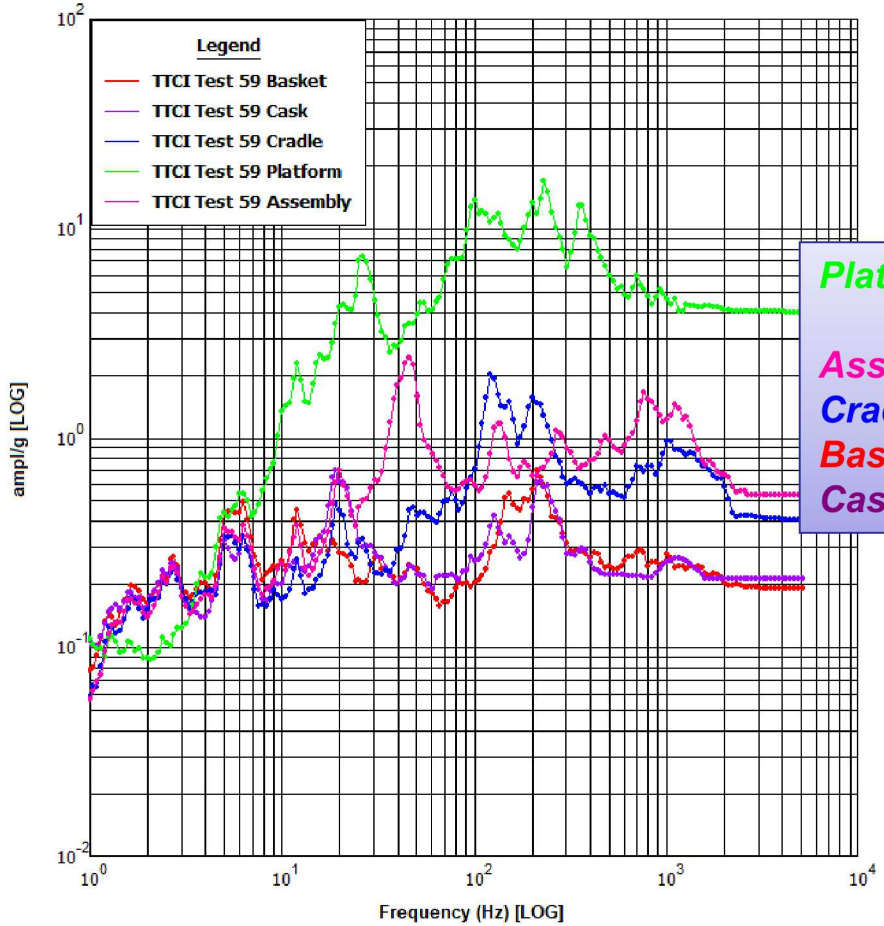
Platform Max

Platform Min

How do Accelerations Travel in the Transportation System?

Vertical Accelerations in the System

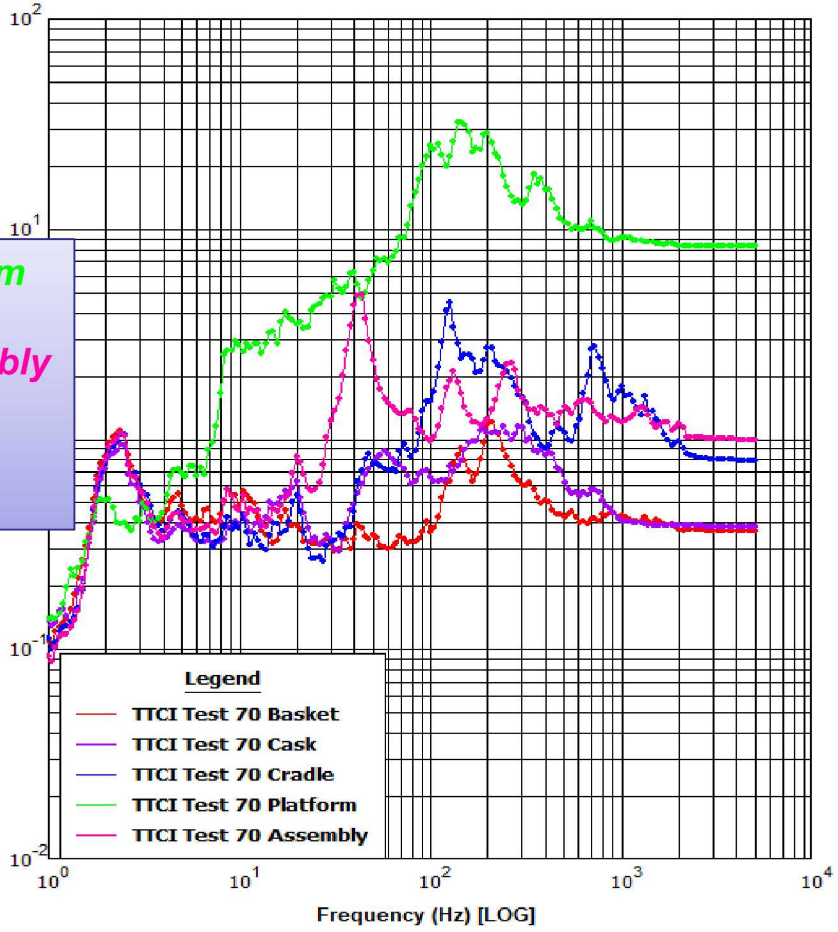
Test 59: Speed 40 mph



Platform

Assembly
Cradle
Basket
Cask

Test 70: Speed 75 mph



What frequencies are amplified from the platform to the cask?

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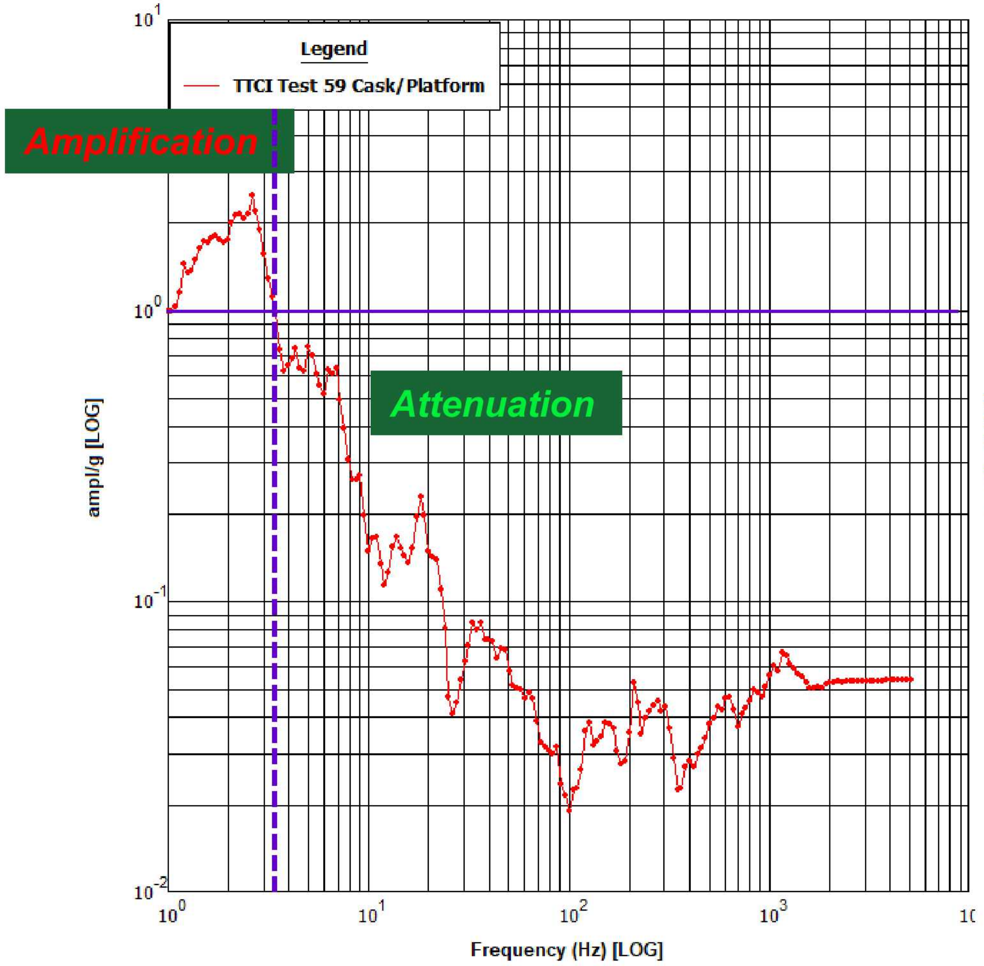
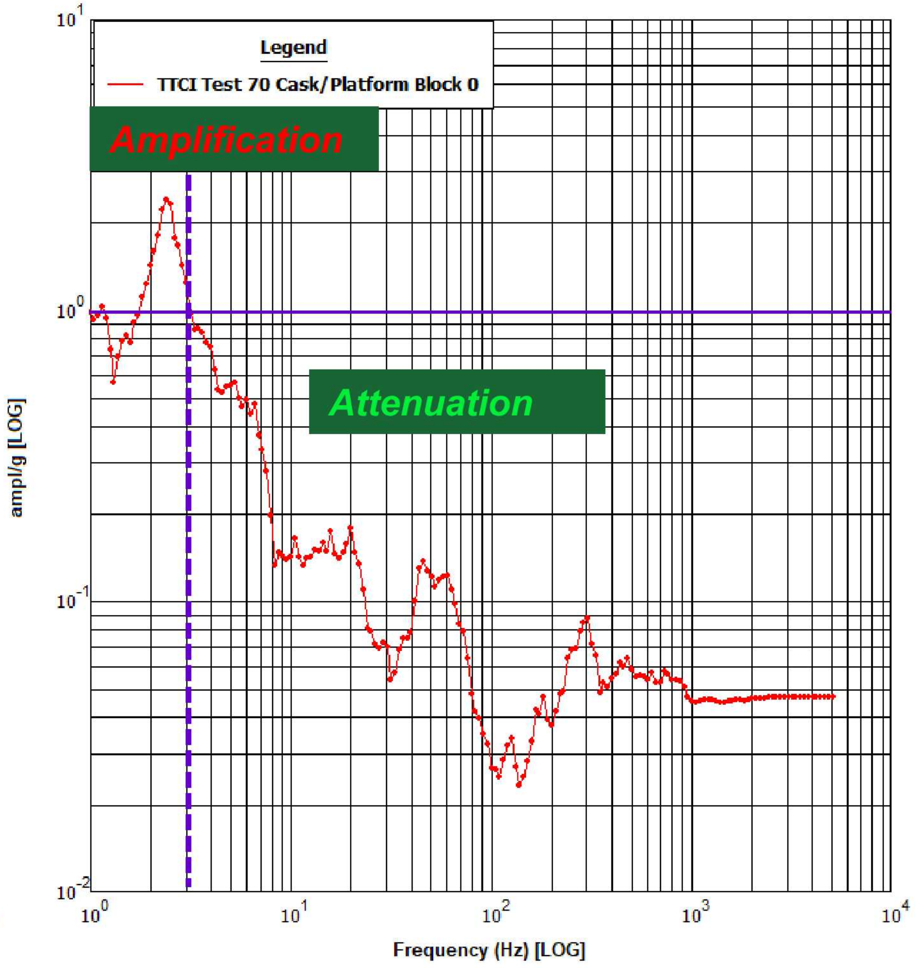
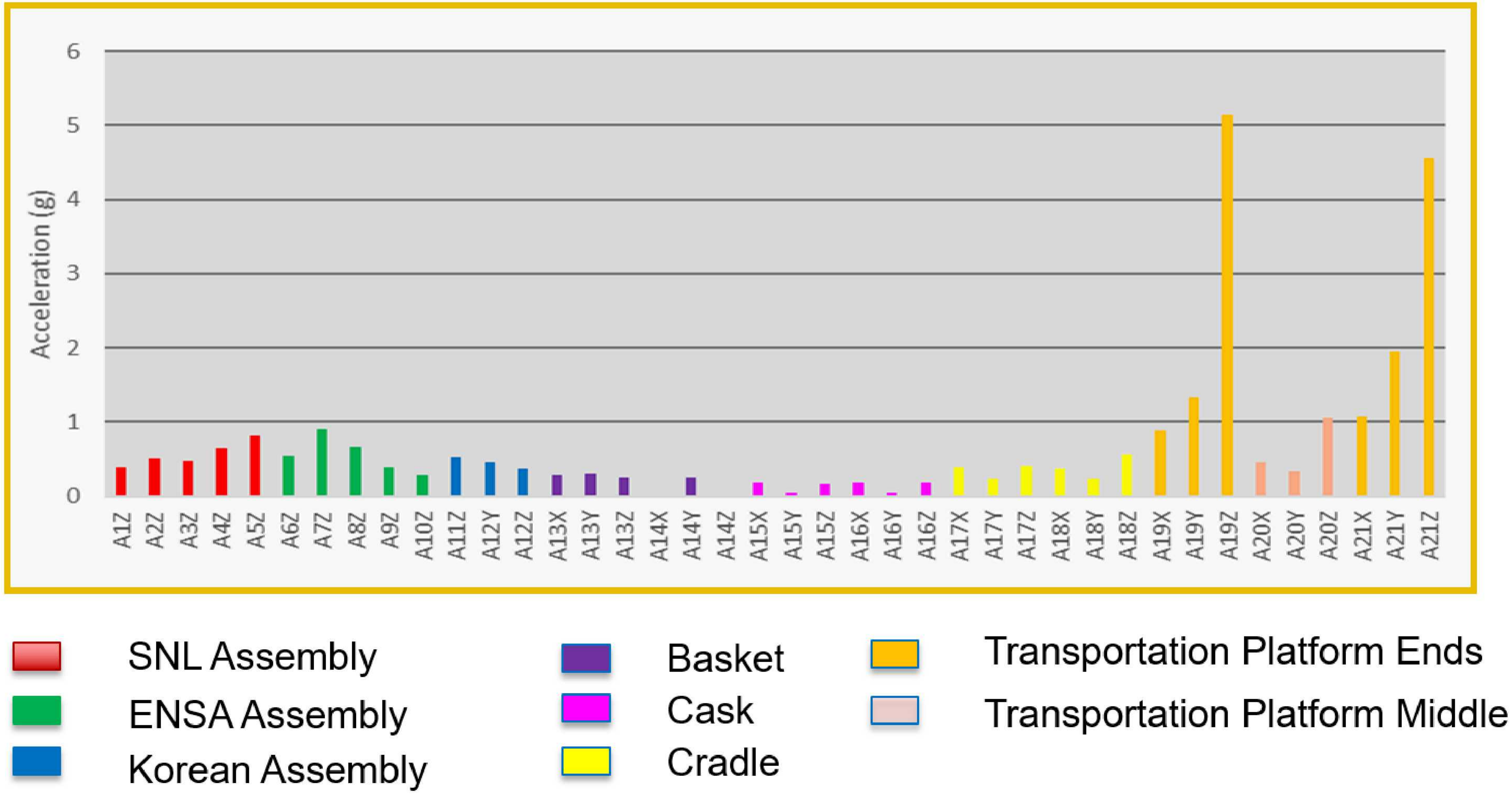
Test 59: Speed 40 mph



Test 70: Speed 75 mph



Where Do We See the Highest Accelerations?

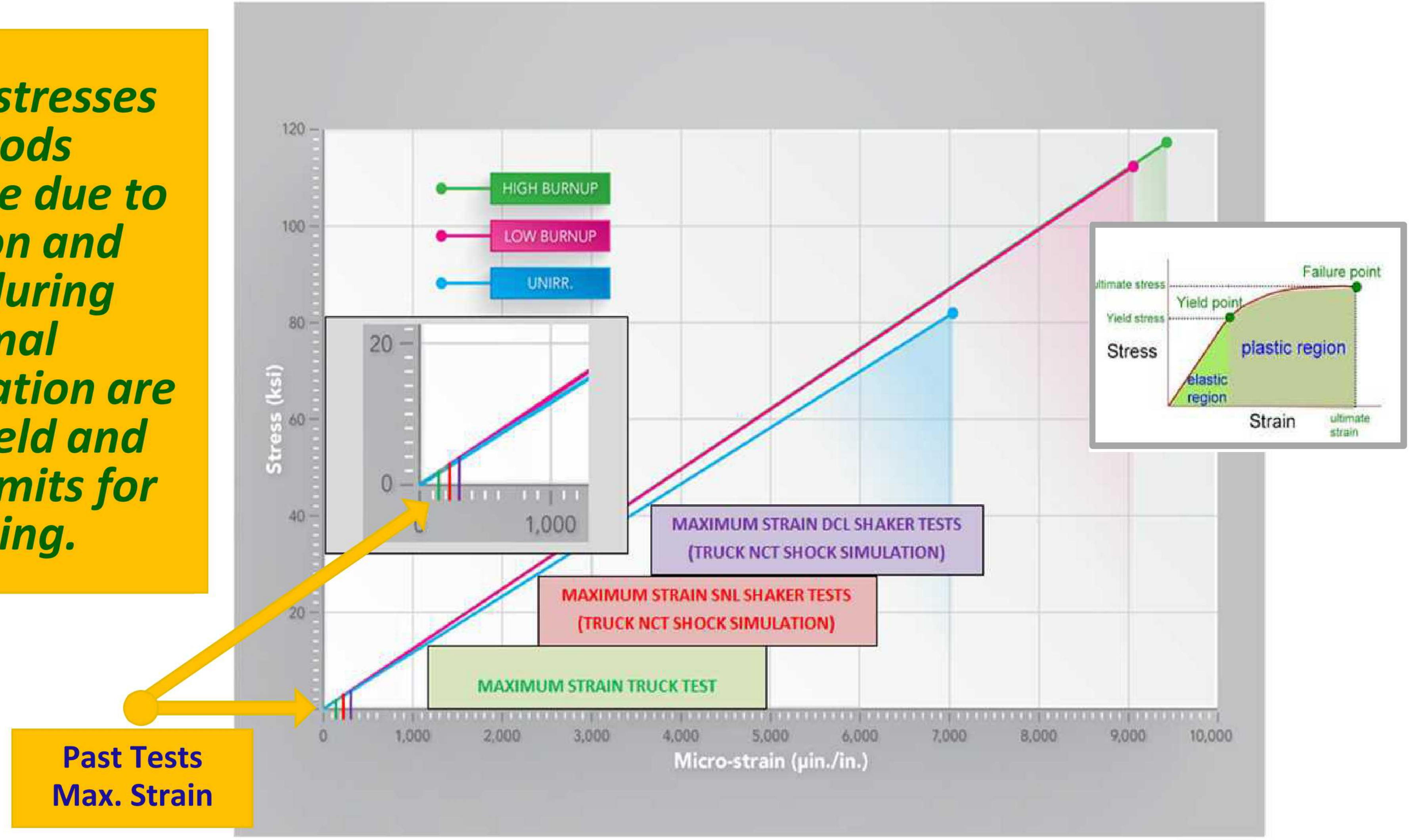


But, let’s put this into context…

Assembly Strains in Rail-Cask Tests

Demo Sister Rod Tests Will Confirm Post-drying High-burnup Cladding Yield Points

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



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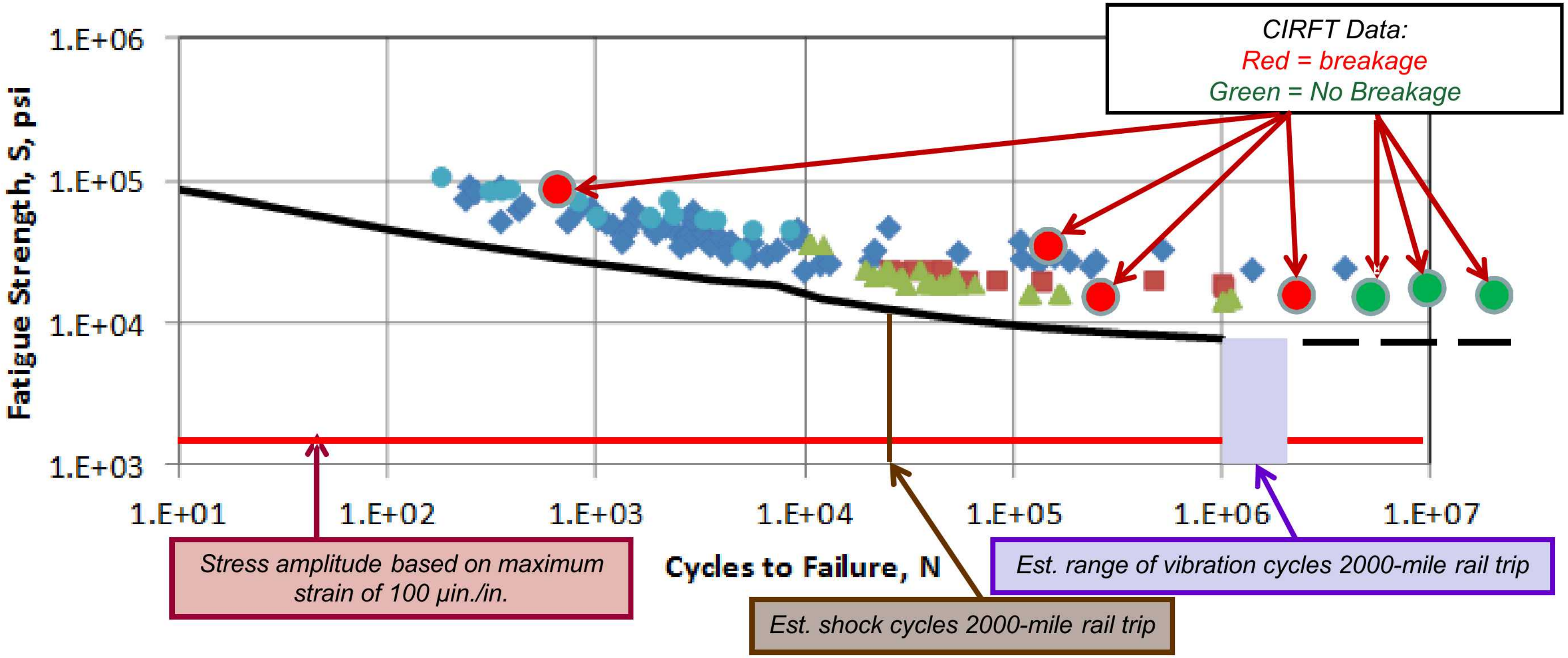
Could Vibrations or Shocks Result in Fatigue Failure?



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

The Shocks and Vibrations we measured are well below the failure points found in Spent Fuel past tests.

How do we know what Shocks and Vibrations Spent Fuel can Withstand?

Questions?

Three Research Efforts are Working to this Goal.

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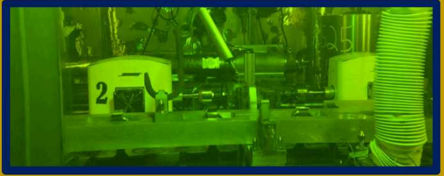
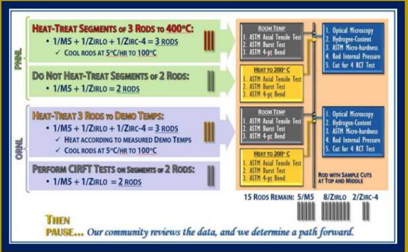
We have fuel in hot cells.



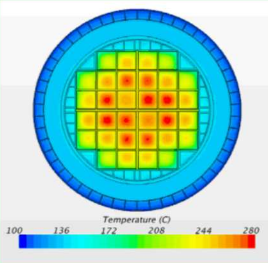
We completed non-destructive tests.



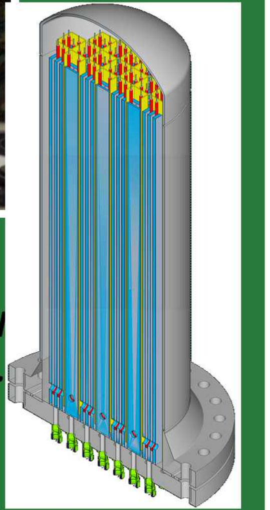
We are starting destructive analysis.

SISTER ROD MECHANICAL TESTING DATA

We have thermal models.



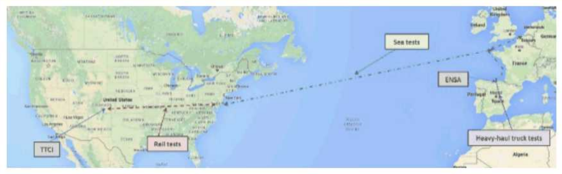
We are getting new thermal data from the Demo.

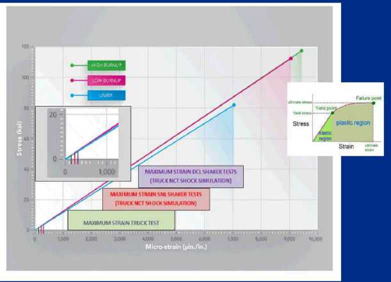


We will build a test apparatus to identify thermal conservatisms & develop more realistic assumptions.

THERMAL BEHAVIOR

PROVIDES KNOWLEDGE ABOUT SPENT FUEL INTEGRITY WHICH IS COMPARED TO DATA FROM THE TRANSPORTATION TESTS





SPENT FUEL TRANSPORTATION TEST:
QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS

SJS5

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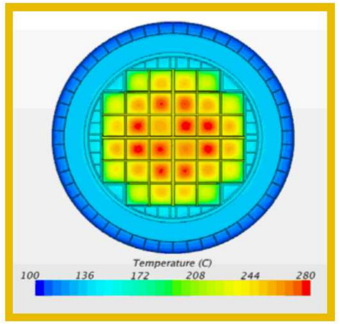
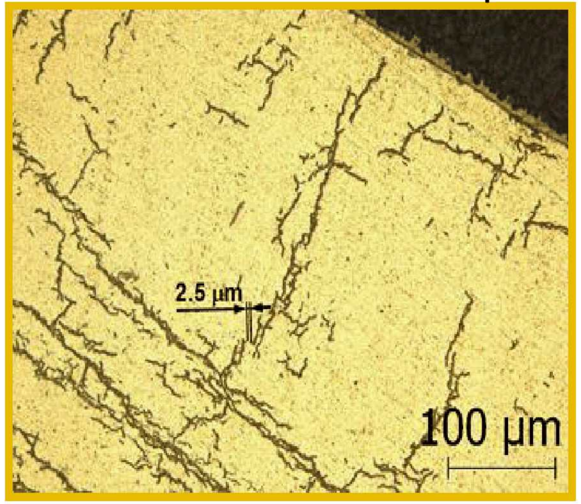
Understanding High Burn-up Cladding Performance through Years of R&D

Thermal Analysis

- More detailed modeling shows considerable margin between design basis loading and actual loading resulting in lower temperatures than previously thought



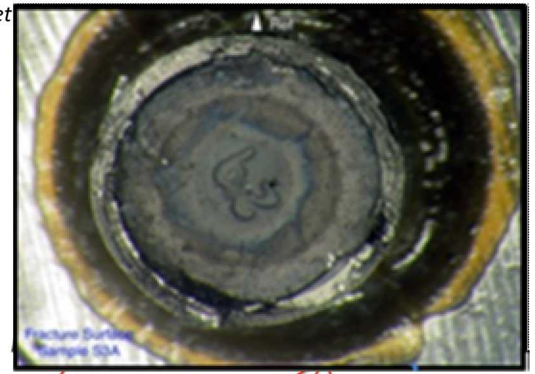
Maximum cladding surface temp. (°C) for each assembly in one type of licensed cask.
(Fort, et

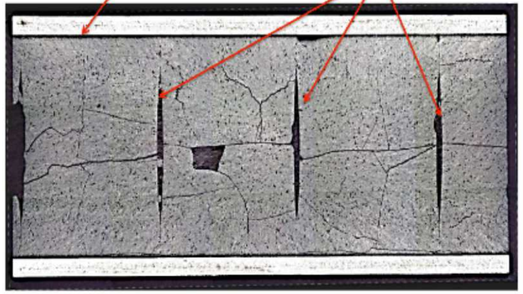


Circumferential and Radial hydrides in High Burn-up ZIRLO cladding subjected to peak temperatures of 350°C and 92 MPa hoop stress. (Billone, 2015. ANL)

Ductile/Brittle Transition Temperatures

- Lower temperatures and lower rod internal pressures than previously assumed results in fewer radial hydrides
- Temperature where cladding loses significant ductility is thus lower than previously thought

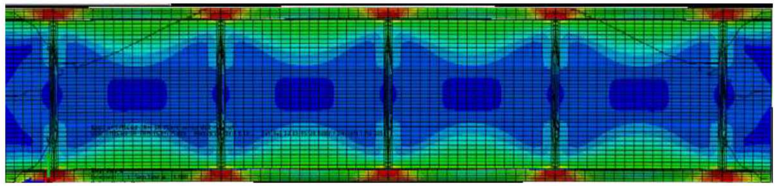




Fuel rod segment before bend testing
(Wang, et al., 2016. ORNL)

Strength and Fatigue

- Cyclic bending tests of irradiated fuel segments identify increased strength due to pellet/clad and pellet/pellet bonding effects.



Stress distribution in fuel showing the fuel pellets supporting the clad due to cohesive bonding.(Wang, et al., 2014, ORNL)

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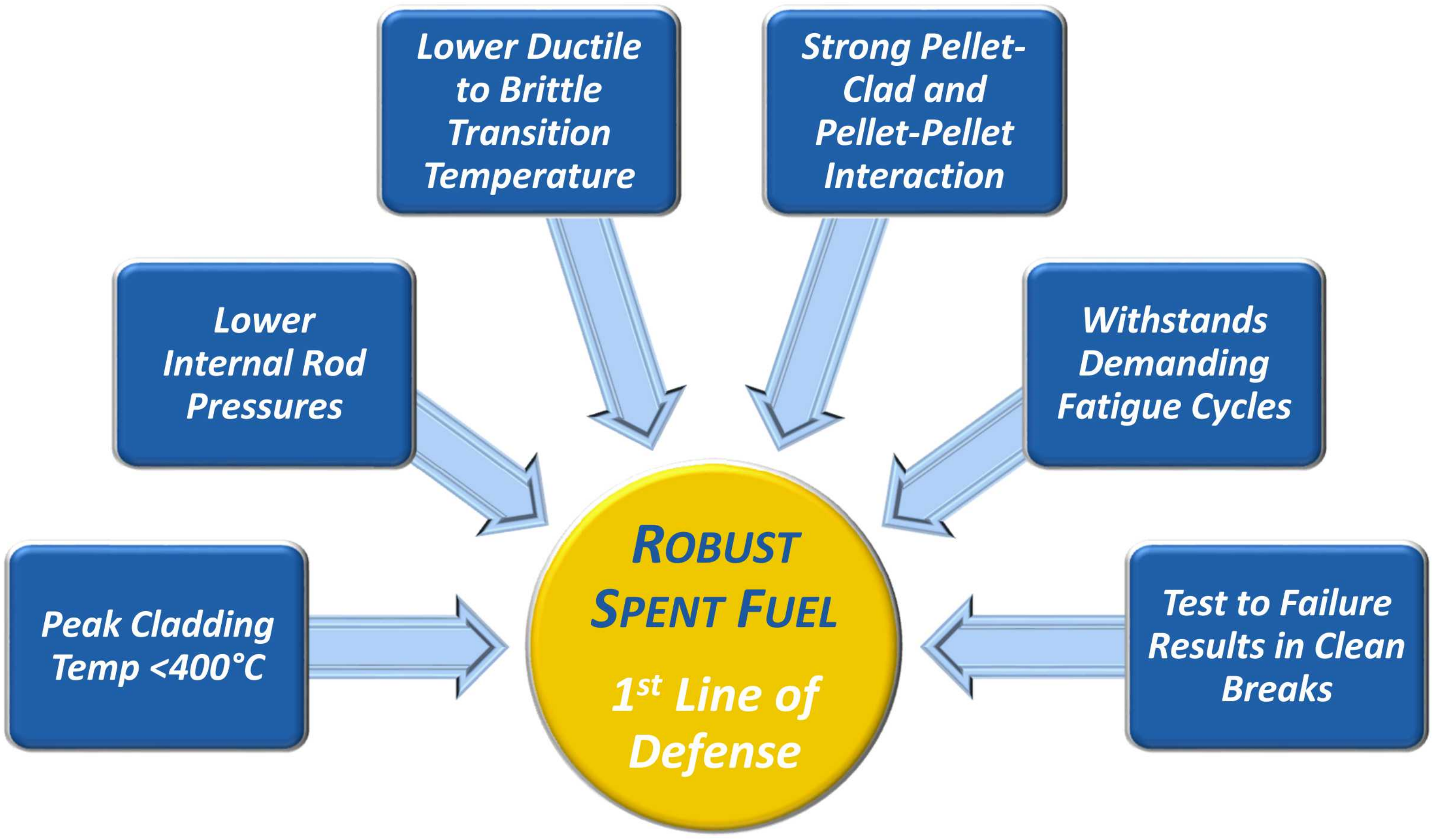
SJS5 You could add some of the Non-destructive test pictures and state that all the sister rods looked as expected; there were no surprises.

Ho Family, 4/16/2018

Current Lab Tests & Analyses Indicate Spent Fuel *More* Robust than Previously Thought



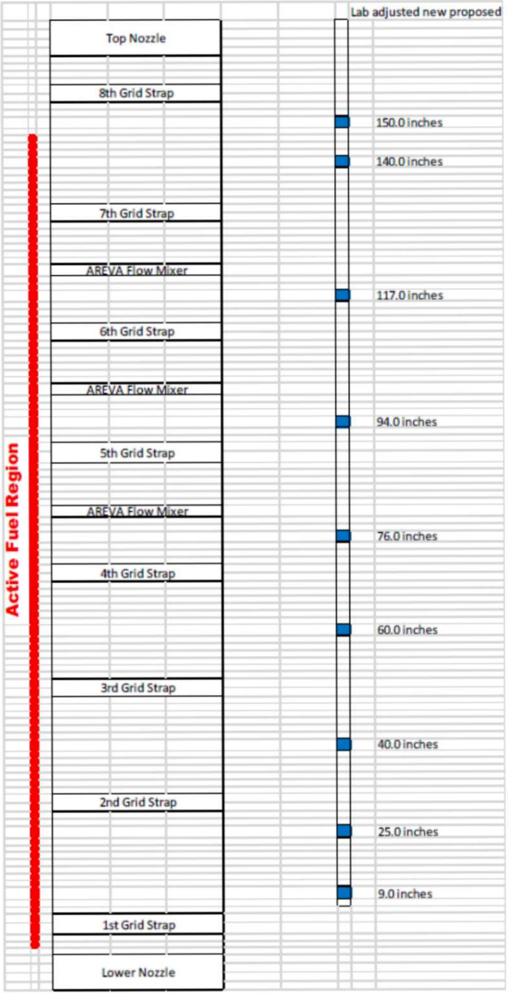
Obtaining Data on High Burnup Cladding After 10 Years of Dry Storage

- **DOE/EPRI High Burnup Confirmatory Data Project Goal:**
  To provide confirmatory data for models, future SNF dry storage cask design, to support license renewals and new licenses for ISFSIs

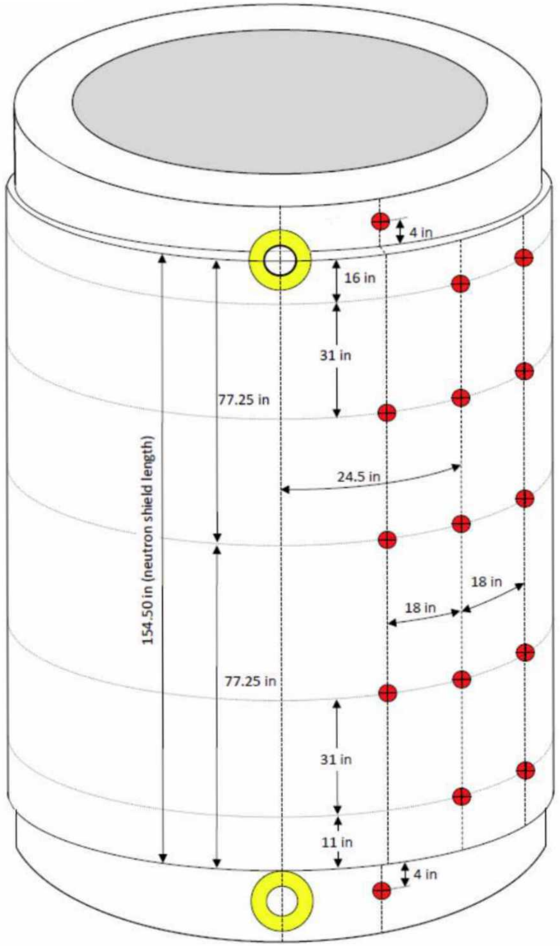
- **Steps**
  1. Loaded a commercially licensed TN-32B storage cask with high burn-up fuel in a utility storage pool
     Loading well characterized fuel of 4 common cladding alloys
  2. Instrumented cask outfitted with thermocouples
  3. Gas samples taken before going to pad
  4. Handled using industry standard practices
  5. Storing at utility dry cask storage site – 10 years
  6. Transporting to lab to open
  7. Testing rods to understand mechanical properties

Prairie Island Dry Storage

Temperature Measurements



Thermocouple axial locations



External surface measurement locations

- 63 Thermocouples - 7 radial, 9 axial
- Also external surface temperature measurements with IR gun

SJS6

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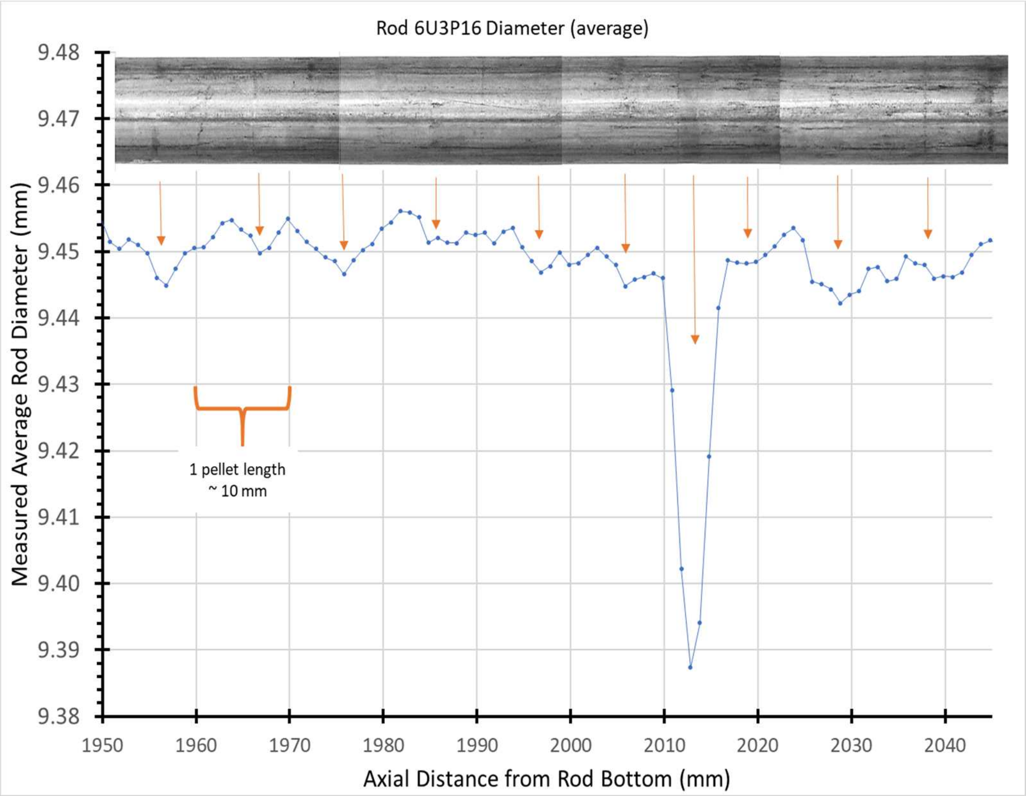
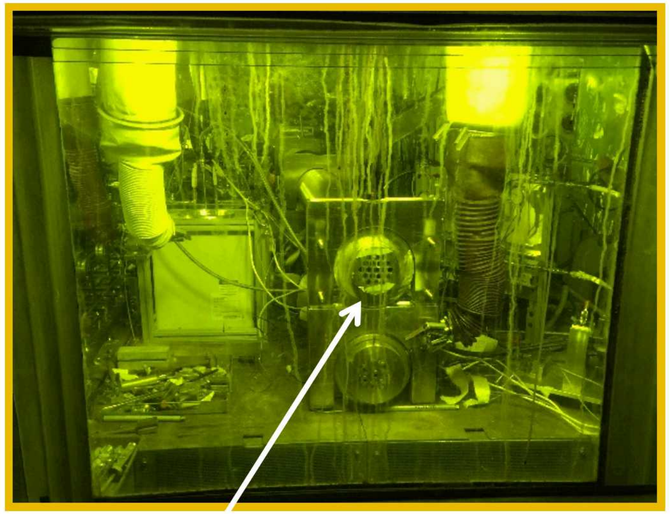
High Burnup Confirmatory Data Project – Obtaining *Baseline* Data

- **25 fuel rods with similar histories to those in the cask will be tested to document pre-storage properties.**
- **"Sister Rod" Acquisition & Testing**
  - Areva and Westinghouse rods pulled in June and January 2015 from different assemblies
    - *9 AREVA M5® rods*
    - *12 Westinghouse Zirlo® rods*
    - *4 Westinghouse Zircaloy-4*
      - 2 Low-tin
      - 2 Standard



2018). There are no indications of significant rod swelling or major cladding defects based on profilometry.(EPRI ESCP, Montgomery R,



25 Sister Rods in ORNL Hot Cell
Photo: Saltzstein, SNL

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SJS6 Ho Family, 4/16/2018

High Burnup Spent Fuel Data Project Sister Rod Test Plan Visualization

4-17-18

We start with 25 Sister Rods. Ten will be used for this test plan[1] – 5 tested by PNNL and 5 tested by ORNL. Both labs will perform the same tests, but ORNL will test fueled rods and PNNL will test defueled rods. ANL will perform RCT & RHT on segments of the rods.

PNNL | **Heat Treatment of Segments or Whole Rods to 400 °C:** | ORNL

- ✓ 3 Rods: 1 M5®, 1 Zirlo®, 1 Zirc-4
- ✓ Cool at ≤5 °C/hr. to 100 °C[2]

PNNL | **No Heat Treatment (as irradiated):** | ORNL

2 Rods: 1 M5®, 1 Zirlo®

6 rods are heat treated and 4 are not; all rods undergo the same series of initial tests at room temperature.

PNNL | **Initial Tests at Room Temperature** | ORNL

- ✓ Rod Internal Pressure
- ✓ Gas Communication
- ✓ Optical Microscopy
- ✓ Hydrogen-Content
- ✓ ASTM Micro-hardness
- ✓ Cut and Defuel RCT & RHT Test Samples; Send to ANL. RCT Tests at 20°C to 200°C , RHT at a PCT of 400°C.

Rods are then cut into segments which will be tested at either room temperature or 200°C[3].

PNNL to Test Defueled Rods

PNNL | **Test at 200°C[4]** | ORNL

- ✓ ASTM Axial Tensile Test
- ✓ ASTM Burst Test
- ✓ ASTM 4-pt Bend
- ✓ Fueled RCT @ ORNL

ORNL to Test Fueled Rods

PNNL | **Room Temperature** | ORNL

- ✓ ASTM Axial Tensile Test
- ✓ ASTM Burst Test
- ✓ ASTM 4-pt Bend
- ✓ Fueled RCT @ ORNL
- ✓ CIRFT @ ORNL
- ✓ Particle Release @ ORNL

1) 10 rods tested; 15 (of 25) remain: 5 M5®, 8 Zirlo®, 2 Zirc-4.
2) Cooling rate may change based on PNNL cooling rate test results.
3) All tests are repeated at two places along each rod, preferably at the top and near the middle.
4) Not all tests may be able to be performed at 200°C.
5) Deviations from this test plan will be based on continuous learning and approved before execution.
6) As test results are obtained, our community reviews the data, and DOE determines a path forward.

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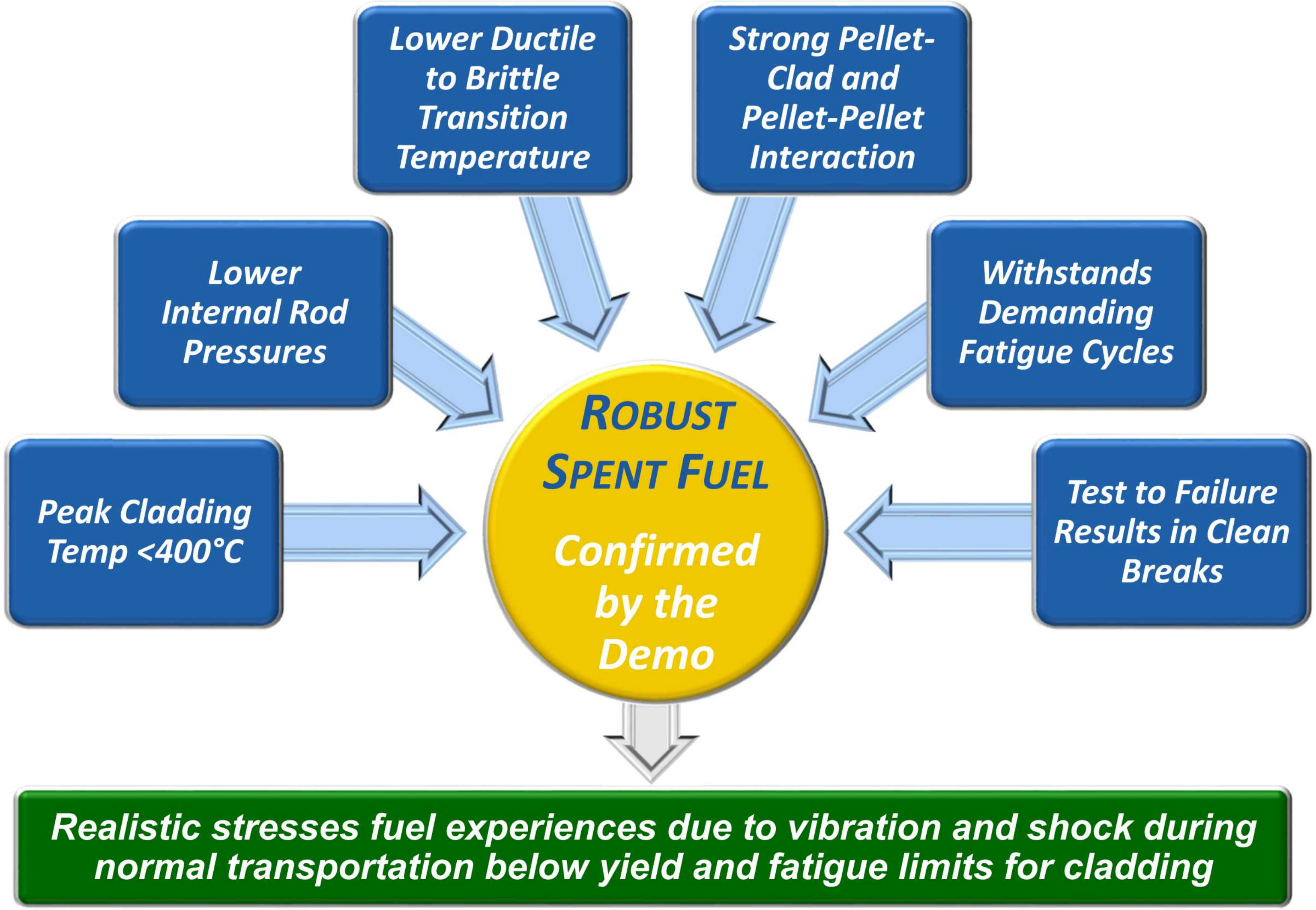
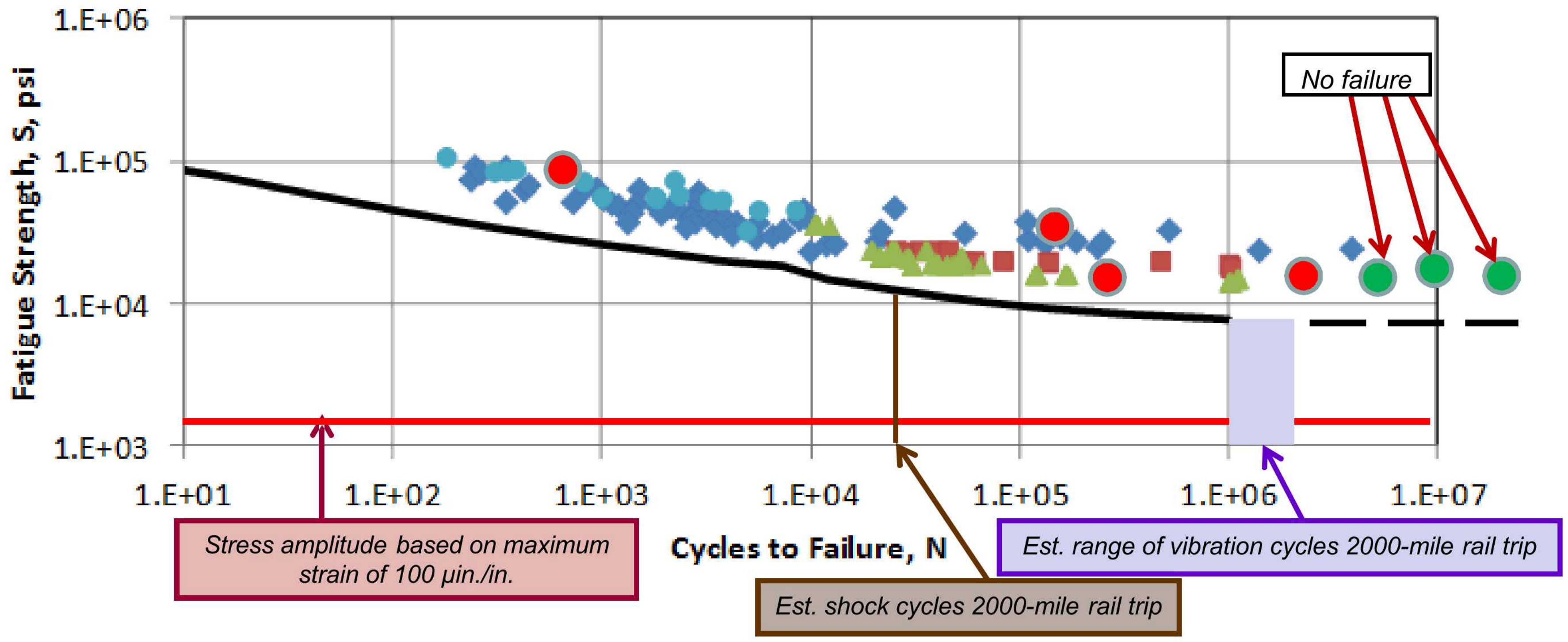
Current R&D Indicates SNF is Robust and Loads Expected During Handling/Transport Less Than What We Previously Thought



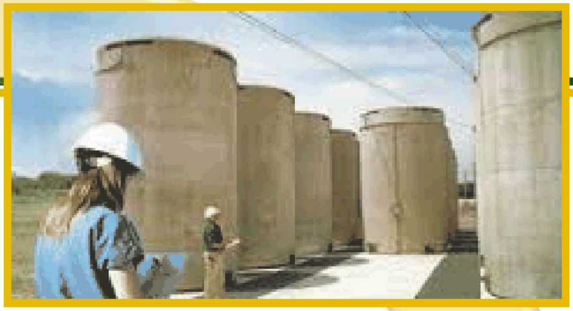
Could Vibrations or Shocks Result in Fatigue Failure?

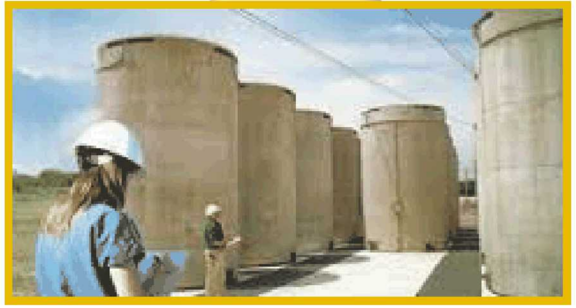


Fatigue design curve (▬▬): O'Donnel and Langer, "Fatigue Design Basis for Zircaloy Components," Nucl. Sci. Eng. 20, 1, 1964. (cited in NUREG-0800, Chapter 4)

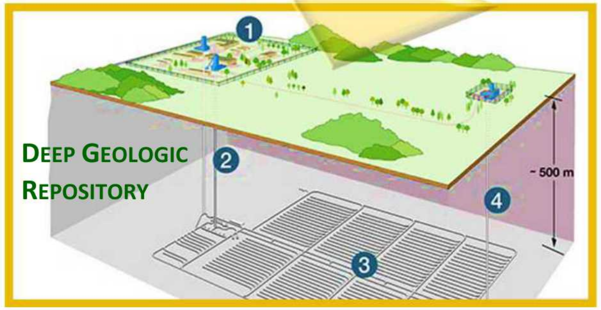
Data plot courtesy of Ken Geelhood, PNNL
The large circles are ORNL HBR data

The Shocks and Vibrations we measured are well below the failure points found in Spent Fuel past tests.





OUR PRELIMINARY RESULTS INDICATE THAT NORMAL CONDITIONS OF TRANSPORT PROVIDE VERY LITTLE CHANCE OF DAMAGING SPENT NUCLEAR FUEL.



How Does This Impact Being Ready to Move Fuel?

The Bottom Line…

Our preliminary results indicate that normal conditions of transport provide very little chance of damaging spent nuclear fuel.

"Accurate measurement is worth a thousand expert opinions."
Admiral Grace Murray Hopper

Concluded …thank you.

Questions ?

Research on Long-Term Storage and Transportation of Spent Nuclear Fuel

Sylvia Saltzstein, Brady Hanson, John Scaglione, Mike Billone, Steve Ross, Doug Ammerman, Elena Kalinina, Rose Montgomery

Sandia National Laboratories, Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory

National Transportation Stakeholders Forum 2018 Annual Meeting

June 4-7, 2018, Omaha, Nebraska

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