Collaborators

- U.S. Department of Energy
- Pacific Northwest National Laboratory (PNNL)
- Equipos Nucleares Sociedad Anónima (ENSA)
- Korea Hydro and Nuclear Power (KHNP)
- 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
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
Loaded ENUN-32P with Three Instrumented Surrogate Assemblies

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

Lid being placed on cask
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)
What is a Micro Strain?

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

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

This means that a 13-foot (3.96 m) rod subjected to 100 microstrain would experience a change of length of 1/64 in (0.4 mm).
Cask Handling Tests (Max 40 μE and 8 g)

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 15.6 μE and 0.52 g)

- 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 3.8 μE 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

Train icons indicate places the train stopped.
Rail 1: Baltimore to Colorado: (Max 35.8 μE and 0.95 g)

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)
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

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twist and Roll</td>
<td>19</td>
</tr>
<tr>
<td>Pitch and Bounce</td>
<td>9</td>
</tr>
<tr>
<td>Dynamic Curve</td>
<td>24</td>
</tr>
<tr>
<td>Class 2 Rail Track (PCD)</td>
<td>17</td>
</tr>
<tr>
<td>Single Bump</td>
<td>8</td>
</tr>
<tr>
<td>Crossing Diamond</td>
<td>6</td>
</tr>
<tr>
<td>Hunting</td>
<td>23</td>
</tr>
<tr>
<td>Coupling Impact</td>
<td>10</td>
</tr>
</tbody>
</table>
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

![Graph showing maximum strains from TTCI tests compared to maximum strains from different modes of transportation](image)
Rail 2: TTCI (Pueblo, CO) to Baltimore (Max 38 μE and 1.05 g)

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

Locations of shock events.
Strain Energy Perspective: SNF Rod Shock and Vibration Energy Comparisons

Structural-dynamic models predict that the strain energy implied by the strain values recorded on the fuel cladding is so low that it is comparable to the kinetic energy in one raindrop.

<table>
<thead>
<tr>
<th>Moving Object</th>
<th>Specific Example</th>
<th>Kinetic Energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet (Muzzle Energy)</td>
<td>AR-15 9 mm Handgun</td>
<td>1,854,000.0</td>
</tr>
</tbody>
</table>
| Golf Ball (Off the Tee)| PGA Tour, Male (168 mph)  
                        | Amateur, Bogey Golfer (131 mph)           | 129,000.0           |
| Bird Flying           | Robin (25 mph)  
                        | European Swallow (19 mph)                  | 4,400.0             |
| Ping Pong Ball (Table Tennis)| World Record (70 mph)  
                        | Average (25 mph)                          | 1,300.0             |
| Single Raindrop       | Heavy Thundershower (130 mg, 20 mph)      | 5.2                 |
|                       | Moderate Rain (37 mg, 17 mph)             | 1.0                 |
|                       | Light Drizzle (8 mg, 14 mph)              | 0.1                 |
| Fuel Rod Vibration (Strain Energy Estimates)| Maximum Strain in MMTT: (Railcar Coupling Test, 8 mph)  
                        | Representative Strain in MMTT: (Railcar P&B, 50 mph)  
                        | Gravity                          | 3.6                 |
|                       |                                           | 1.3                 |
|                       |                                           | 0.7                 |
| Flying Insect         | Wasp (15 mph)                             | 2.2                 |
|                       | Housefly (4 mph)                          | < 0.1               |

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.
All DOE-NE R&D is laying the foundation for this conclusion:

Irradiated fuel rod conditions and structural capacity >> NCT transportation loads, therefore it is safe to ship UNF and to expect it to arrive with no additional damage.
Questions?