U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST))

Clean. Reliable. Nuclear.

Putting it all Together….

Ned Larson

NWTRB Meeting

Albuquerque, NM

October 24, 2018

R&D Goal & Presentation Objective

R&D Goal

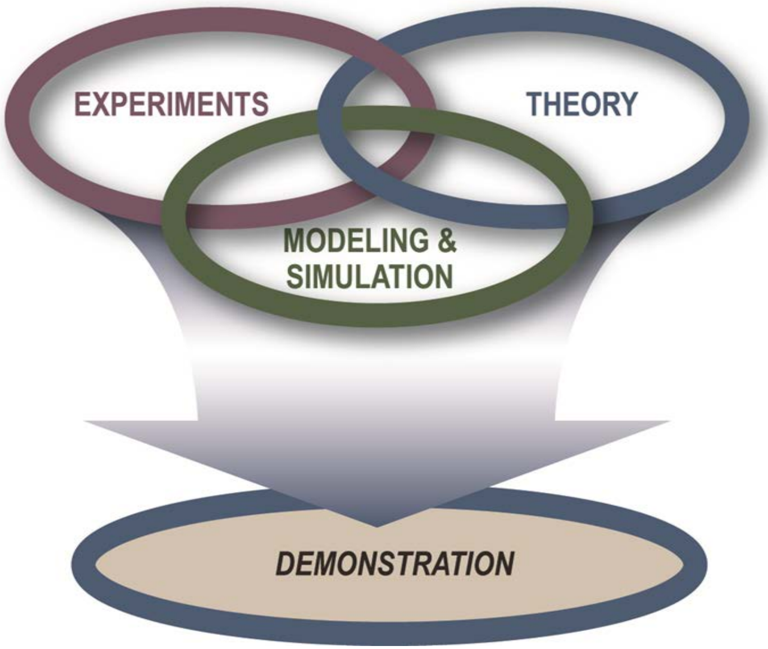
To provide data and analysis to support decisions regarding storage and transportation of spent nuclear fuel

Presentation Objective

To provide a brief overview of some current R&D in DOE and show that our R&D points to a stronger fuel system and lower external loads than previously thought

Collaboration Leverages Research Dollars – Enables Diversity of Perspectives & Ideas

Technical Direction



Partnerships

- **Industry**
  - Utilities – EPRI and NEI
  - Cask manufacturers
  - Fuel suppliers
  - Rail and trucking companies
- **National Laboratories**
  - 11 National Labs
  - Specialized personnel, facilities and equipment are available
- **Small Businesses**
  - $5.2 million and 13 contracts awarded
- **Universities**
  - 39 university awards, numerous students and professors are involved ($49M)
- **Nuclear Regulatory Commission**
  - Jointly fund research when appropriate
  - Continue some testing NRC began
- **International – ESCP**
  - Extended Storage Collaboration Program

International Interactions
Extended Storage Collaboration Program (ESCP)

ESCP History

2010-2017

- Regular Spring and Winter meetings, in US
- 13 International SC meetings
- 6 subcommittees

2009

- 1st ESCP meeting
- 1 country,
- 39 participants
- 2 subcommittees

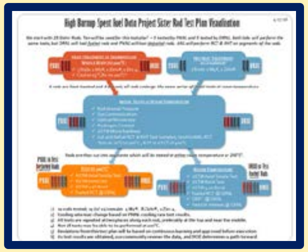
2018

- ~575 members from 19 countries
- Over 150 attendees to Winter 2017 meeting

S&T R&D is Driven by the 2017 Gap Analysis & NEI R&D Priorities and Is Enhanced by the Demo Data

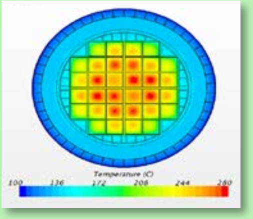
We have fuel in hot cells. (ORNL & PNNL)

We completed non-destructive tests.

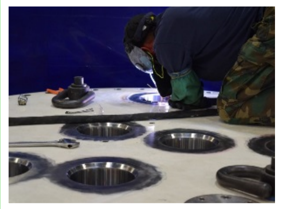


Have begun destructive analysis.

Sister Rod Mechanical Testing Data

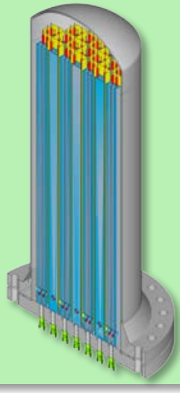


We have thermal models.



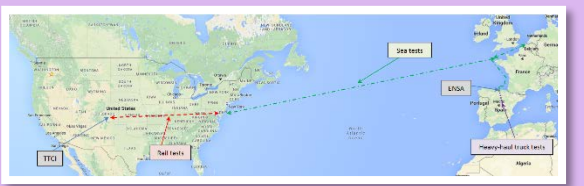
We are getting new thermal data from the Demo.

We working to ID conservatisms & develop more realistic assumptions.

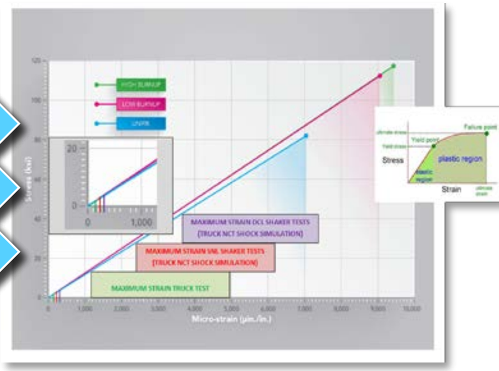


Thermal Behavior

Provides Knowledge about Spent Fuel Integrity Which is Compared to Data from the Transportation Tests



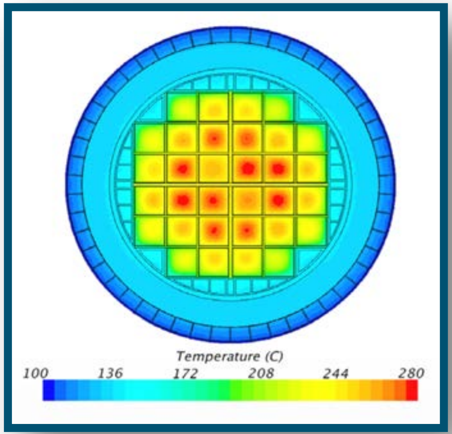
Spent Fuel Triathlon: Quantification of Normal Transport Shocks & Vibrations



Understanding High Burn-up Cladding Performance - Thermal

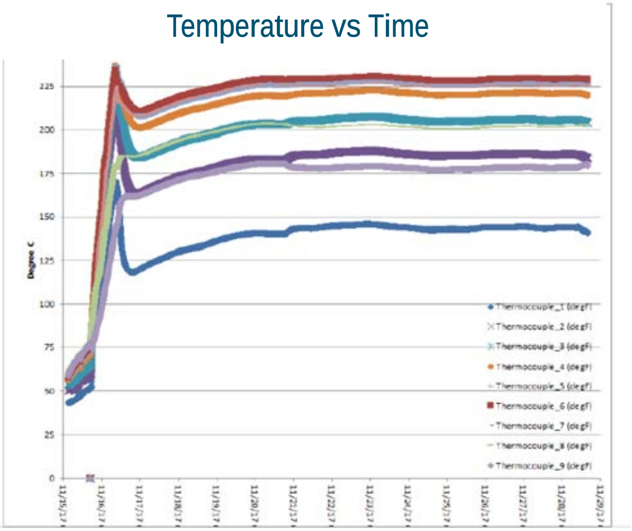
Thermal Analysis

- High Burnup Demonstration Project was performed at North Anna to understand thermal behavior in a loaded cask.
- More detailed modeling shows considerable margin between design basis loading and actual loading resulting in lower temperatures than previously thought



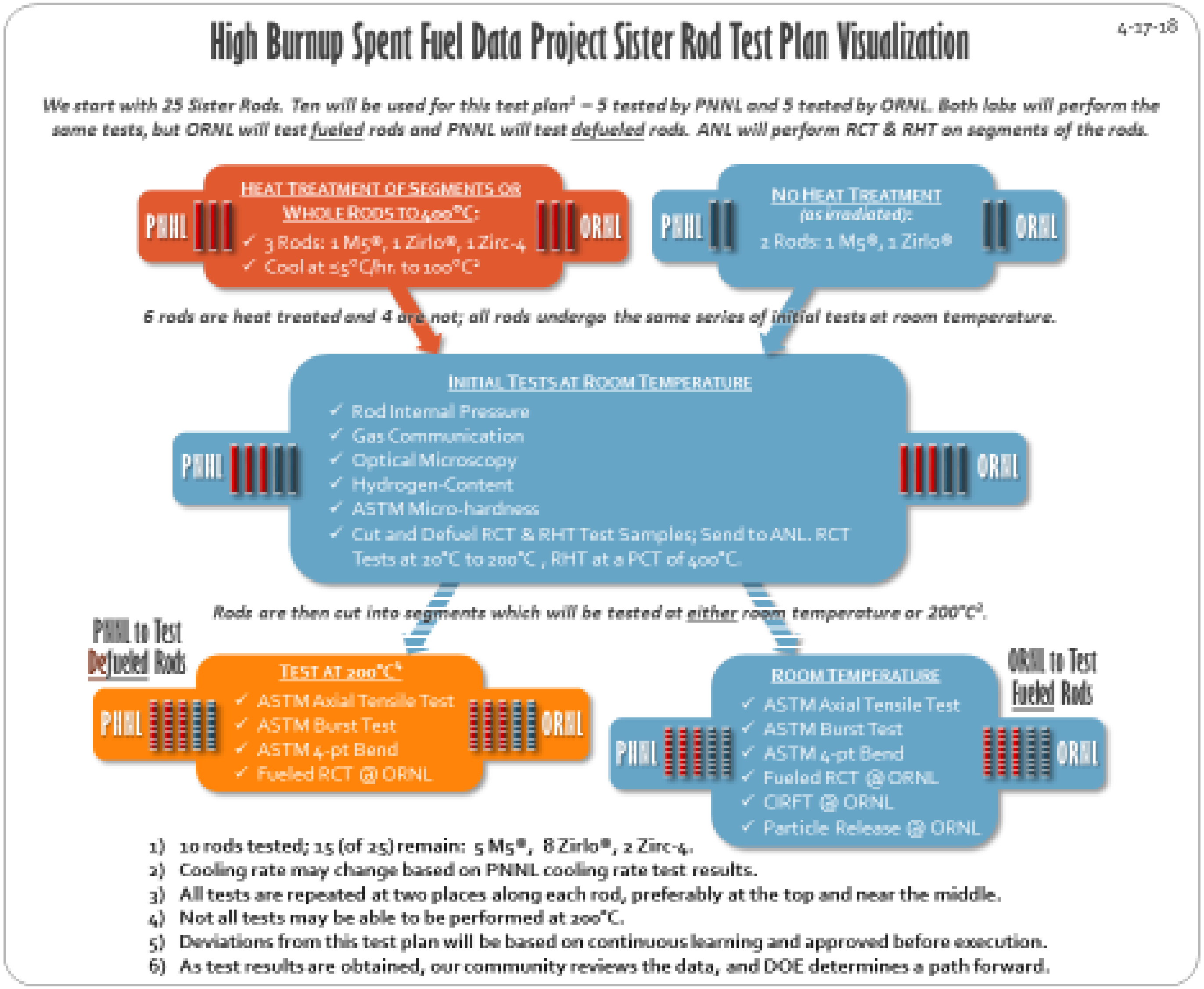
Maximum cladding surface temp. (°C) for each assembly in *one* type of licensed cask. (Fort, et al, 2016. PNNL)

Loaded TN-32 for High Burnup Demo at North Anna

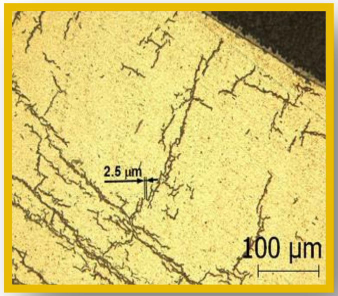


Experiment at SNL on thermal behavior of an assembly

Laboratory Test Plan Summary

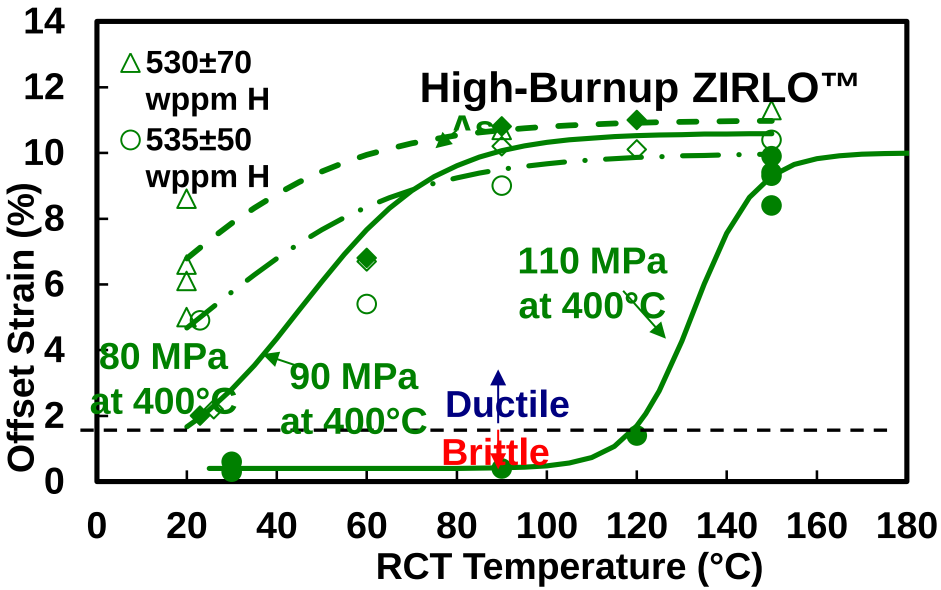


Understanding High Burn-up Cladding Performance – Ductile Transition



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 lower than previously thought
  - The results of these tests are also very important for transportation



Understanding High Burn-up Cladding Performance – Conclusion

- With the data this is currently available, it is believed that the cladding will remain intact and its integrity will not be challenged during extended storage






Canister Performance: *Stress Corrosion Cracking (SCC) Requires 3 Concurrent Conditions*

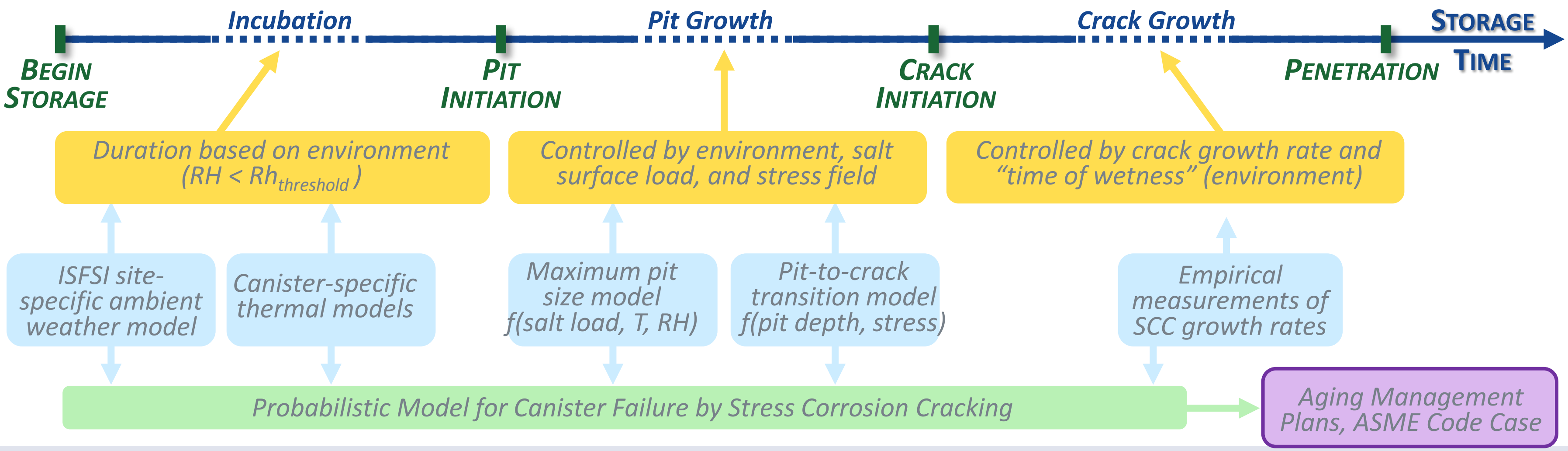
Dust on canister surface at Calvert Cliffs (EPRI 2014)

Photo of dry canister weld. Photo: SNL

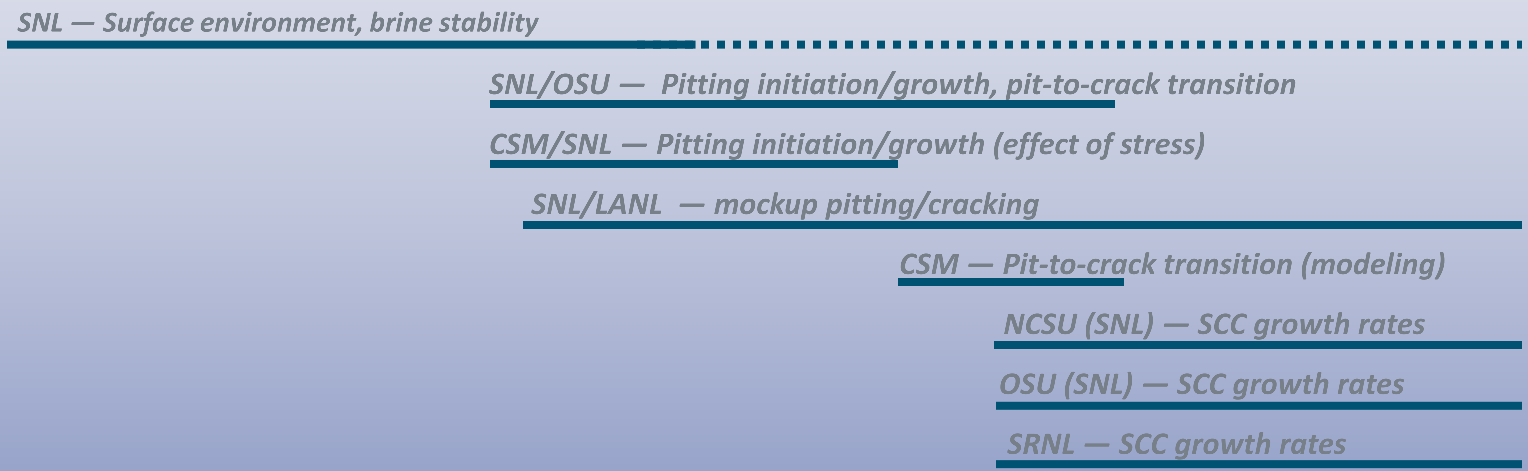
Mock-up Canister
Photo: Enos, SNL

Stress Corrosion Cracking R&D

Evaluate Time DSCs Can Be Safely Stored as a Function of ISFSI Location



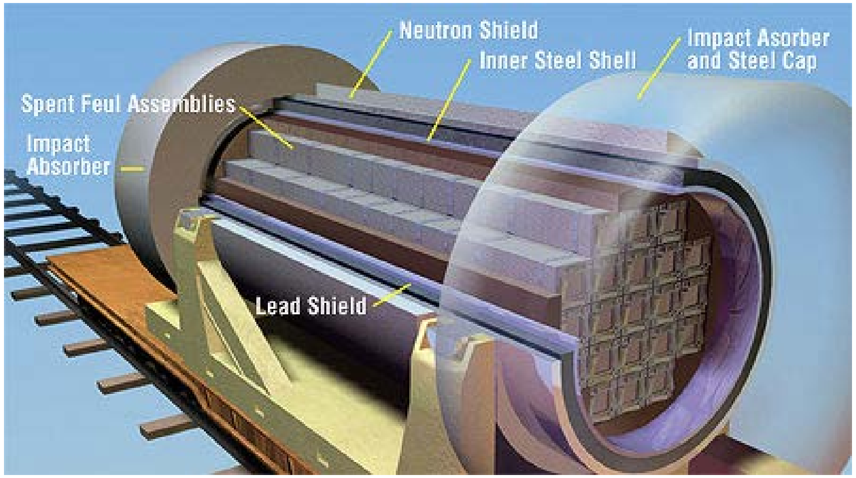
Current and future work in each of the above areas



Canister Integrity

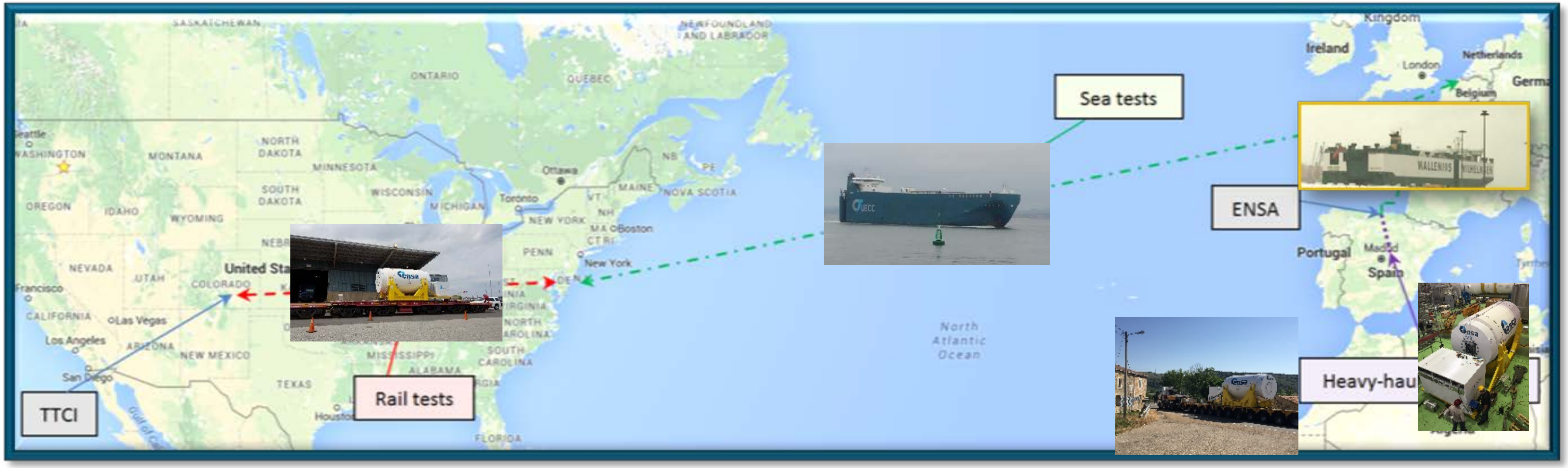
- Three conditions needed for stress corrosion cracking
  - We know some sites have chloride available to cause corrosion
  - We know some canister materials are susceptible to chlorides
  - We know that tensile stresses exist in parts of the canister after welding
- Conclusion: Currently is it believed that some stress corrosion cracking may exist but it is not known if it will go through the entire thickness of the canister wall.

Transportation of Spent Fuel



- How will the spent fuel behave during transport?
  - Cladding integrity
    - Shock and vibration
  - Canister integrity
    - No issues
  - Cask components
    - No issues

Routing of Instrumented Cask and Assemblies Multi-Modal Transportation Test (MMTT)

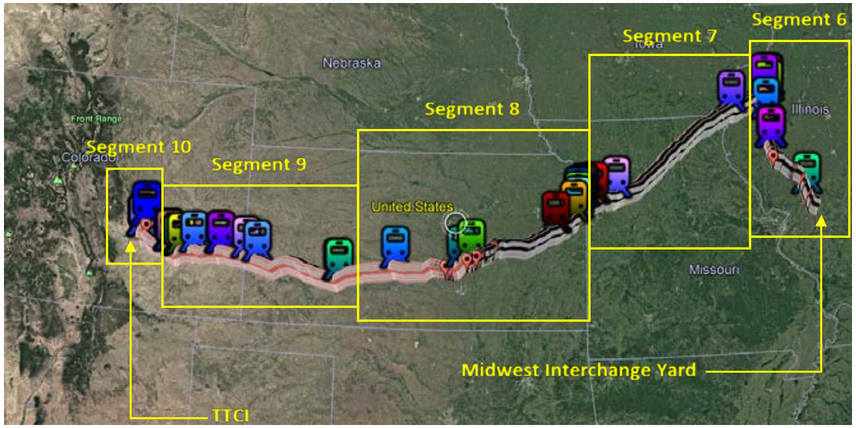


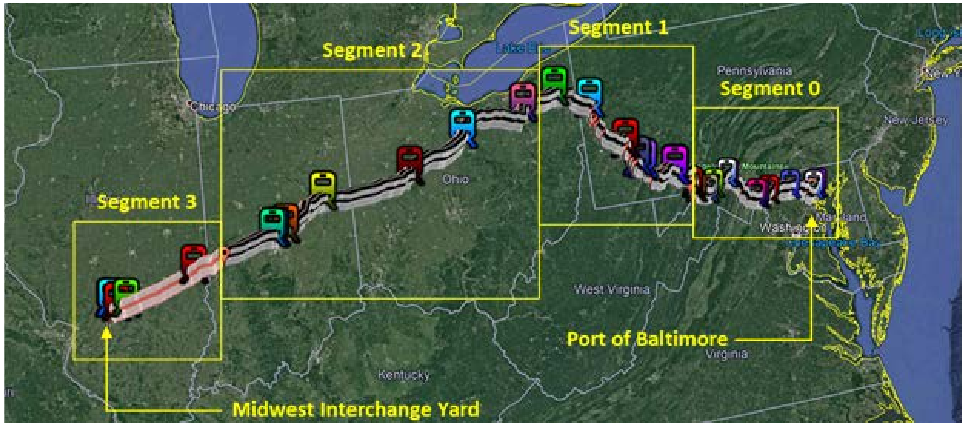
Photos provided by Steve Ross, PNNL

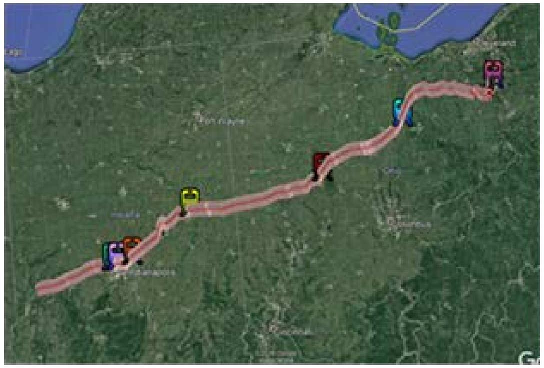
1) **Heavy-haul truck from within Spain** ~ June 14, 2017
2) **Coastal sea shipment from Santander to large northern European port** ~ June 27, 2017
3) **Ocean transport from Europe to Baltimore**
4) **Commercial rail shipment from Baltimore to Pueblo, Colorado** ~ Aug 3, 2017
5) **Testing completed at the Transportation Technology Center, Inc.**
6) **Return trip to ENSA, September 5, 2017**

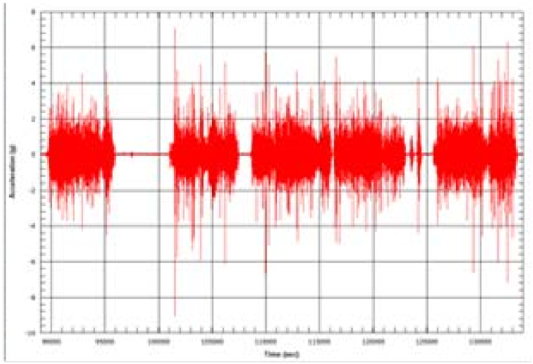
Data was collected throughout all legs of the transport as well as the transfers between legs.

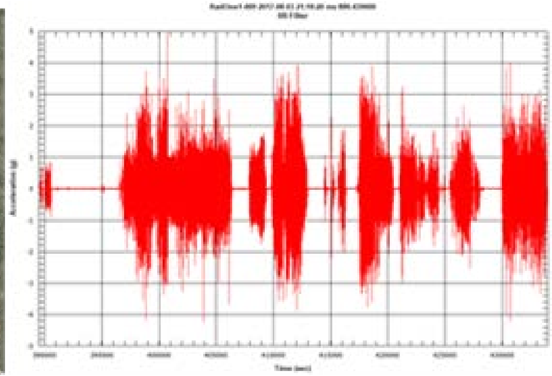
Shock and Vibration for the Trip to TTCI



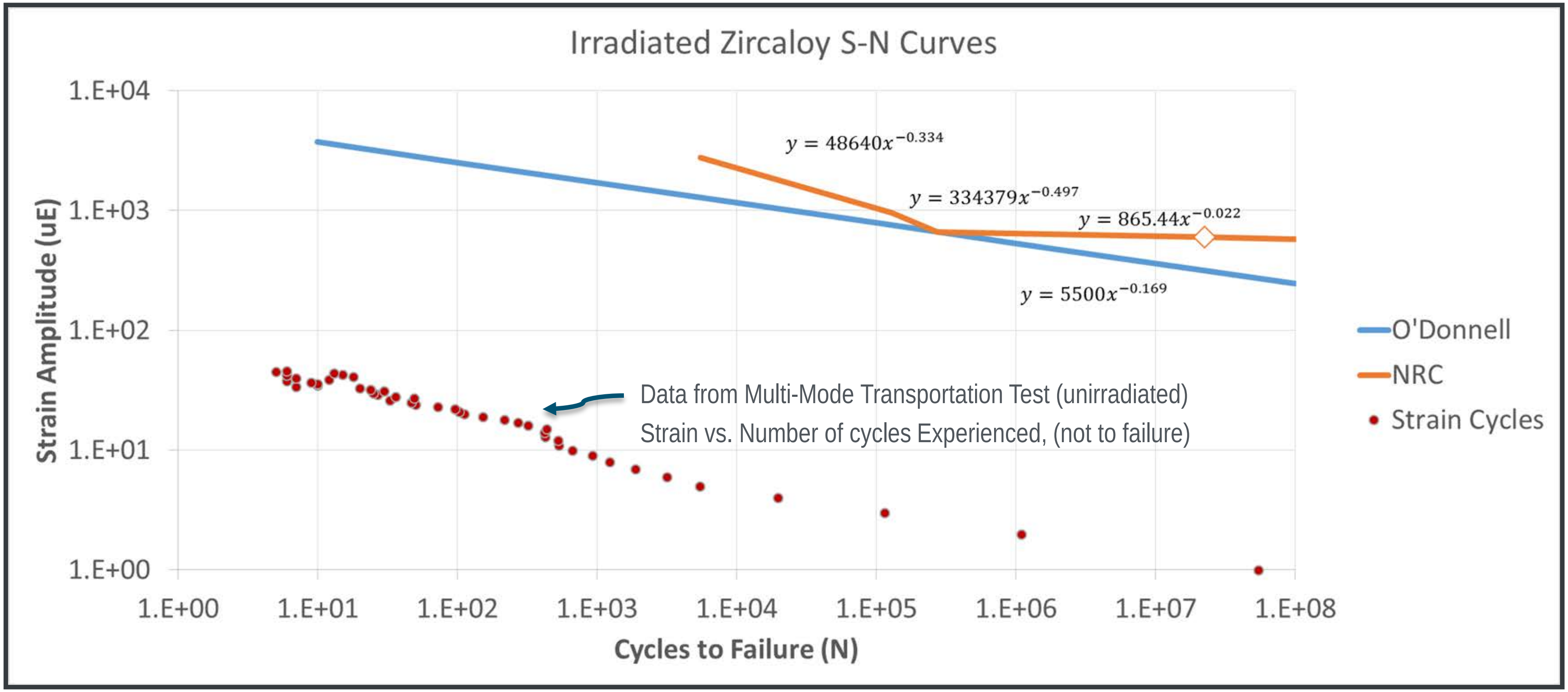








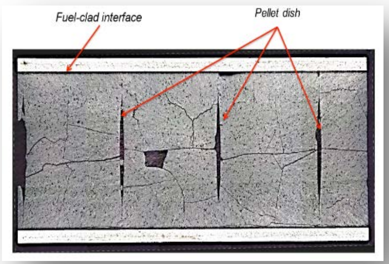
Fatigue Curves for Irradiated Zircaloy



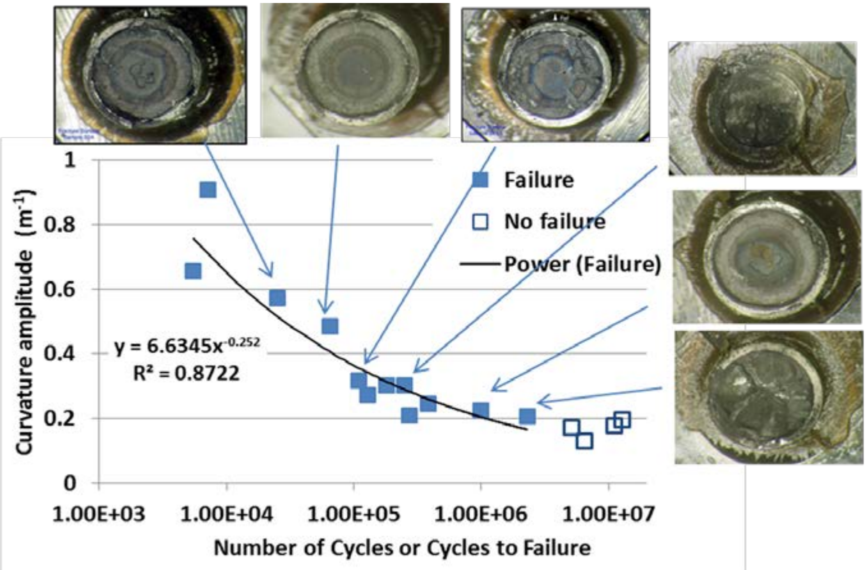
- O'Donnell: S-N curve used to define accumulated damage in this work. O'Donnell WJ and BF Langer. 1964. "Fatigue design basis for zircaloy components." Nuclear Science and Engineering(20):1–12
- NRC: S-N curve based on CIRFT data. Defined in NUREG-2224, Dry Storage and Transportation of High Burnup Spent Nuclear Fuel. Draft for Comment, 2018.

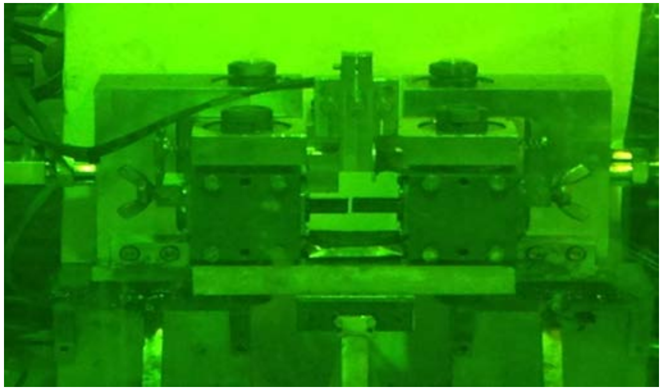
Understanding High Burn-up Cladding Performance – Irradiated Cyclic Strength

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

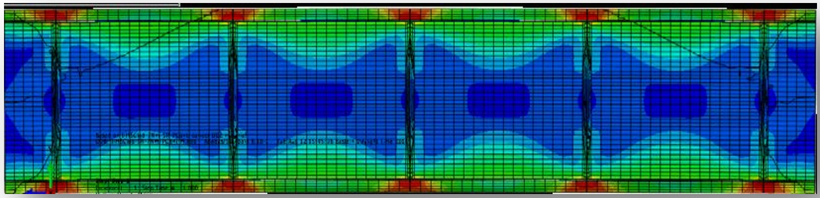


Fuel rod segment before bend testing (Wang, et al., 2016. ORNL)



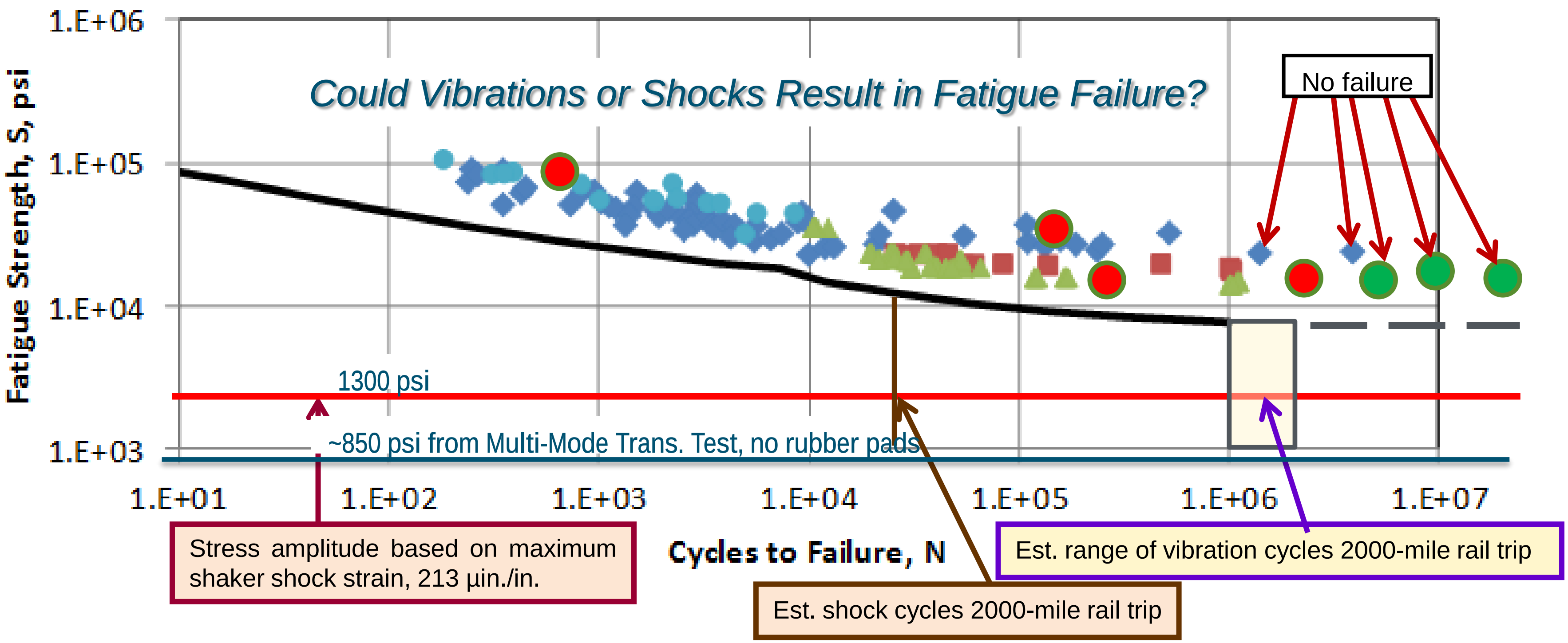


Cyclic Integrated Reversible–bending Fatigue Tester (CIRFT) located at ORNL



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

Transporting Spent Nuclear Fuel



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

CONCLUSIONS

The realistic stresses fuel experiences due to vibration and shock during normal transportation are far below yield and fatigue limits for cladding. We have recently gathered actual rail data which most likely will be the prevailing transportation mode.

Transportation Conclusion

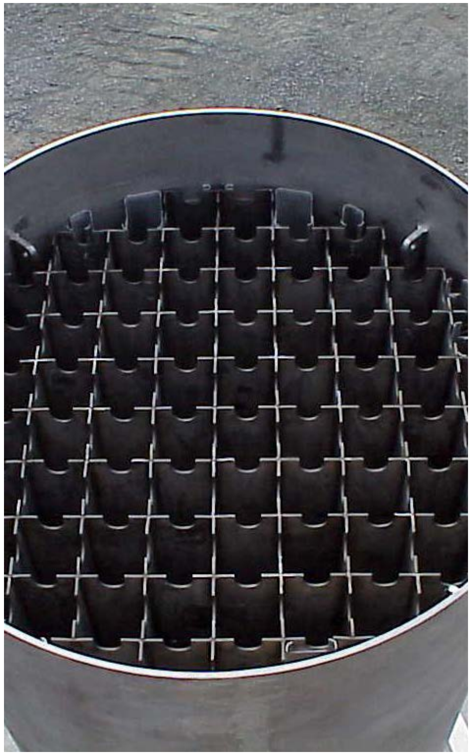
- No shock or vibration was encountered during the entire length of the test that would exceed the strength of the cladding, either for static or dynamic conditions
  - Measured data are orders of magnitude below yield strength
- This is even considering the fact that a standard freight car was used instead of the S 2043 rail car

Future Work: Cladding Integrity

- Laboratory Testing
  - Static and dynamic lab testing on the cladding (RCT, CIRFT, etc.)
- Numerical Modeling and Benchmarking
  - Continue numerical thermal modeling on the cask behavior to match what was measured
- Scaled drop test will be performed
  - 30 cm drop at BAM with ENSA cask
- Drying and understanding the moisture conditions in a cask
  - Possibly sample internal gas samples of other casks
  - NEUP work on cask drying and behavior

Future Work: Canister Integrity

- Stress Corrosion Cracking
  - Technologies to detect any cracking and repair in place
  - Analysis of canister failure mechanisms to develop reasonably bounding estimates of the consequences of a hypothetical loss of canister confinement integrity
  - Acquisition of additional data on how environmental conditions affect potential crack growth rates for Stress Corrosion Cracking (SCC) on stainless steel canisters
  - Possibility of alternate manufacturing processes



Future Work: Transportation

- Conduct broad scope transportation-related activities to assure readiness for transportation when needed, including work on transportation loads and stress limits as well as rail car and cask development.
  - 8 axle rail car
  - Work with other countries who are also gathering data in this area
  - Development of sensor technology to monitor the condition of the cask internals (i.e. helium concentration, presence of water, temp, shock, vibration) without the need for confinement penetrations.

Questions?