



Research for Spent Fuel Storage & Transportation: What Have We Learned and What is Next?

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2020 INMM Spent Fuel Management Seminar
January 20, 2020
Alexandria, VA

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Planning Long-Term

The DOE R&D is driven by peer-reviewed Gap Analyses

Gap Analysis to Support Extended Storage and Transportation of Spent Nuclear Fuel: Five-Year Delta

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and
Technology

Brady D. Hanson (PNNL)
Halim A. Alsaed (ENS)

May 17, 2019
SFWD-SFWST-2017-000005, Rev 1
PNNL-28711

Gap Analysis to Guide DOE R&D in Supporting Extended Storage and Transportation of Spent Nuclear Fuel: An FY2019 Assessment

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
Melissa Teague¹, Sylvia Saltzstein¹, Brady Hanson²,
Ken Sorenson³, Geoff Freeze¹

¹Sandia National Laboratories
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December 23, 2019

SAND2019-15479 R

Current R&D Priorities

Priority 1

- Thermal Profiles
- Stress Profiles
- Welded Canister –
Atmospheric Corrosion
(Priority increased)

Priority 2

- Drying Issues

Priority 3

- External Monitoring
- Cladding – H₂ Effects
- Consequence of Canister Failure
- Fuel Transfer Options

2017 Five-Year Delta report

- Updated the 2014 Gap Analysis
- Covers R&D results through FY17

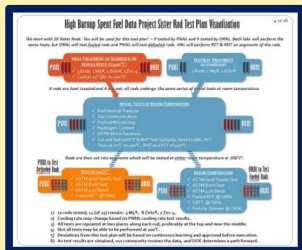
FY2019 Assessment report

- Adds R&D results from FY18 & 19
- Main priorities remain the same.
Some rankings have changed
based on recent R&D results

The S&T R&D Projects Combine to Develop the Technical Basis for Safe Storage and Transport of Spent Nuclear Fuel



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

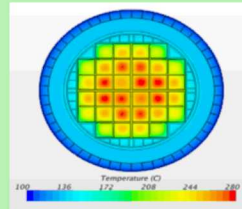


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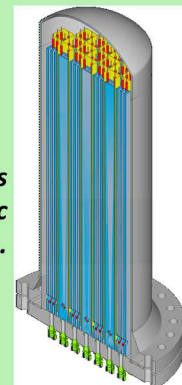
SISTER ROD MECHANICAL TESTING DATA



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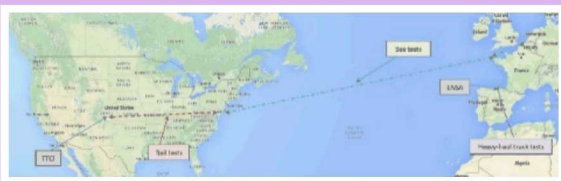
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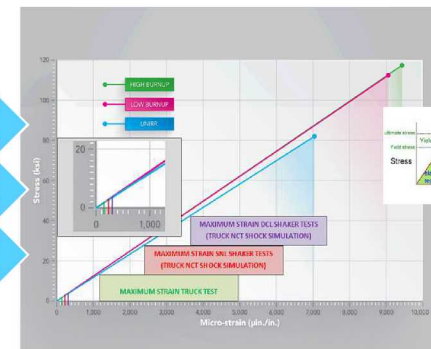
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THERMAL BEHAVIOR

PROVIDES KNOWLEDGE ABOUT SPENT FUEL AND CANISTER INTEGRITY



**SPENT FUEL TRIATHLON:
QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS**



DOE/EPRI High Burnup Project

Goal: To provide confirmatory data for models, future SNF dry storage cask designs, and to support license renewals and new licenses for ISFSIs.

Has provided vital data for the technical basis for the safe storage and transport of spent nuclear fuel.

- Commercially-licensed TN-32 cask at North Anna NPP ISFSI in Virginia. Loaded with high burn-up spent fuel in November, 2017, with 4 common cladding alloys.
- Cask monitored to determine thermal and environmental conditions experienced by the fuel during drying and storage.
 - Fuel cladding temperature
 - indirectly, via 63 thermocouples inside the cask
 - Cavity gas composition
 - via three gas samples after drying and filling with He backfill gas
- Provided 25 sibling pins for mechanical testing



High Burnup Spent Fuel Data Project Participants

- A contract was awarded to EPRI on April 16, 2013



- National Labs are performing the technical evaluations of the data



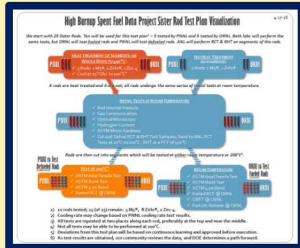
Temperature Drives Everything!

How do we get accurate thermal data and analysis?



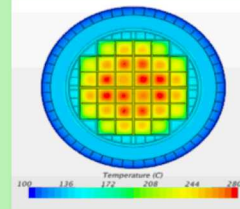
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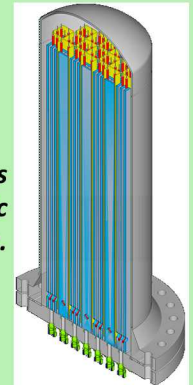
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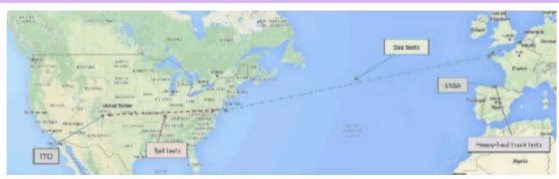
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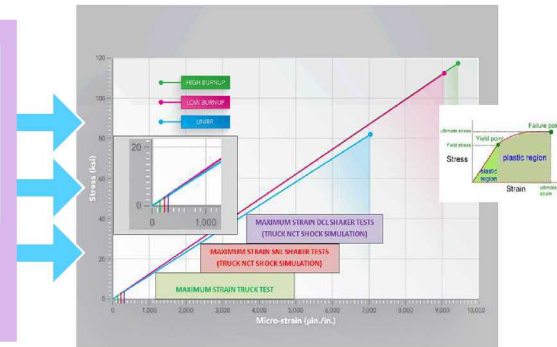
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Thermal Profiles:

Round Robin Analysis Comparison with Measured Data



- Steady state PCTs from all models and measurements significantly lower than the design licensing basis:

Parameter	FSAR	LAR	Best-Estimate	HBU Cask Measurements
PCT (model vs data)	348°C	318°C	254-288°C	229°C
Heat Loadouts	36.96kW	32.934kW	30.456kW	30.456kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?

FSAR: Final Safety Analysis Report

LAR: License Amendment Report (submitted after refinement of model inputs to FSAR)

Courtesy of Al Csontos, Co-chair of EPRI ESCP Thermal Subcommittee

The aluminum basket expands and closes the gaps, but we don't know by how much.

Current Work is focused on identifying biases and conservatisms that overestimate thermal environment.

Slide 7

SSJ2 Why the question mark? after gaps?

Saltzstein, Sylvia J, 8/1/2019

SSJ3 This is for the Demo task.

Saltzstein, Sylvia J, 8/1/2019

SSJ4 aluminum basket will expand and close gaps, but we don't know by how much.

Saltzstein, Sylvia J, 8/1/2019

Thermal Profiles:

Obtaining Temperature Data in Controlled Environments for More Model Validation

- Collect data to validate models
 - Simplified geometry based on real-world systems
- Wide range of parameters
 - Decay heat and internal pressures
 - Different storage configurations (above and below ground)
- Better confidence in predictive modeling to understand fuel behavior
- EPRI Thermal PIRT

Built a **Vertical Convective** System

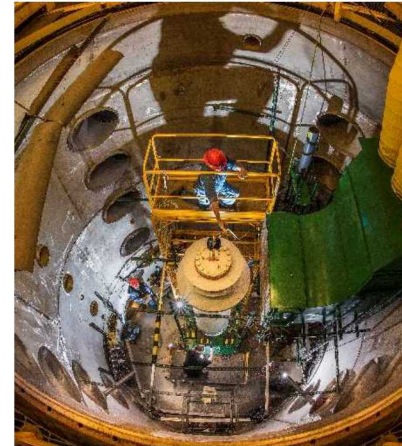
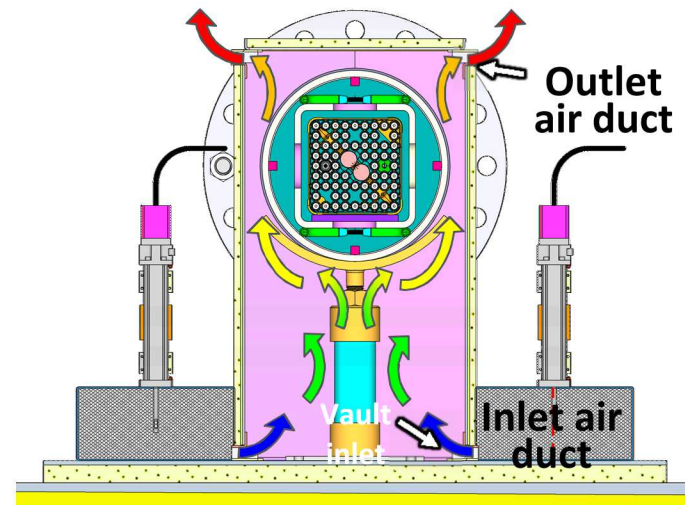


Photo: Sam Durbin, SNL

FY19-20 Focus

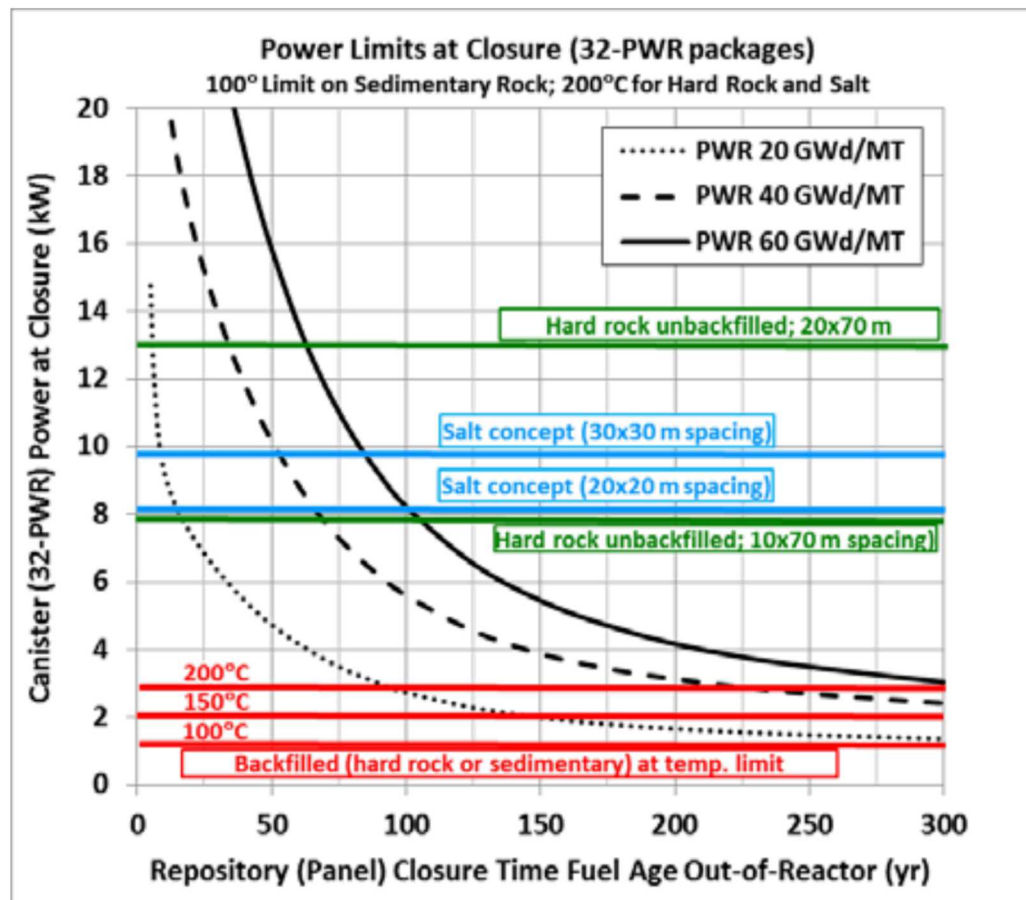
Now Testing a **Horizontal Convective** System



SNL: Durbin, Lindgrin, Pulido

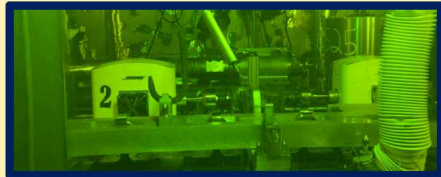
The Big Picture: Why is Predicting Thermal Conditions Important?

- Lower temperatures better for cladding.
- Lower temperatures are better for transferring from pool to dry storage.
- Lower temperatures are worse for CISCC.
- Lower temperatures reduce the time before we can transport a package.
- Lower temperatures allow more repository host rock possibilities, reduce spacing within a repository, and time before the repository can be closed.

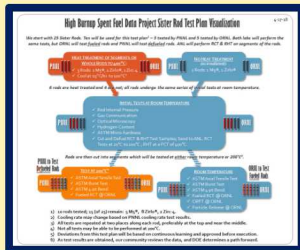


Bonano, Kalinina, Swift, *The Need for Integrating the Back End of the Nuclear Fuel Cycle in the United States of America*, MRS Advances, 2018

How Strong is our Fuel?



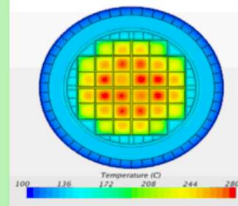
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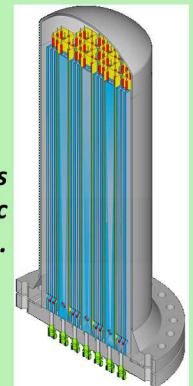
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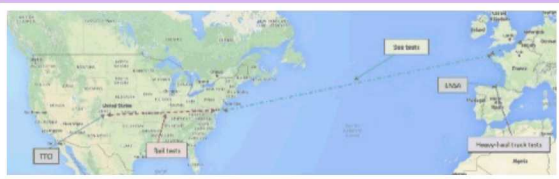
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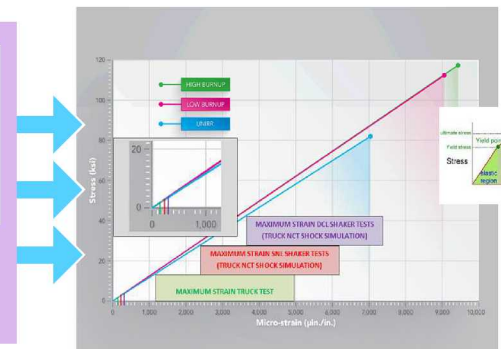
THERMAL BEHAVIOR



PROVIDES KNOWLEDGE ABOUT SPENT FUEL AND CANISTER INTEGRITY

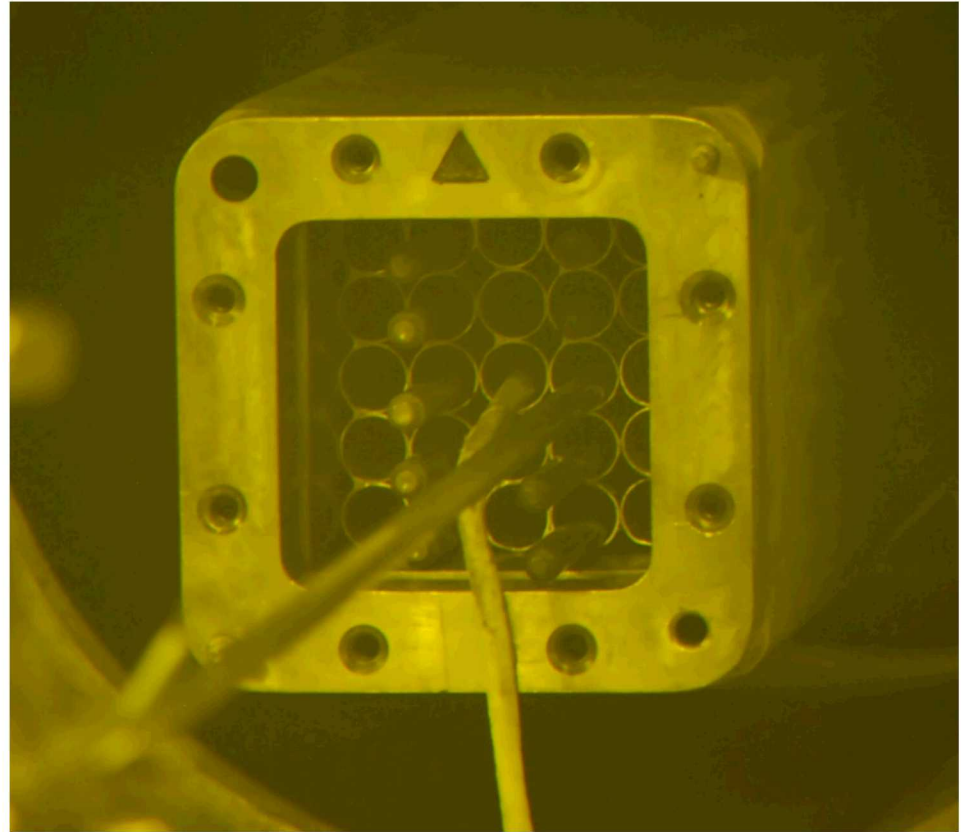


**SPENT FUEL TRIATHLON:
QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS**



Twenty-five Fuel Rods Similar to those in the Demo Cask are being tested for mechanical properties

- 25 fuel rods from representative fuel assemblies were selected
- These rods will form the baseline for pre-storage characterization
- Rods or segments have been heated to simulate drying conditions to predict material properties post-drying
- ORNL is testing fueled cladding and PNNL is testing defueled cladding
- ANL is performing Ring Compression Tests



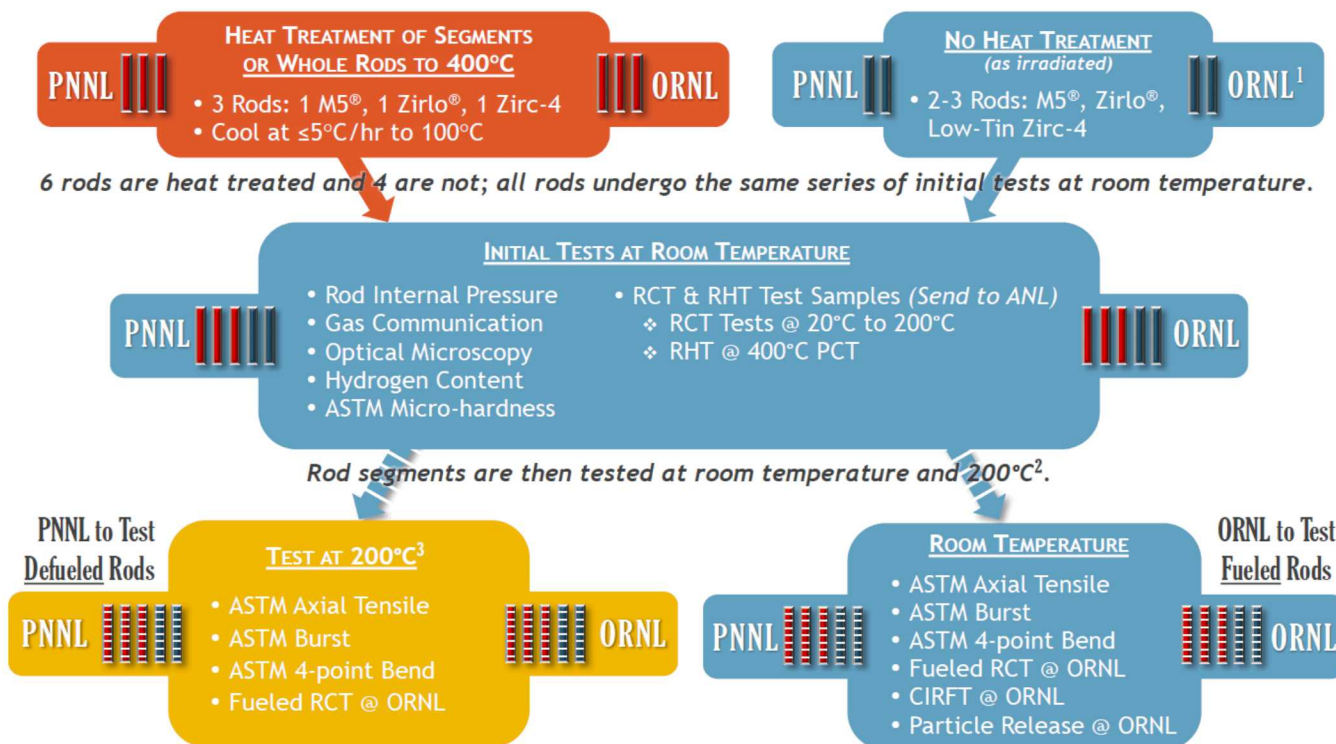
NAC LWT basket with 10 Sister Rods in PNNL hot cell

A Peer-Reviewed Test Plan was Developed for the 25 Rods

High-Burnup Spent Fuel Rod Phase 1 Test Plan Visualization

7-5-18

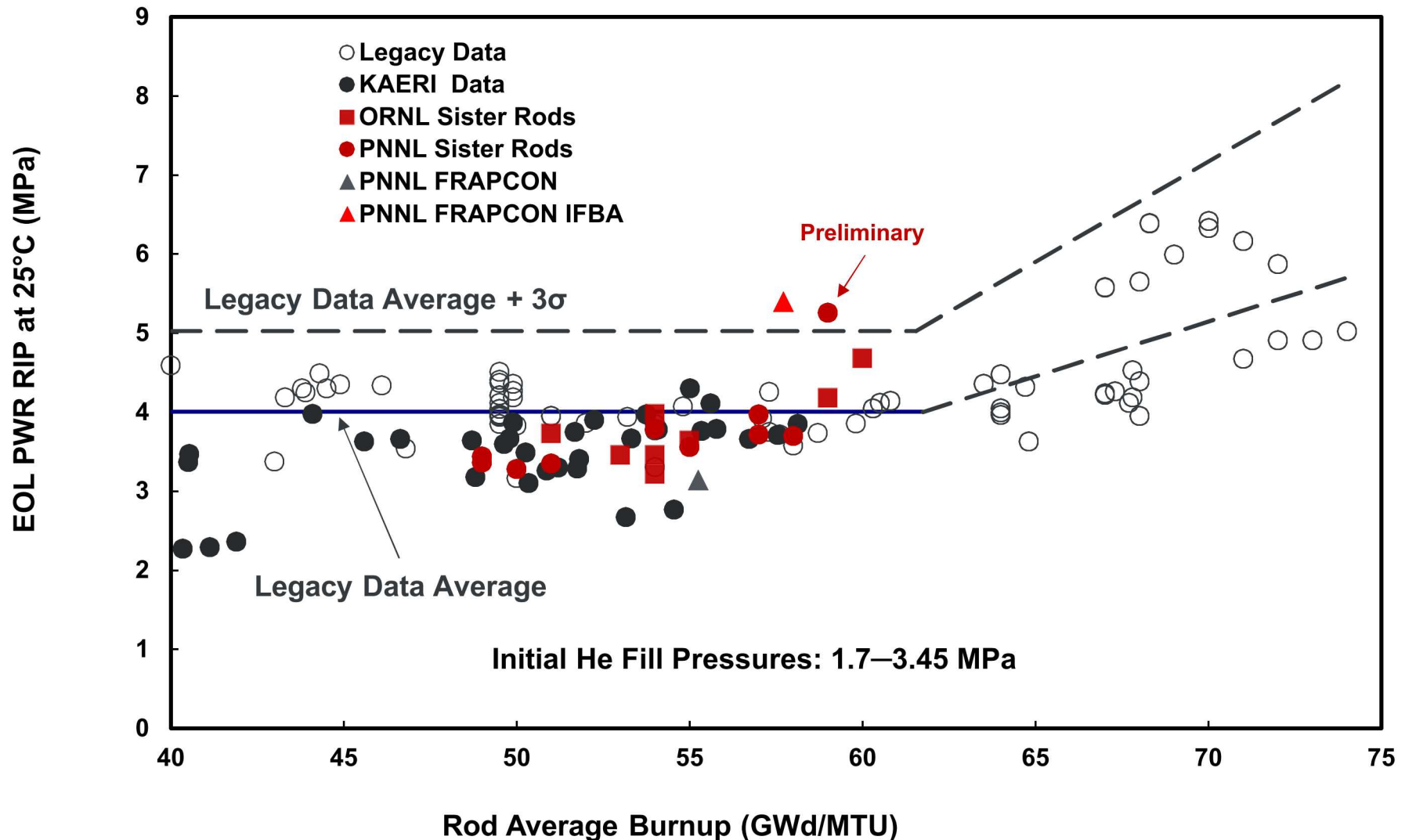
We start with 25 rods. Both labs will perform similar tests, but ORNL will test fueled rods and PNNL will test defueled rods. ANL will perform RCT and RHT on rod segments.



- 1) ORNL may use multiple M5® or Zirlo® rods as well as Low-Tin Zirc-4 rod segments for testing.
- 2) Tests will be conducted on samples from multiple axial regions of each fuel rod.
- 3) Not all tests may be able to be performed at 200°C .

- Deviations from this test plan will be based on continuous learning and approved before execution.
- As test results are obtained, our community reviews the data, and DOE determines a path forward.

Demo Sibling Rod End of Life Rod Internal Pressures are Consistent with other Data and are Generally less than 4 MPa



Modeled Hoop Stress from Rod Internal Pressure indicate Hoop Stress is less than 53MPa.

Table 1. Maximum Hoop Stress (MPa) 400°C Peak Temperature

Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	40.0	43.8	41.7
17x17	49.9	53.4	50.5
17x17 IFBA	84.4	88.1	86.3

Model results similar to the Research Project Cask conditions show 53.4MPa @ 400°C, but the Research Project Cask only reached 229 °C.

Table 2. End of Life Rod Internal Pressure (MPa) 400°C Peak Temperature

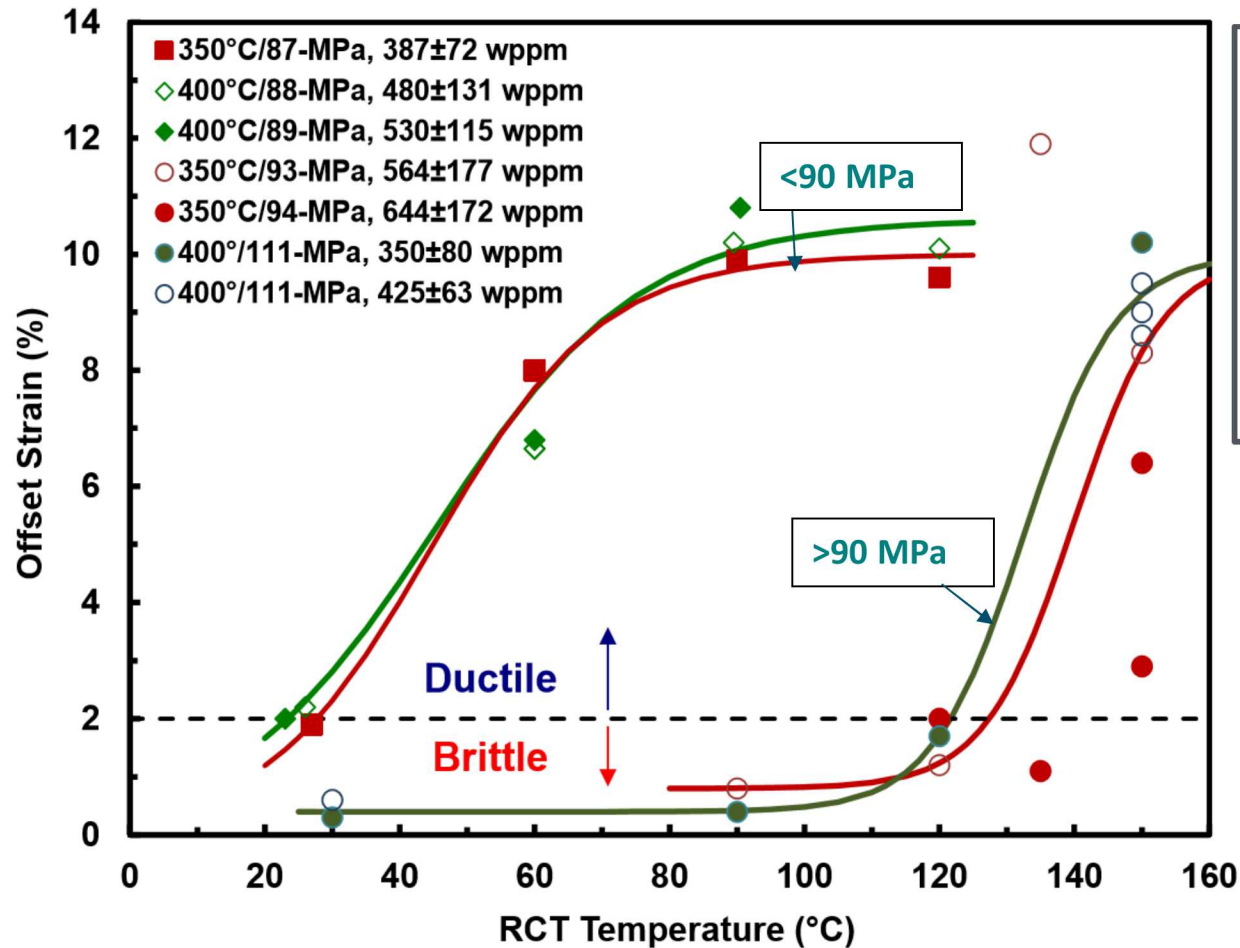
Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	5.4	6.1	6.4
17x17	6.2	6.8	7.0
17x17 IFBA	10.6	11.1	11.5

Table 3. Maximum Plenum Temperature (all fuel types)

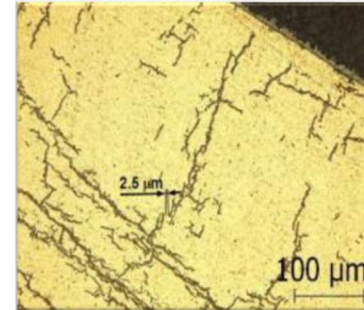
Profile	Temperature (°C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

Hoop Stress <90MPa will result in Few Radial Hydrides and Ductile Cladding above Room Temperature.

Apparent threshold for reduced ductility with radial hydride treatment at >90MPa Hoop Stress.



As long as hoop stress is below 90MPa, it remains ductile until room temperature. The fuel rods in the Research Project Cask will have a hoop stress <53 MPa.



“Data collected during the past five years suggest that radial-hydride-induced embrittlement may not occur in standard PWR fuel-rod cladding because

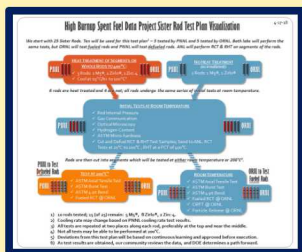
- EOL RIP values (< 5 MPa at 25° C),
- PCTs (< 400° C),
- average gas temperatures (< 400° C),
- average assembly discharge burnups (< 50 GWd/MTU)

are all much lower than previously anticipated.”

What are the Shocks and Vibrations the Fuel Sees in its Lifetime?



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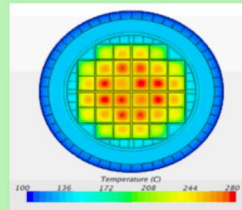


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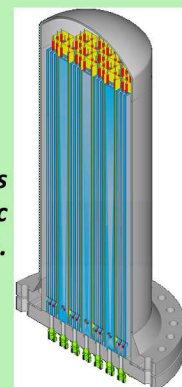
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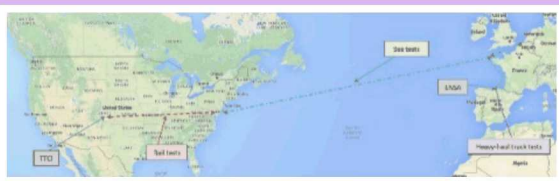
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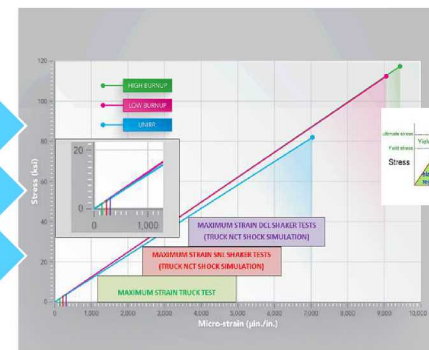
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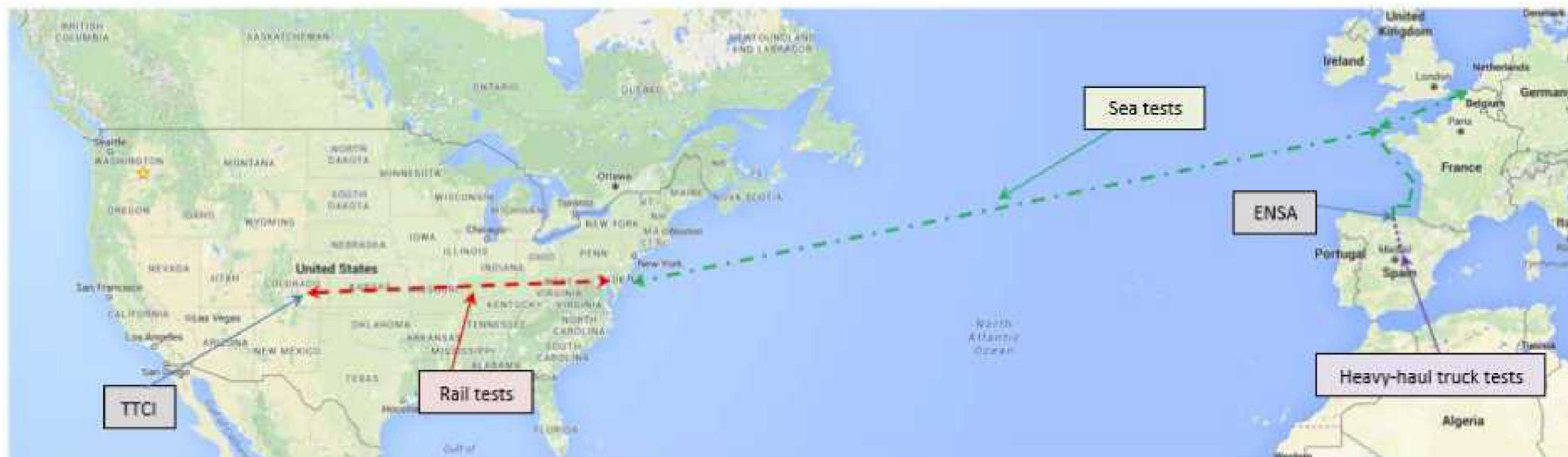
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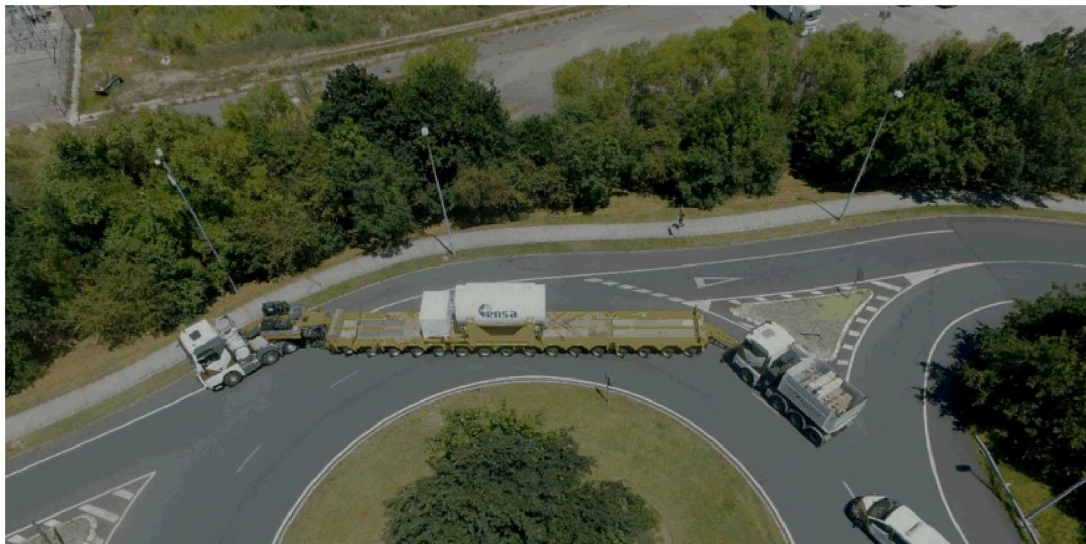
Transportation Triathlon collected Strain and Acceleration Data on Surrogate Fuel over Rail, Truck, and Ship.



- 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)

Normal Conditions of Transport Included Truck, Ship and Rail



16-axle heavy haul truck transport through Spain



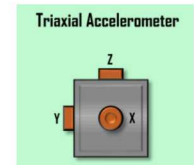
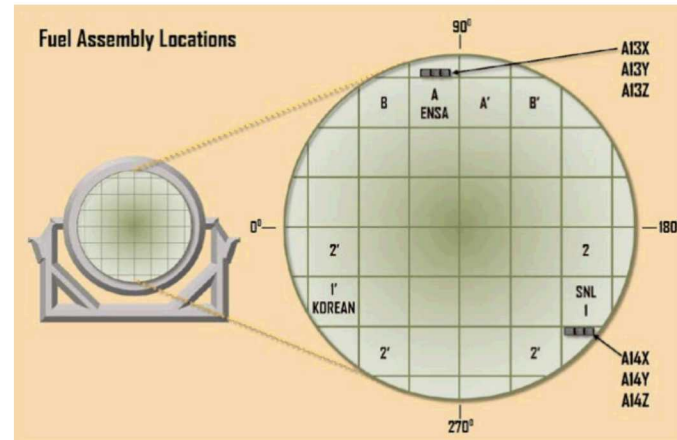
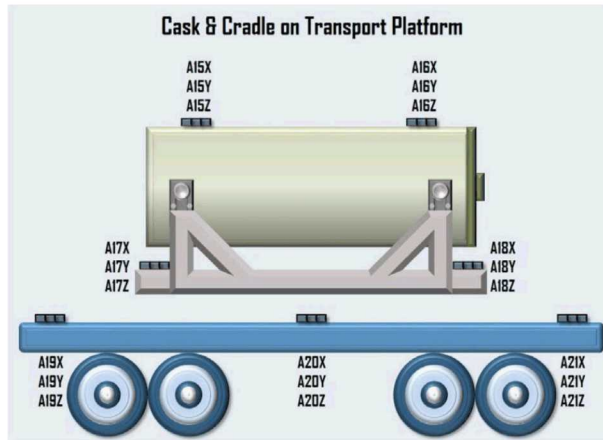
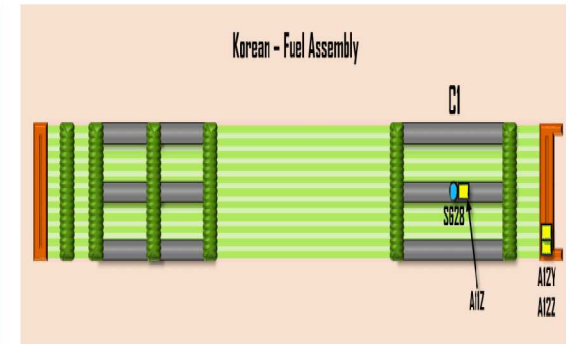
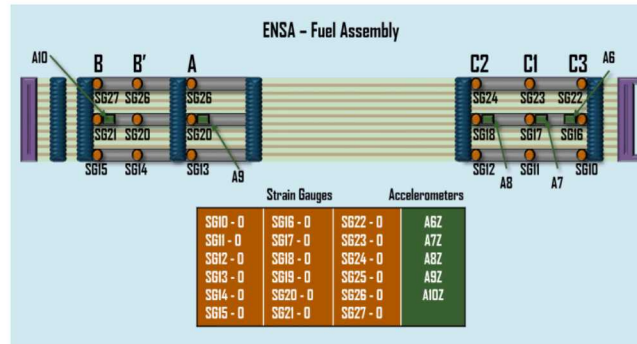
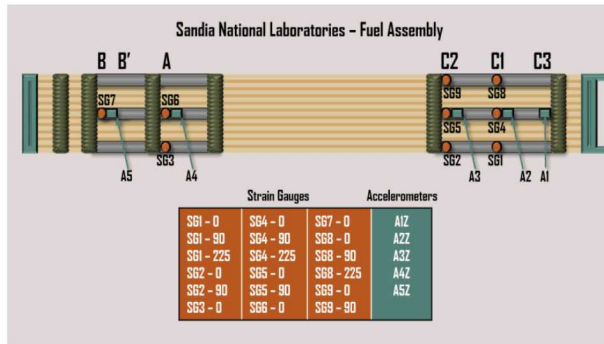
Rail transport and testing in the US – Kasgro 12-axle railcar

Barge and ocean ship transport



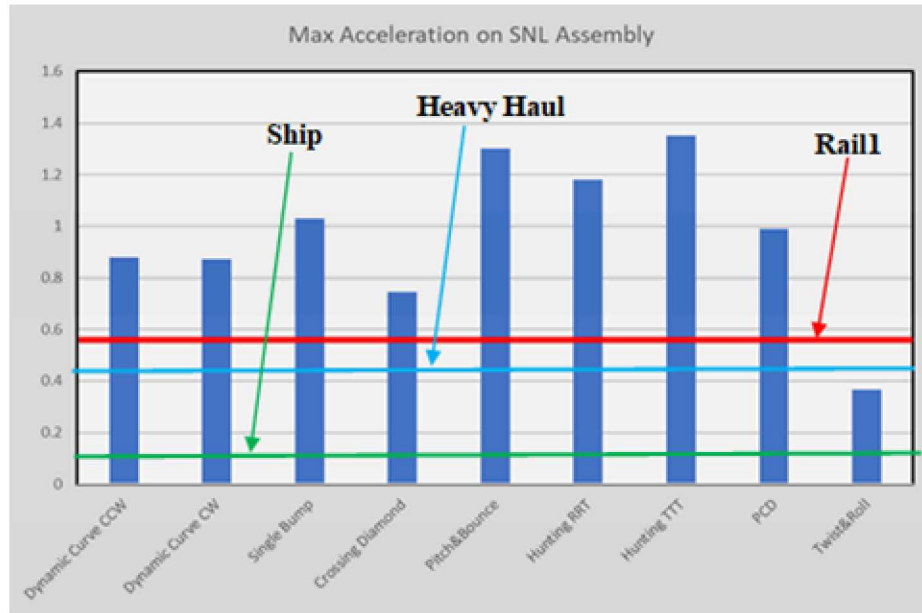
Strain and Acceleration was Measured on Surrogate Fuel, Assembly Hardware, Basket, Cask, Cradle, and Transportation Platform

40 accelerometers, 37 strain gauges



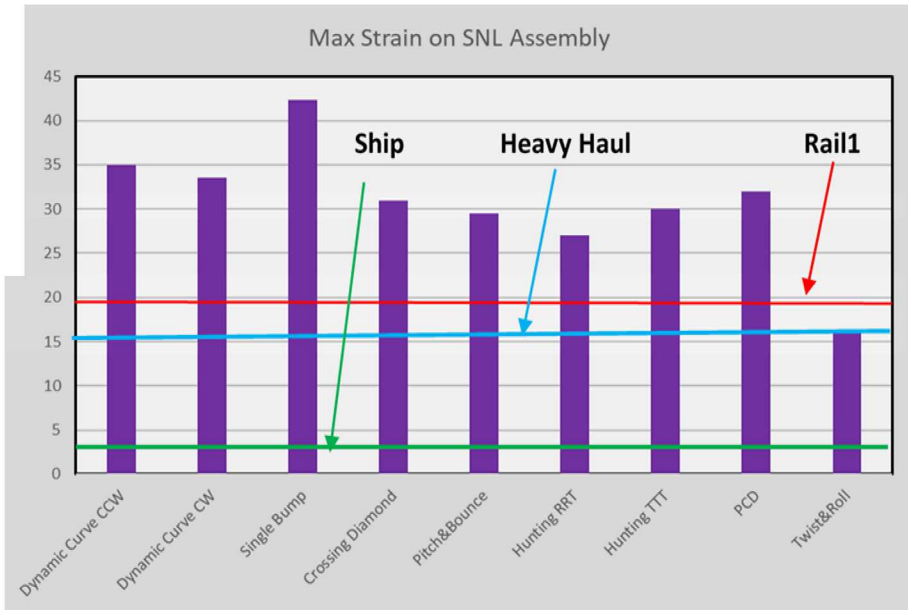
Images not to scale

Maximum Strains and Accelerations from all Transportation Tests were well below the cladding measured Yield Stress.



Measured in g

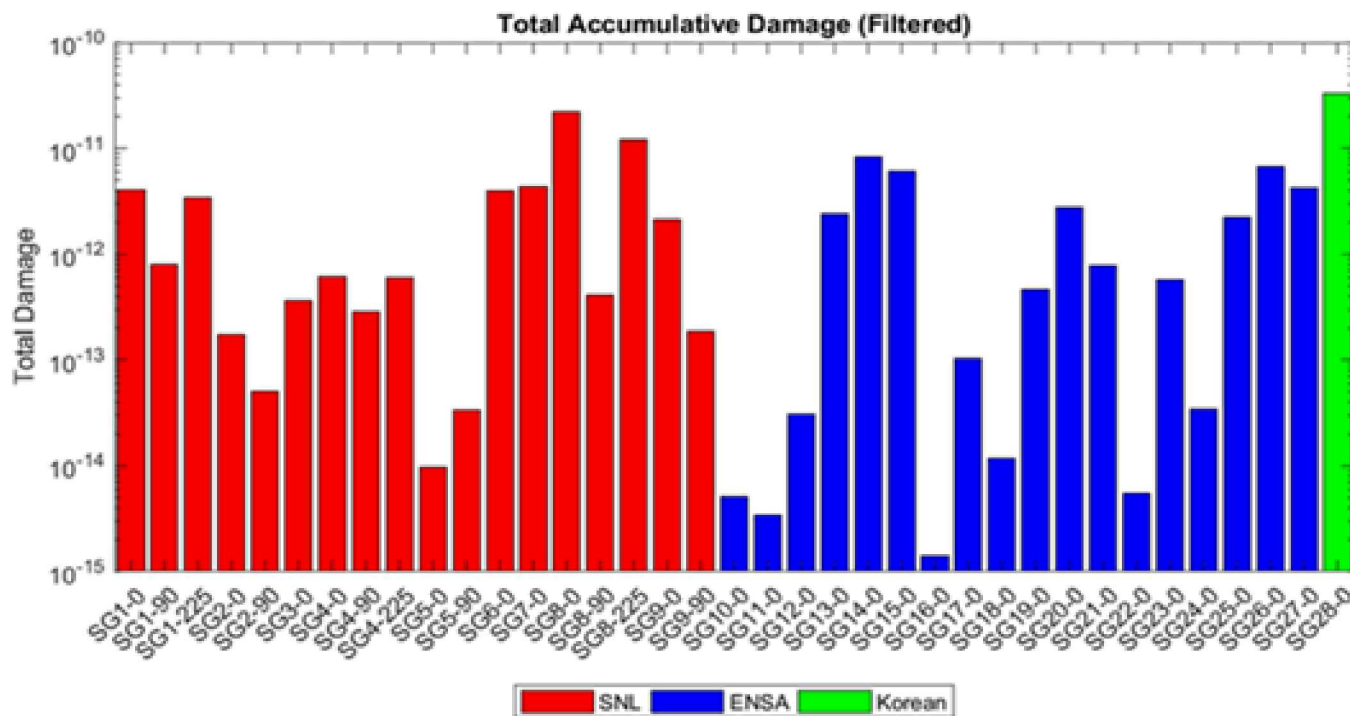
Blue bars: TTCI test results in g's.
Purple bars: TTCI test results in microstrain
Red line: Max acceleration or strain during the rail transport
Blue line: Max acceleration or strain during the heavy haul truck transport
Green line: Max acceleration or strain during the ship transport.



Measured in $\mu\epsilon$

Measured yield stress levels for irradiated SNF cladding is $\sim 7000 - 9000 \mu\epsilon$

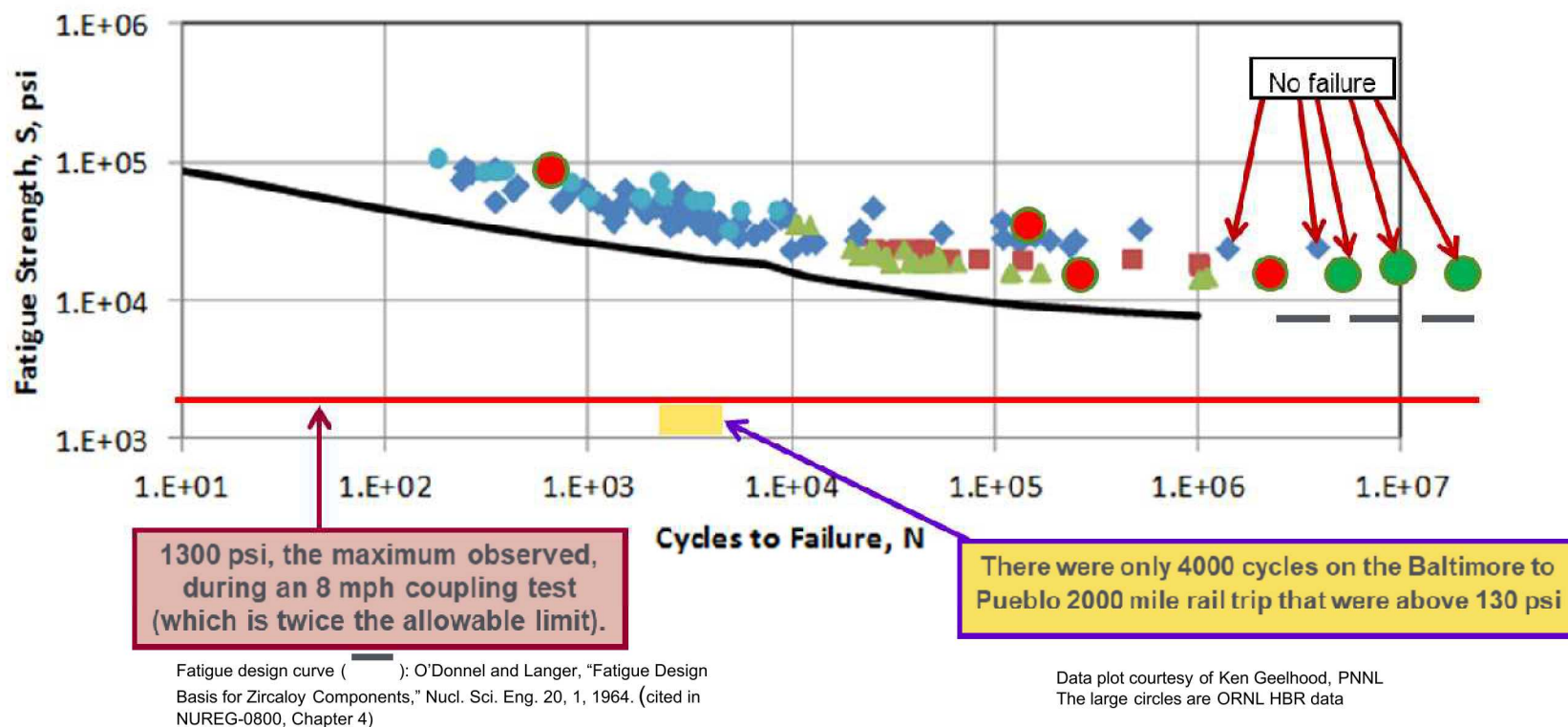
Data Shows that Fatigue is Not a Concern



- Damage fraction of 1.0 indicates fatigue failure. Accumulated damage in all cases is below 10^{-10}
- This calculation estimates it would take 10 billion cross-country (2,000-mile) trips to challenge the fatigue strength of irradiated fuel cladding.

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

The Sister Rod Data Compared to the Transportation Data Indicate a Good Safety Margin



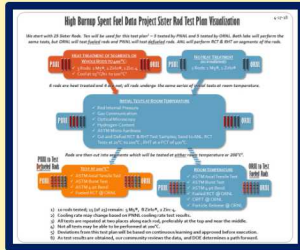
CONCLUSIONS

The realistic stresses that fuel may experience due to vibration and shock during normal conditions of transportation are far below yield and fatigue limits for cladding. Data for transportation via rail, truck, and ship has been gathered to develop and support this conclusion.

Temperature, Fuel Integrity, and Stress Profile all Effect Canister Integrity



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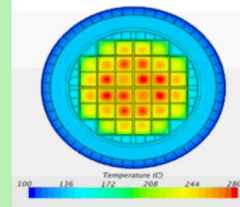


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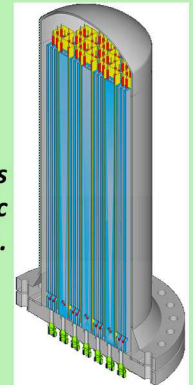
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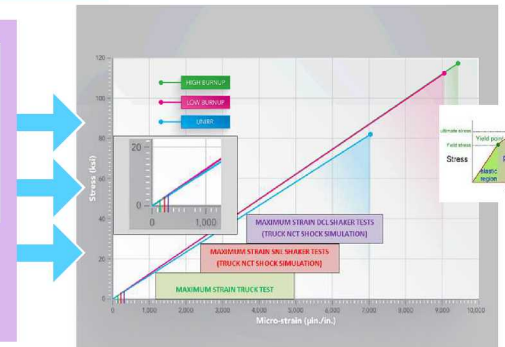
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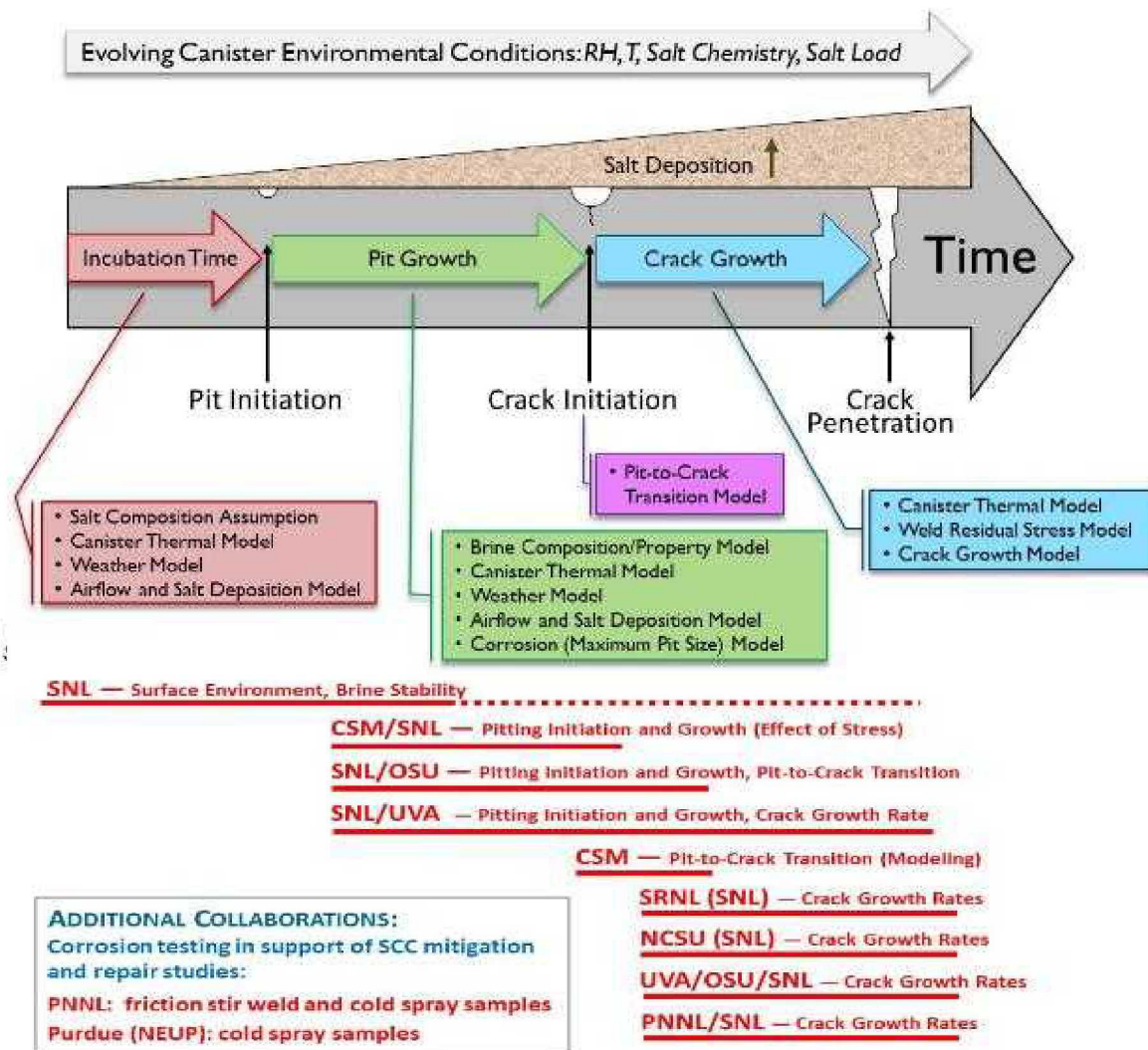


**SPENT FUEL TRIATHLON:
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Canister Stress Corrosion Cracking: Goal: When, Where, and How to Mitigate?

- GOAL: Develop an Integrated Mechanistic/Probabilistic Model for Canister SCC** to improve ability to predict timing and location of potential canister penetration by SCC cracks
- We need to understand the basic science to know how to effectively mitigate stress corrosion cracking.

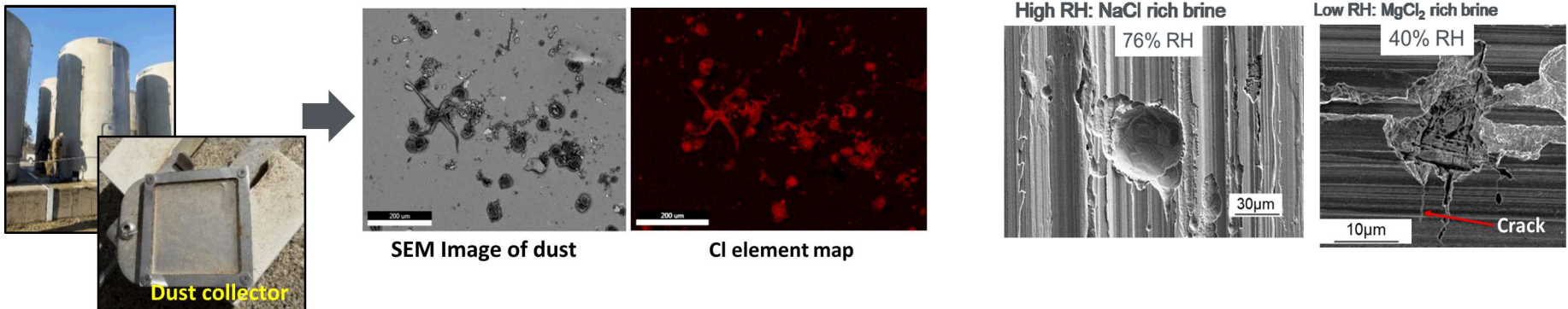


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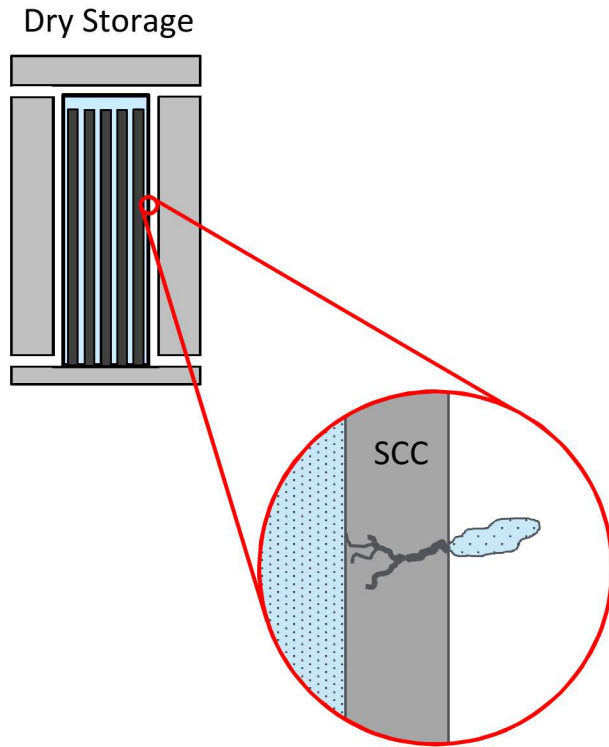
Collaborative effort to understand:

1. How do canister surface depositions evolve over time?
 2. What is the relationship between surface environment (*temperature, humidity and salt load/distribution*) and damage (*pitting/SCC*) distributions/rates?
 3. How does the microstructure and mechanical environment (*residual stress intensity and depth profile*) of the canister contribute to corrosion distributions and rates?
- What is the primary factor that governs pit morphology?
 - Is pit-crack transition influenced by environment and pit morphology?
 - Is crack growth rate a function of the environment?

Maine Yankee ISFSI Sampling, Aug. 2017 - Oct. 2019

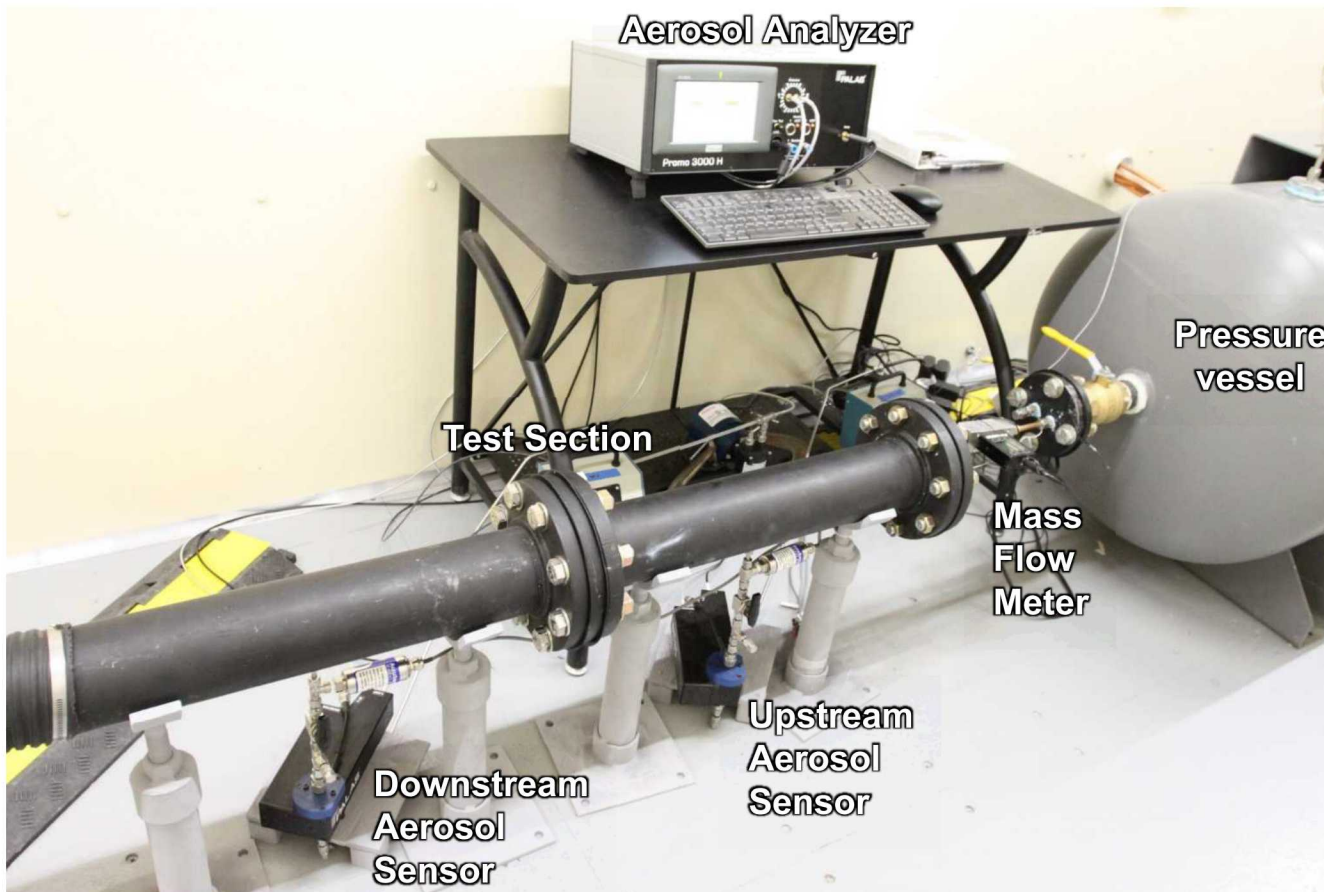


What is the potential impact of a through-wall stress corrosion crack (SCC)?



- What is the potential impact of a through-wall stress corrosion crack (SCC)?
 - Relatively low availability of mobile radionuclides under normal storage and transportation
- Significant amount of literature on aerosol transport through idealized leak paths
 - Primarily for moderate pressure differentials
- Information for combined analysis needed from following topics
 - Available source term inside canister
 - Characteristics of SCC
 - Flow and particle transport through prototypic SCC's

Test Apparatus to Collect Data on the Potential Impact of a Through-wall Stress Corrosion Crack (SCC).



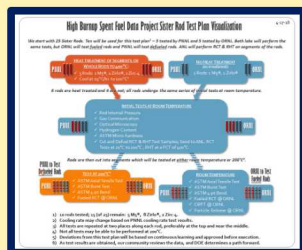
The S&T R&D Projects Combine to Develop the Technical Basis for Safe Storage and Transport of Spent Nuclear Fuel



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

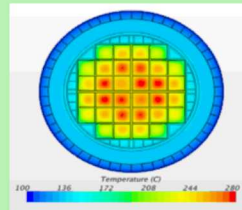
We completed non-destructive tests.

3CBE14-May-11-2017_A225_D3452_5694.jpg



Have begun destructive analysis.

SISTER ROD MECHANICAL TESTING DATA



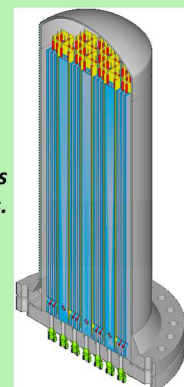
We have thermal models.

We have thermal data from the Demo.

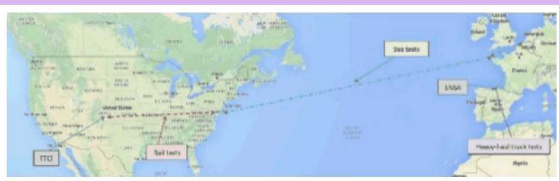


We are identifying conservatism & biases to develop more realistic assumptions.

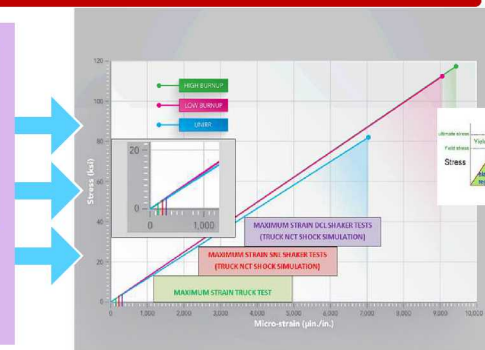
THERMAL BEHAVIOR



PROVIDES KNOWLEDGE ABOUT SPENT FUEL AND CANISTER INTEGRITY



SPENT FUEL TRIATHLON: QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS



What is Next?

SFWST program has the necessary hardware and funding to continue the R&D as defined in the Gap Analysis reports

Focus for the next 2 years:

Gap Priority 1: Temperature drives everything.

- Continue thermal modeling validation work. Continue the Thermal PIRT.
- **Can we get more temperature data from in-service canisters?**

Gap Priority 1: Need to know how to mitigate CISCC effectively.

- Continue to learn about CISCC time frames, and regions of concern.
- **Can we get more dust samples?**

Gap Priority 1: A transportation campaign will happen and we need to know safety margin.

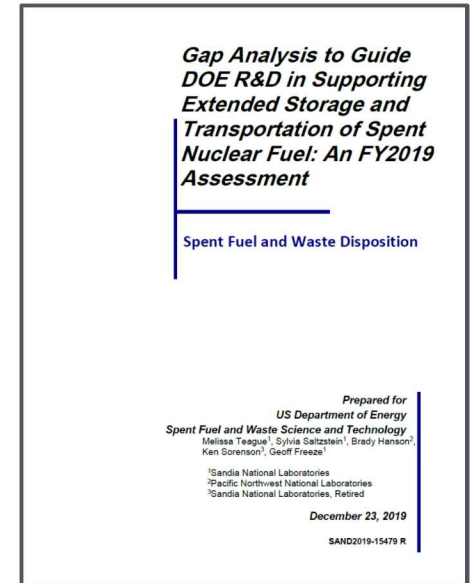
- Obtain data on fuel accelerations during handling and pinch load conditions.

Gap Priority 2: We need to know how much water remains in a cask after drying.

- Testing and sampling to better understand impacts, if any, of residual water
- **Can we get gas samples?**

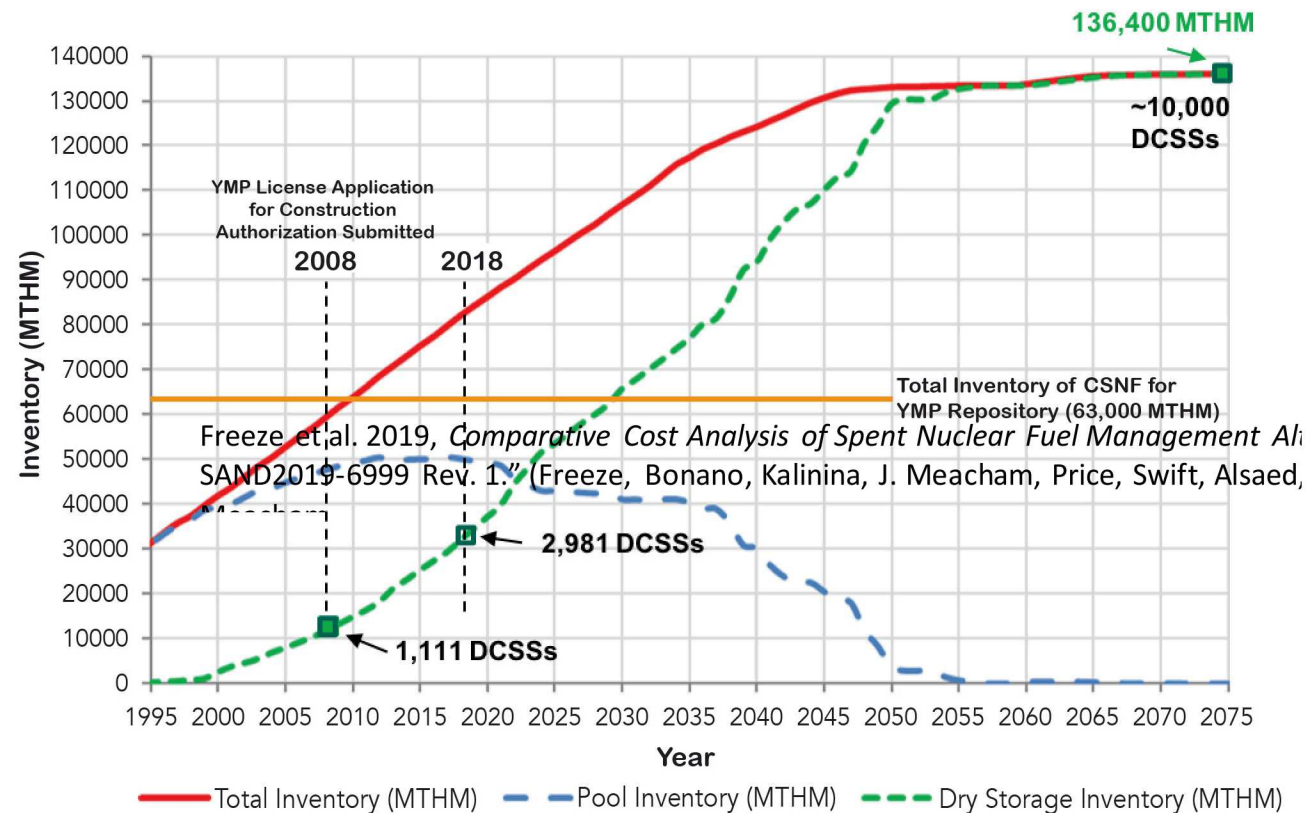
Gap Priority 3: Continue the sister rod destructive testing to get mechanical properties.

Investigate ATF



Why We are Here:

We must have the Technical Flexibility to Support any Policy Decision



Freeze et al. 2019, Comparative Cost Analysis of Spent Nuclear Fuel Management Alternatives, SAND2019-6999 Rev. 1." (Freeze, Bonano, Kalinina, J. Meacham, Price, Swift, Alsaed, Beckman, and P. Meacham

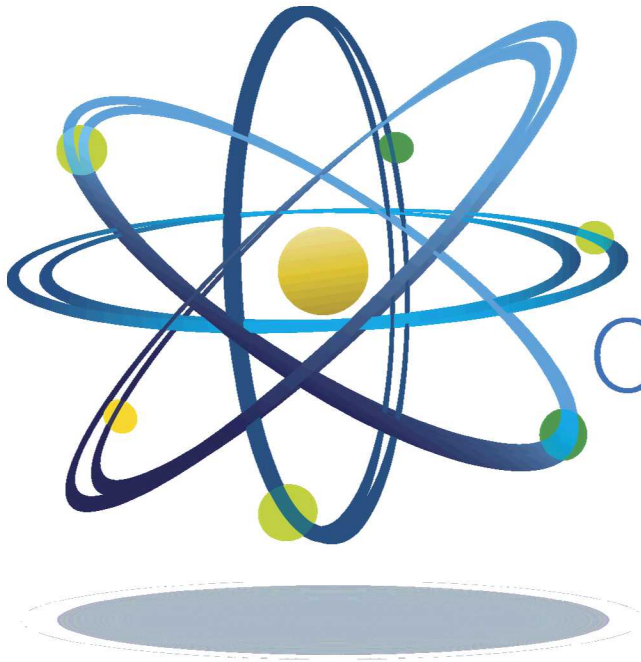
We have three options

1. Repackage all the fuel before going into a repository
2. Dispose of it as-is.
3. Do nothing

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Questions?



Clean. **Reliable. Nuclear.**