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

SAND2020-6201C ar.

SWFST Seminar Series

SWFST ST Overview

Sylvia Saltzstein, Sandia National Laboratories, SWFST ST Control Account Owner

Virtual Meeting

June 18, 2020

SAND2020-

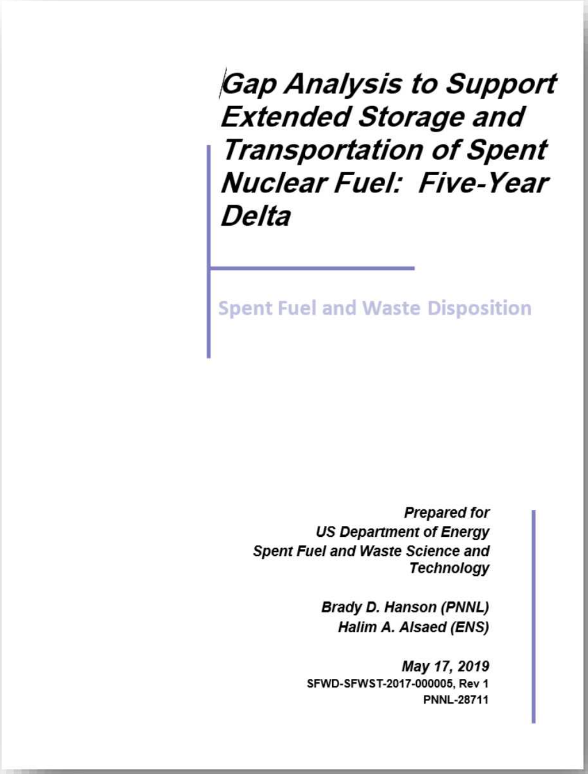
R&D Focus for SFWST Storage and Transportation

Develop the technical basis for

- Extended storage of used nuclear fuel
- Fuel retrievability and transportation after extended storage
- Transportation of high-burnup used nuclear fuel

What do we Need to Know to Develop the Technical Basis?

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

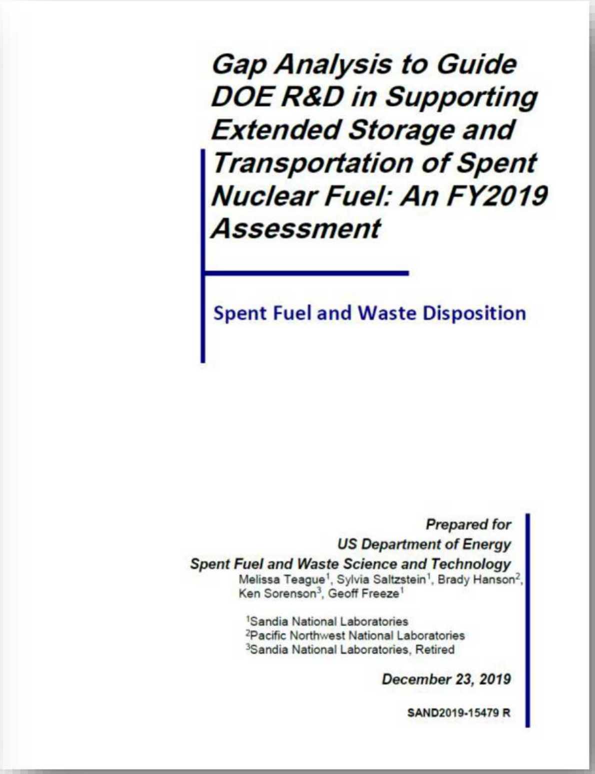
Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

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

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

2017 Five-Year Delta report

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



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 Teague[1], Sylvia Saltzstein[1], Brady Hanson[2], Ken Sorenson[3], Geoff Freeze[1]

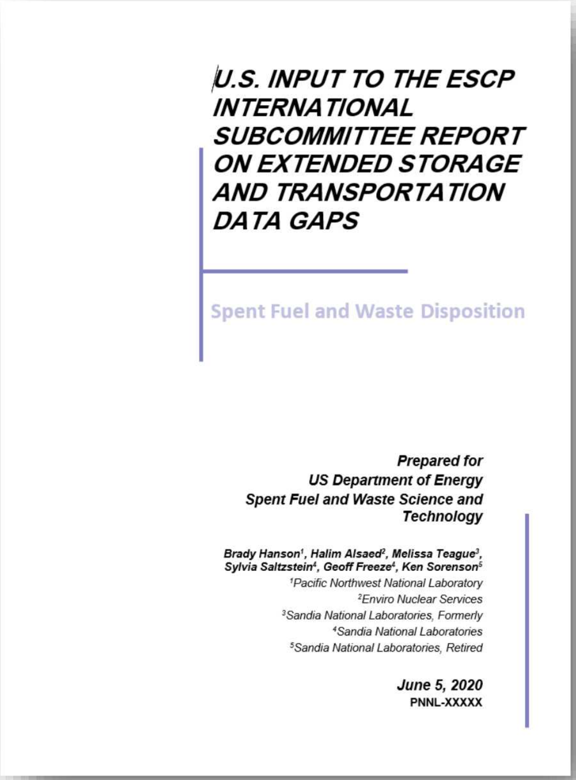
[1]Sandia National Laboratories
[2]Pacific Northwest National Laboratories
[3]Sandia National Laboratories, Retired

December 23, 2019

SAND2019-15479 R

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



U.S. INPUT TO THE ESCP INTERNATIONAL SUBCOMMITTEE REPORT ON EXTENDED STORAGE AND TRANSPORTATION DATA GAPS

Spent Fuel and Waste Disposition

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

Brady Hanson[1], Halim Alsaed[2], Melissa Teague[3], Sylvia Saltzstein[4], Geoff Freeze[4], Ken Sorenson[5]
[1]Pacific Northwest National Laboratory
[2]Enviro Nuclear Services
[3]Sandia National Laboratories, Formerly
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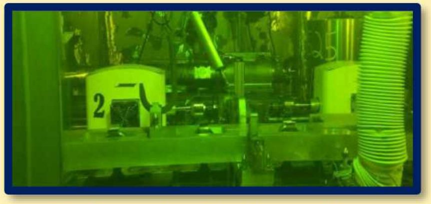
[5]Sandia National Laboratories, Retired

June 5, 2020
PNNL-XXXXX

FY2020 Input to International Gap Report

- Validates US Gaps and prevents duplication of efforts

How the Projects Fit Together



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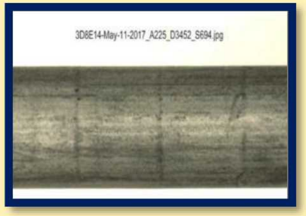
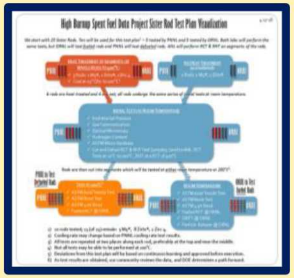
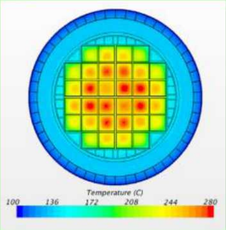




Have begun destructive analysis.

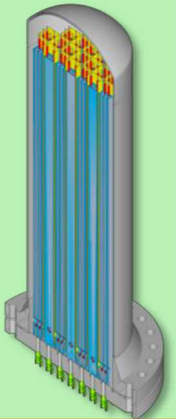
Sibling Pins Mechanical Testing Data



We have thermal models.

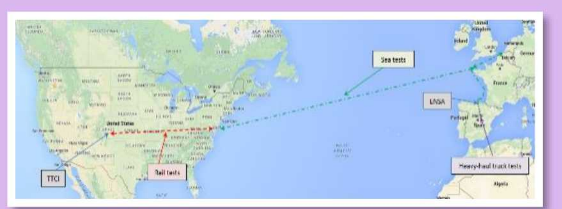
We are getting thermal data from the Demo.

We are working to ID conservatisms & develop more realistic assumptions.



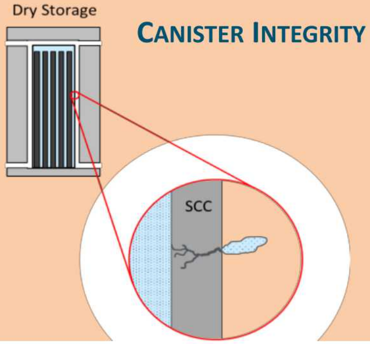
Thermal Behavior

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



Spent Fuel Triathlon and NCT Drop Tests: Quantification of Normal Transport Shocks & Vibrations

Canister Integrity



Program is Focused on Obtaining In-Service Data

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 4 common cladding alloys of high burn-up fuel in the North Anna Nuclear Power Plan storage pool
2. 63 thermocouples inserted within cask
3. Gas samples taken before going to pad
4. Dried using industry standard practices (completed November 2017)
5. Currently storing at utility dry cask storage site for10 years
6. After ten years, the US DOE will test rods to quantify mechanical properties. 25 Sibling Pins are currently being tested to obtain baseline mechanical properties.

The Research Project Cask stored at North Anna with a solar panel to power the internal thermocouple data acquisition system.

Photo courtesy of Dominion Energy

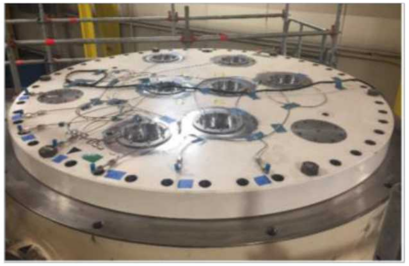
Thermal Profiles:

The TN-32B Research Project Cask Bounds Most Cask Loadings (fuel is hotter and decay is shorter than average)

	TN-32 Safety Evaluation Report (generic)	TN-32B Research Project Cask License Amendment
Maximum burnup (GWd/MTU)	≤45	≤60
Maximum decay heat per assembly	1.02 kW	1.5 kW
Total decay heat	32.7 kW	36.96 kW
Minimum decay time	7-10 years	4.81 years
Est. Peak cladding temperature (PCT)	328°C	348°C

Photo courtesy of Dominion Energy

The 63 Thermocouples in the Demo Cask provided data much cooler than modeled.



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

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

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)

Current Work is to Identify and Understand Uncertainty and Bias in Thermal Models

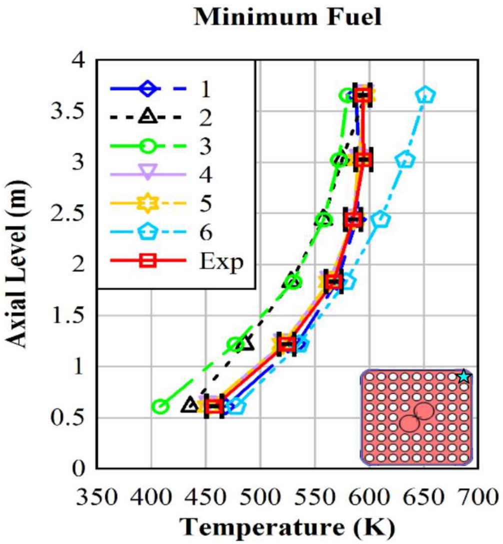
Summary: All modeling overestimated the peak clad temperatures.

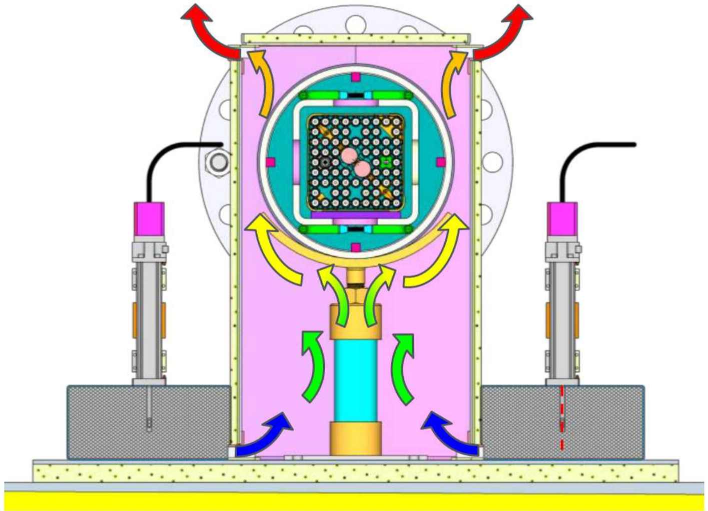
Why?

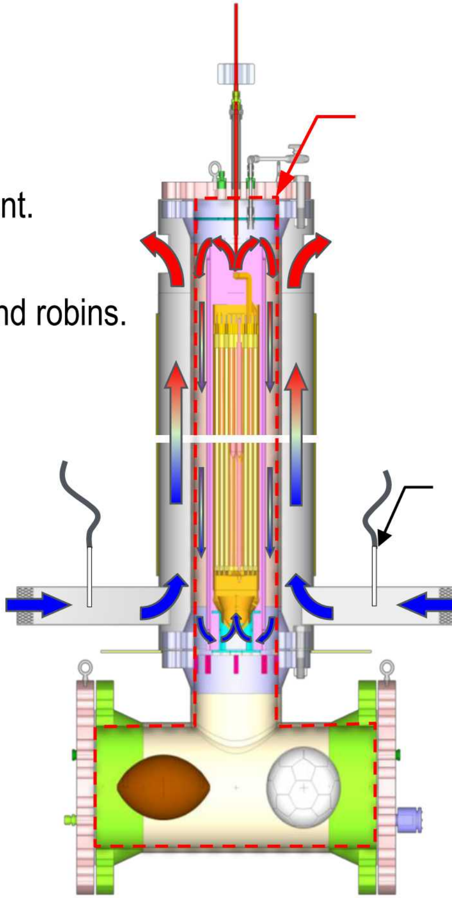
1. **Models add conservativisms at most data entry opportunities. This adds up to an overestimation of the peak clad temperature.**
2. **The aluminum basket expands and closes the gaps, but we don't know by how much.**

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

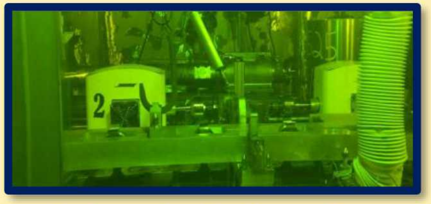
1. Blind Round Robin Modeling exercises of demo data
2. Aboveground horizonal and vertical, belowground vertical experimental setups with blind round robins.







How the Projects Fit Together



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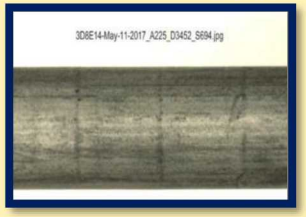

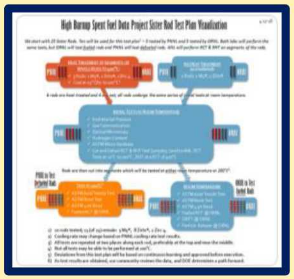

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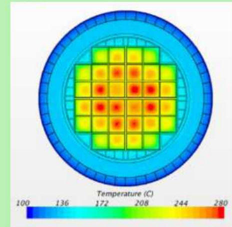
SIBLING PINS MECHANICAL TESTING DATA



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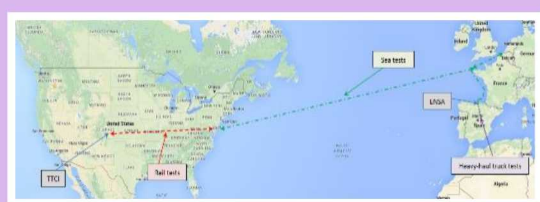
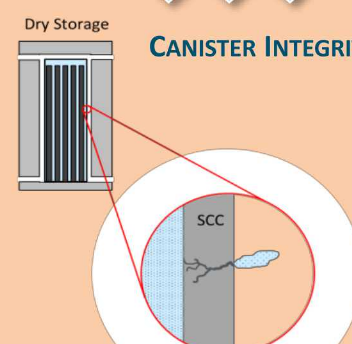
THERMAL BEHAVIOR

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



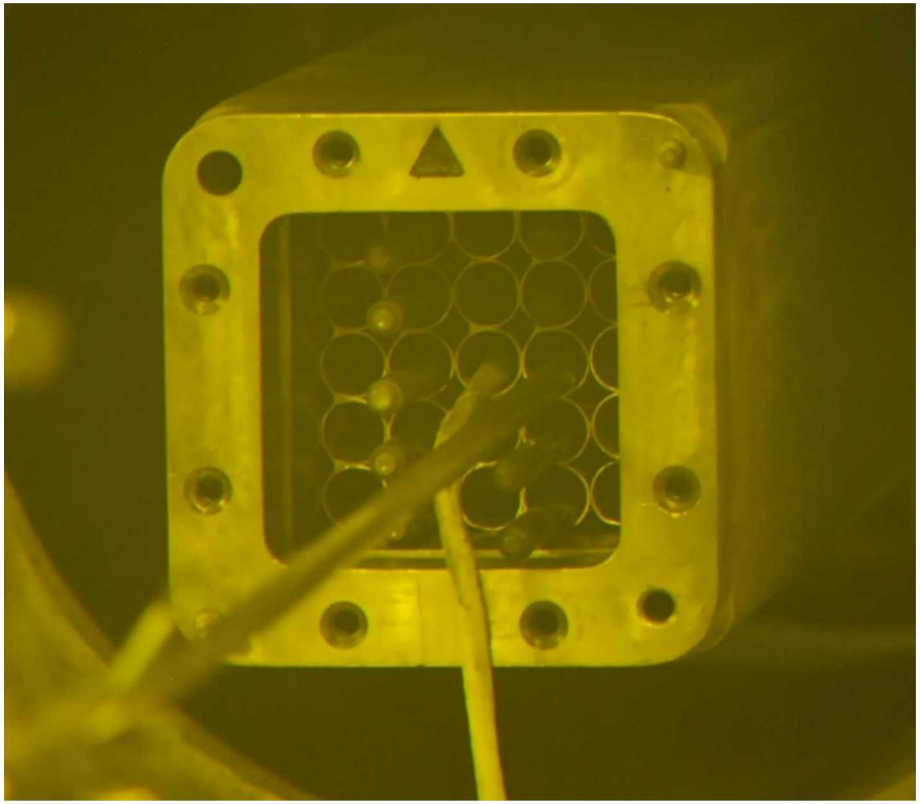
SPENT FUEL TRIATHLON AND NCT DROP TESTS:
QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS

CANISTER INTEGRITY



Sister Rod Selection

- 25 individual rods (Sibling Pins) were selected and pulled from representative fuel assemblies to perform characterization and material property tests
- These rods will form the baseline for pre-storage characterization
- Rods or segments will be heated to simulate drying conditions to predict material properties post-drying
- 25 sibling pins were shipped to ORNL in January of 2016
- 10 sibling pins were shipped to PNNL in September of 2018



NAC LWT basket with 10 Sister Rods in PNNL hot cell

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.

Heat Treatment of Segments or Whole Rods to 400°C (PNNL / ORNL)
- 3 Rods: 1 M5®, 1 Zirlo®, 1 Zirc-4
- Cool at ≤5°C/hr to 100°C

No Heat Treatment *(as irradiated)* (PNNL / ORNL[1])
- 2-3 Rods: M5®, Zirlo®, Low-Tin Zirc-4

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

Initial Tests at Room Temperature (PNNL / ORNL)
- Rod Internal Pressure
- Gas Communication
- Optical Microscopy
- Hydrogen Content
- ASTM Micro-hardness
- RCT & RHT Test Samples *(Send to ANL)*
  - RCT Tests @ 20°C to 200°C
  - RHT @ 400°C PCT

Rod segments are then tested at room temperature and 200°C[2].

PNNL to Test Defueled Rods

Test at 200°C[3] (PNNL / ORNL)
- ASTM Axial Tensile
- ASTM Burst
- ASTM 4-point Bend
- Fueled RCT @ ORNL

ORNL to Test Fueled Rods

Room Temperature (PNNL / ORNL)
- ASTM Axial Tensile
- ASTM Burst
- ASTM 4-point Bend
- Fueled RCT @ ORNL
- CIRFT @ ORNL
- Particle Release @ ORNL

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.

Nondestructive and Destructive Examinations are Producing Data to Close the Gaps on HBU SNF Storage and Transportation

- ORNL heat treated 3 rods prior to puncture to provide data relevant to vacuum drying – 1 ZIRLO-clad, 1 M5-clad, and 1 Zirc-4 clad.

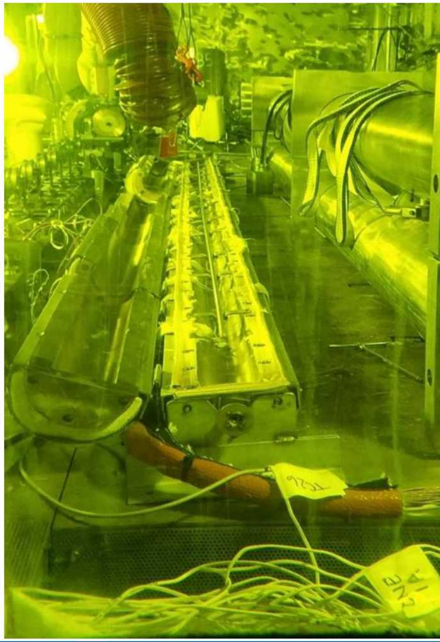
- ORNL and PNNL measured rod internal pressure and void volume of 17 rods. The results compare well with historical data and are self-consistent among labs.
  - $P_f V$ of sibling pins trends very well with burnup
  - An increase in fission gas release is observed at ~54 GWd/MTU

- Gas transmission testing of both full length rods and short segments indicate that at room temperature, good communication exists along the pellet stack. Heat-treated rods and HBU rods have a higher gas permeability; testing at dry storage temperature is recommended.

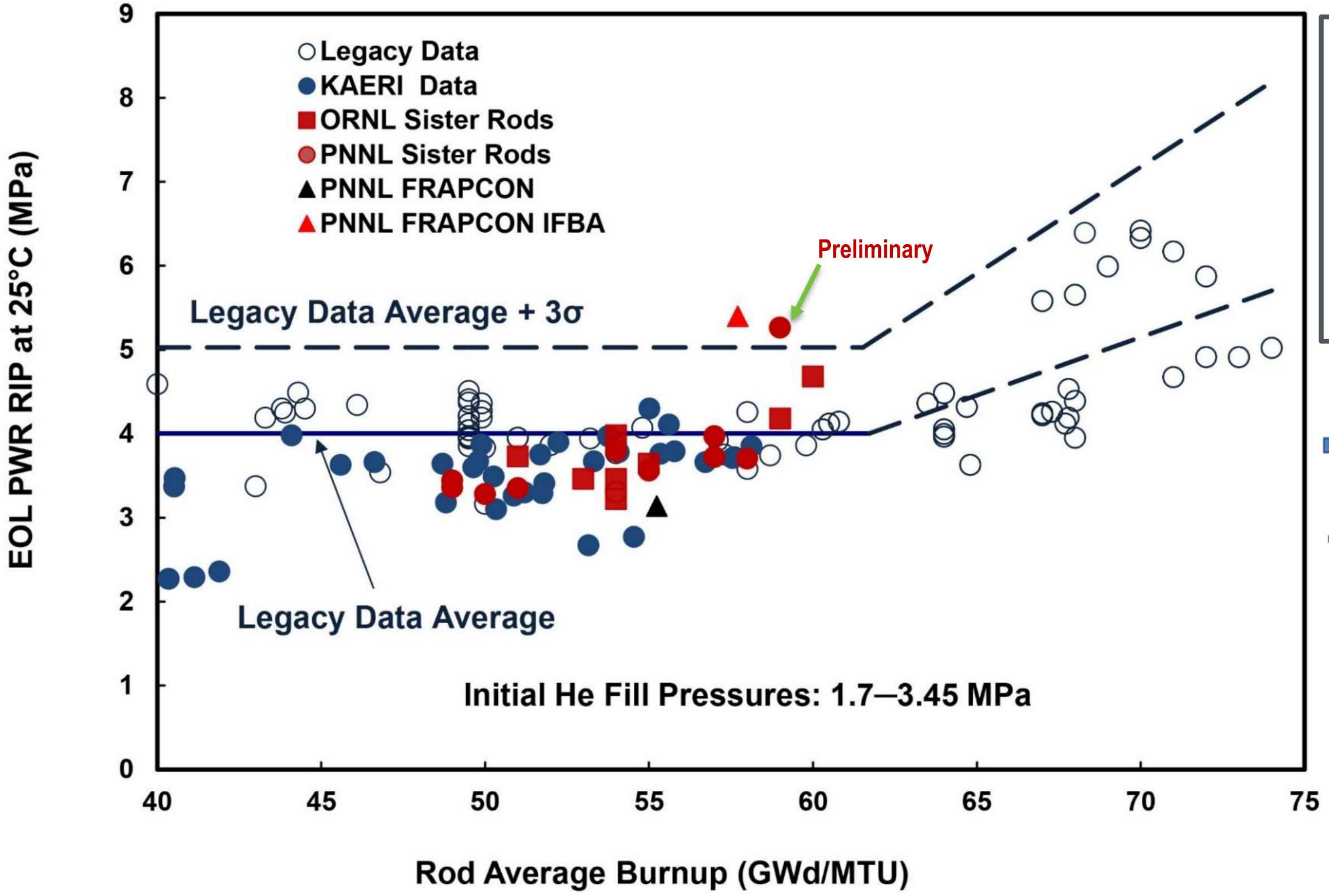
- Fatigue testing results are comparable to historical data and show significant margin to expected transportation loads, with heat-treated rods having a slightly shorter fatigue lifetime

- Metallography identified some radial hydrides in the heat-treated rods, but they are generally short

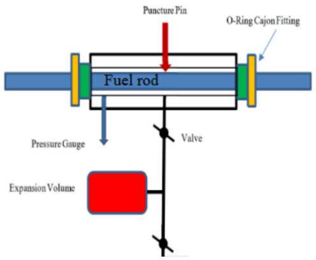
"Flattened" waterside surface of one of the sibling rods (above) and the ORNL full length rod heat treatment oven (below). Photos from Rose Montgomery, ORNL.



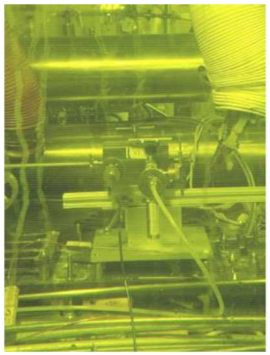
When Temperature is Lower, Rod Internal Pressure is Lower



When converted to 400C, non-IFBA 17 x17 rods to have EOL RIP between 6.2 and 11.5 MPa.



Photos above and below from Montgomery, et al, M2SF-19OR010201028. PNNL performed similar tests in Shimskey et al, M2SF-19PN010201037. Schematic above shows rod internal pressure measurement device. Photo below is the device in the hot cell.



Billone, M., Burtseva, T., “Results of Ring Compression Tests”, SFWD-SFWST-2018-000510, ANL-18/36. September 2018.

Converting Rod Internal Pressure Measurements to Hoop Stress

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

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

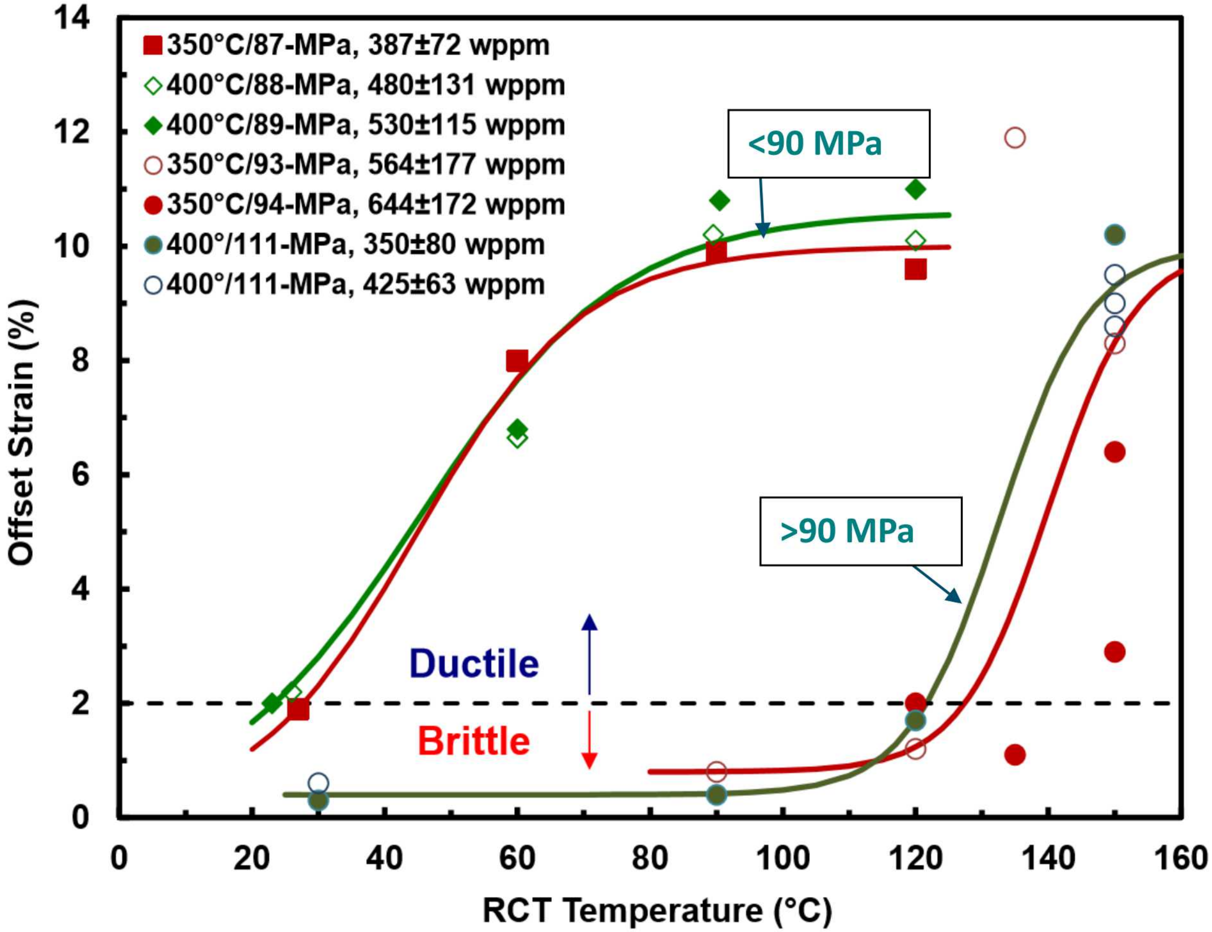
Model results similar to the Research Project Cask conditions show 53.4MPa @ 400°C, but the Research Project Cask only reached 229°C.

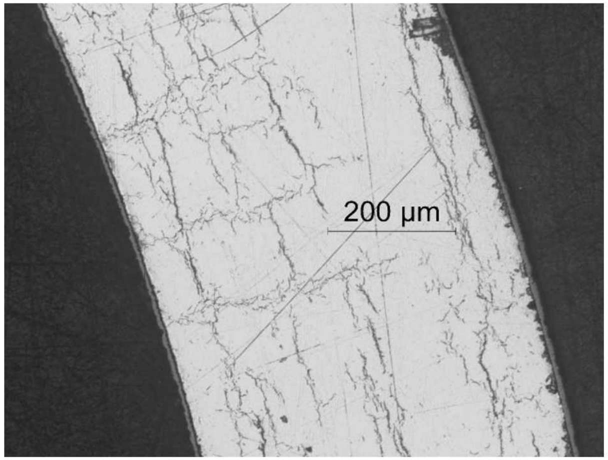
Our Sibling Pin test results were around 4MPa at room temperature.

Richmond, DJ and KJ Geelhood, *FRAPCON Analysis of Cladding Performance during Dry Storage Operations,* PNNL-27418, April 2018.

Ring Compression Test Results Indicate Cladding Ductility until 20 C if less than 90MPa.

As long as hoop stress is below 90MPa, it remains ductile until room temperature.
The Research Project Cask will have a hoop stress of less than **53.4MPa.**





"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."

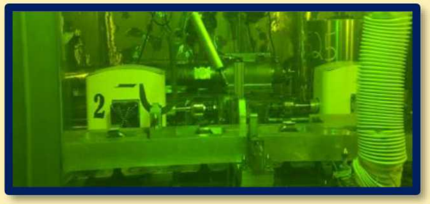
Billone, M., Burtseva, T., "Results of Ring Compression Tests", SFWD-SFWST-2018-000510, ANL-18/36. September 2018.

High Burn-up Mechanical Properties Summary

- **Rod Internal Pressure is lower than that expected to cause radial hydrides** in the 17 rods tested by ORNL and PNNL. High-burnup rods undergoing simulated drying conditions had some radial hydrides, but they discontinuous and short.
- **Gas transmission exists along the pellet stack,** at room temperature in both full length rods and short segments. Areas of high pressure within the rod are not expected.
- **Fuel fatigue testing show rods will not break** during the loads measured in our transportation tests.
- **High burn-up fuel is expected to remain ductile** at temperatures warmer than ambient.

Benchmarking of the PCT data from the Research Project Cask supports the ability to model other dry storage systems without having to perform testing for each specific vertical design.

How the Projects Fit Together



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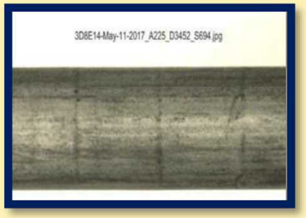
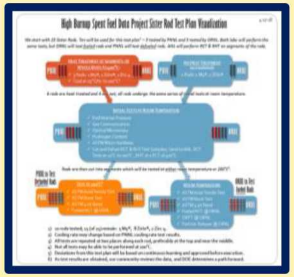
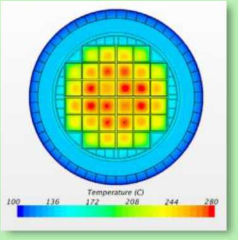



High Burnup Spent Fuel Data Project Sister Rod Test Plan Visualization

Have begun destructive analysis.

SIBLING PINS MECHANICAL TESTING DATA



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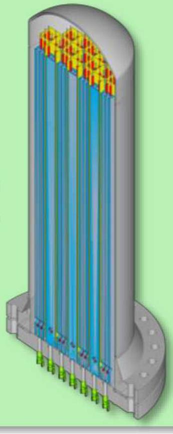

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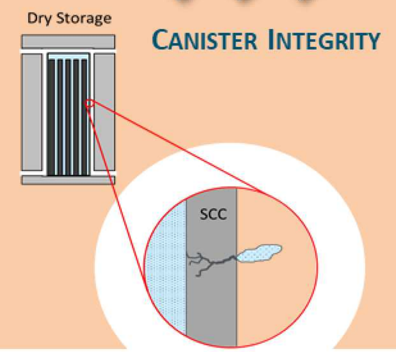
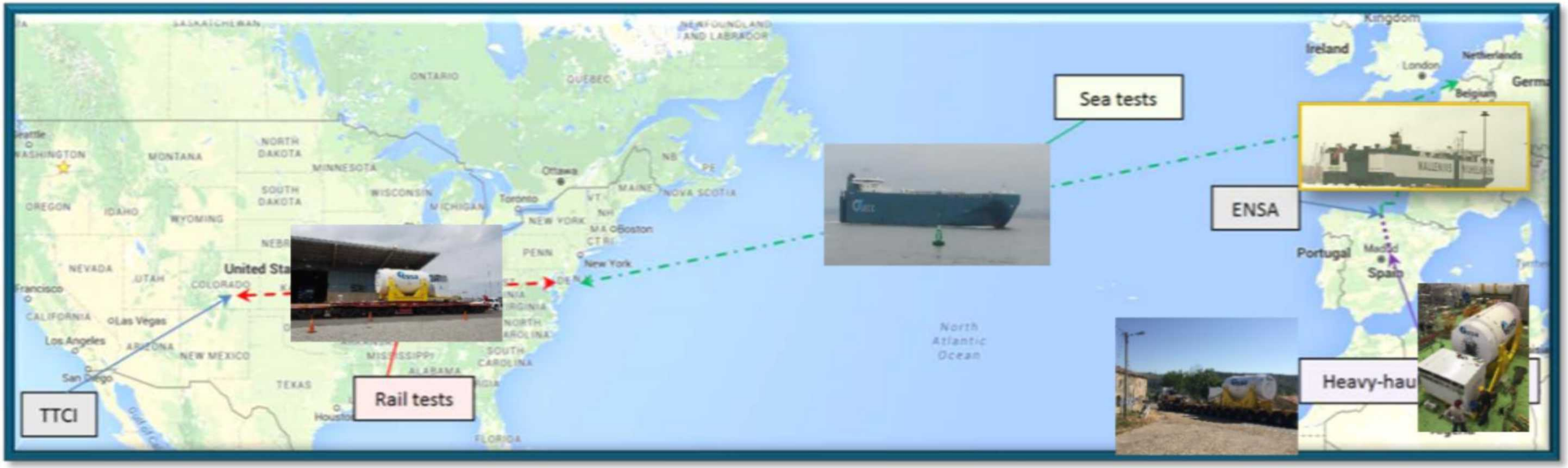


Mechanical Loading:
Multimodal Transportation and Handling Tests



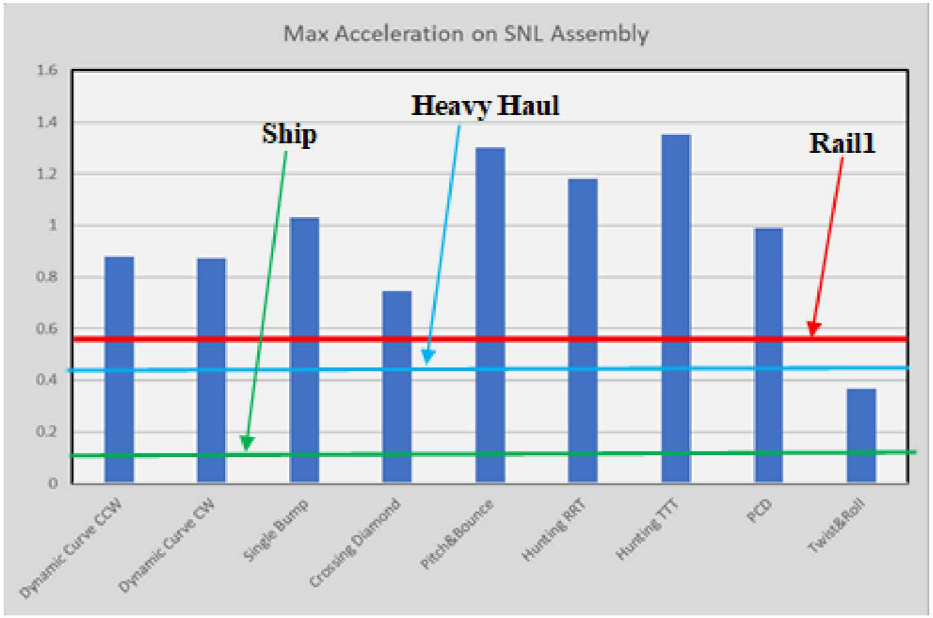
Photos provided by Steve Ross, PNNL

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

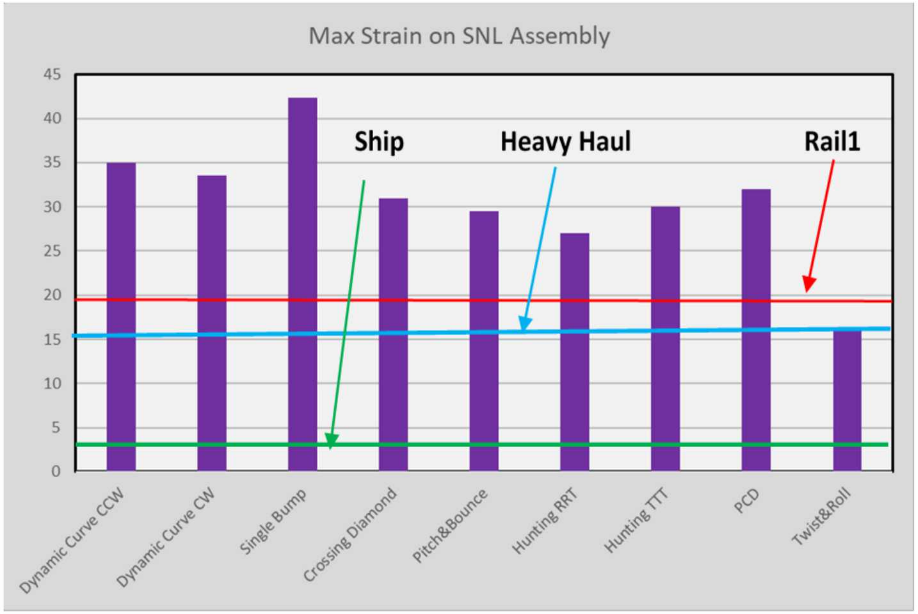
Data was collected throughout all legs of the transport as well as the transfers between legs.

Mechanical Loading:

Maximum Strains and Accelerations from all Transportation Tests



Measured in g



Measured in με

Measured yield stress levels for irradiated SNF cladding is ~ 7000 – 9000 με

Stress Profiles:

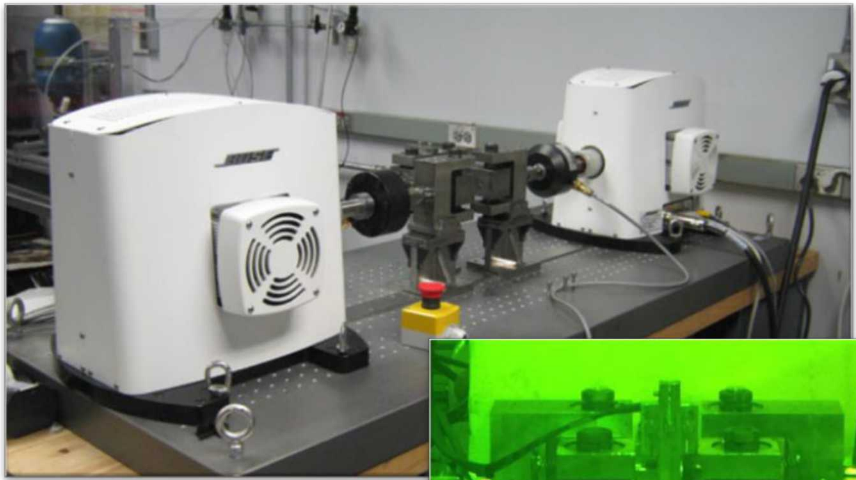
Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) tests fatigue to failure

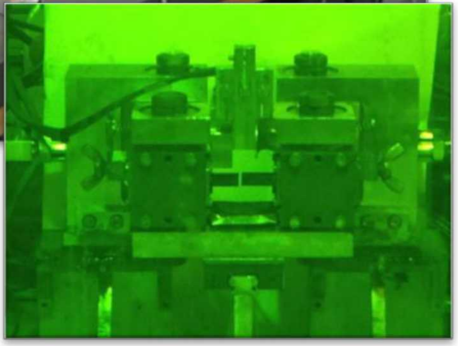
Goal: To determine the number of cycles to fatigue failure as a function of rod curvature and cladding stress and strain

- Both static bending and cyclic fatigue
    - Developed at ORNL under an NRC program and continued with DOE:NE.

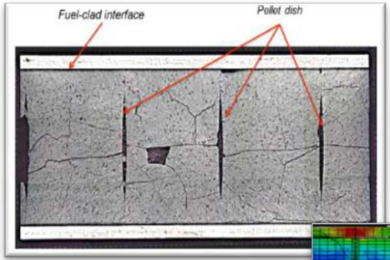
  Fatigue life depends on the level of loading
- Pellet-clad and pellet-pellet bonding provides additional stiffness

J-A Wang et. al. Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications, NUREG/CR-7198/R1 ORNL/TM-2016/689, Oak Ridge National Laboratory, January 2017.

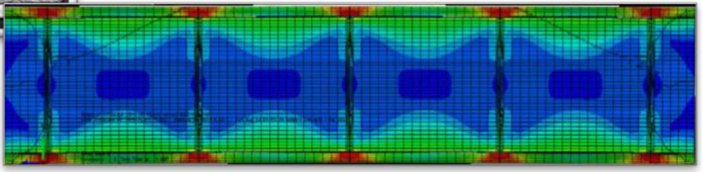




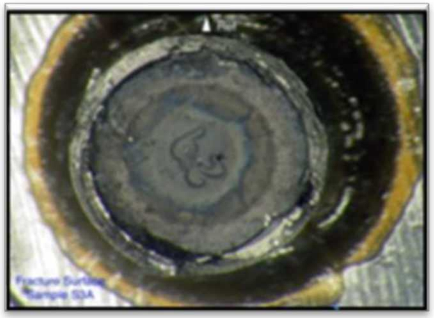
CIRFT tester out of the hot cell (above) and in the hot cell (right) testing High-Burnup Fuel samples.



Pellet Clad Bond and resultant stress distribution



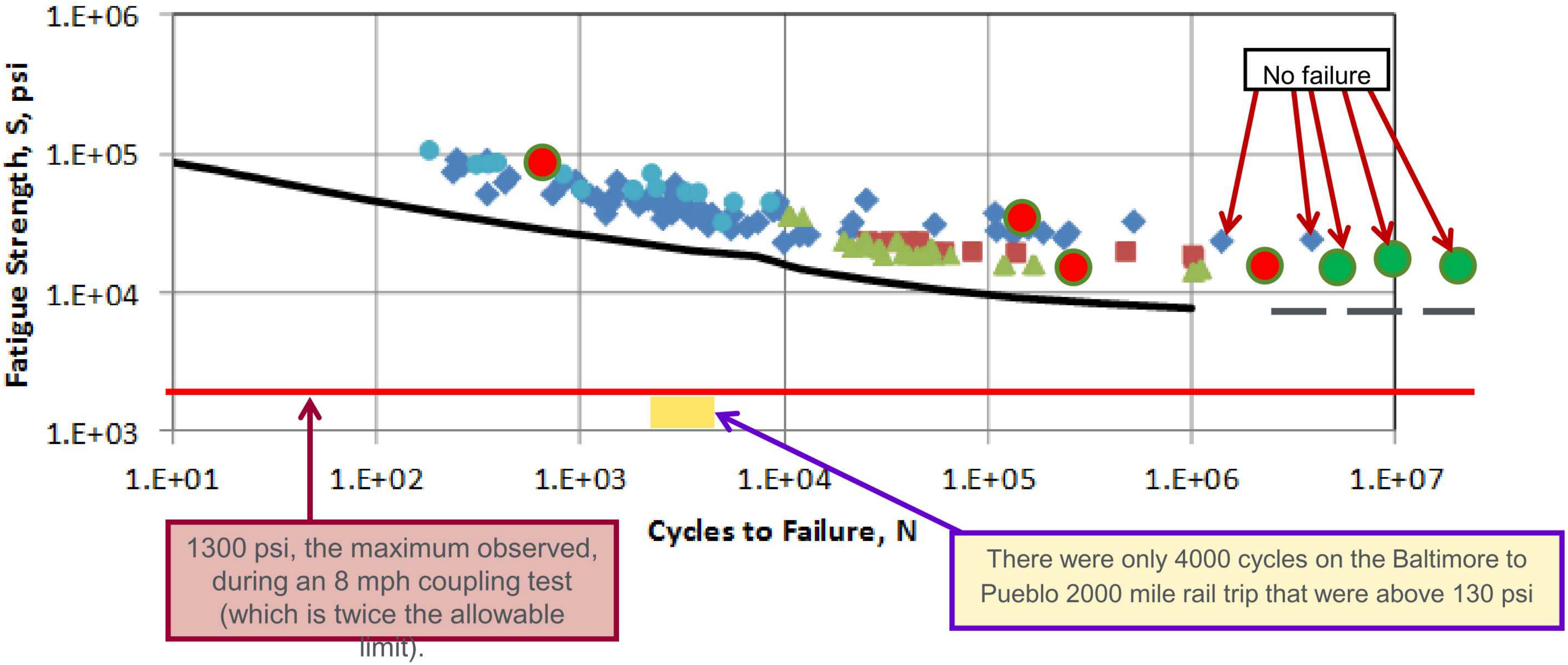
Images courtesy of Rose Montgomery, ORNL.



Most rods break cleanly between two pellets.

Mechanical Loading:

Will Fatigue Failure Occur During Normal Conditions of Transport?



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)

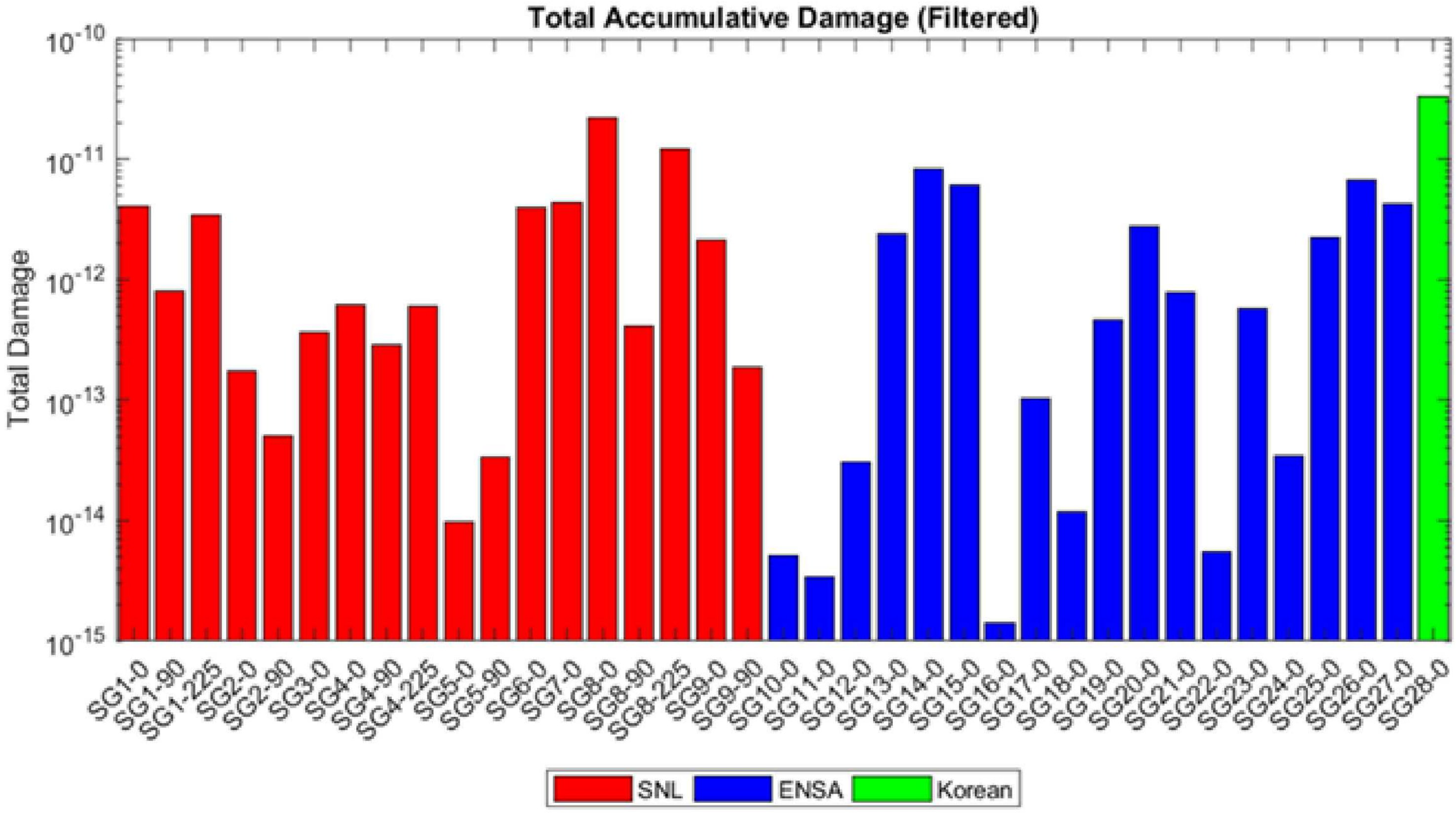
J-A Wang et. al. Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications, NUREG/CR-7198/R1 ORNL/TM-2016/689, Oak Ridge National Laboratory, January 2017.

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

- **Large red and green circles represent CIRFT data.**
- **Horizontal red line represents highest recorded stress value from the multimodal tests.**
- **Bold black line represents failure criteria above which failure may occur. Stress levels and the number of fatigue cycles from the multimodal tests are well below the failure limits.**

Spent Fuel Transportability Following Extended Storage –

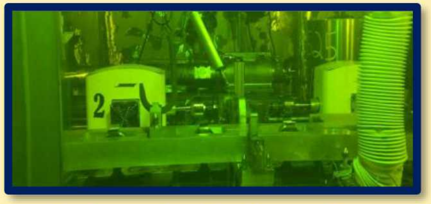
Cladding Fatigue Damage (Baltimore to Pueblo)



Damage Fraction of 1 represents failure. Strain data is 12 orders of magnitude below fatigue failure. Accumulated fatigue damage is approximately zero.

Klymyshyn N.A.et al. 2018. Modeling and Analysis of the ENSA/DOE Multimodal Transportation Campaign. 2018. PNNL-28088. Richland, WA: Pacific Northwest National Laboratory.

How the Projects Fit Together



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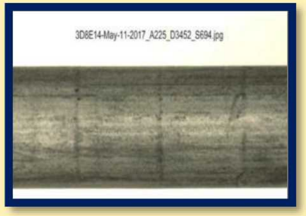
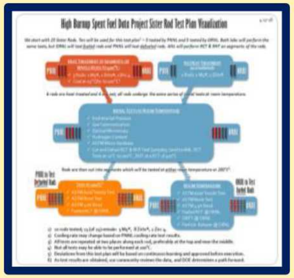
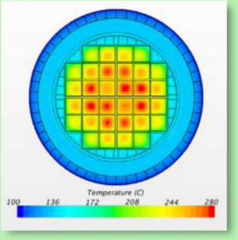




Have begun destructive analysis.

SIBLING PINS MECHANICAL TESTING DATA



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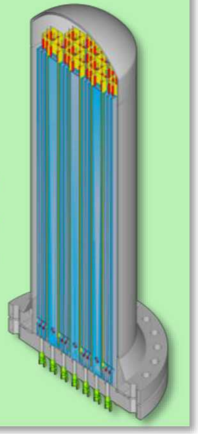
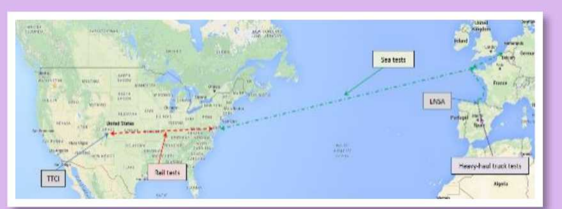


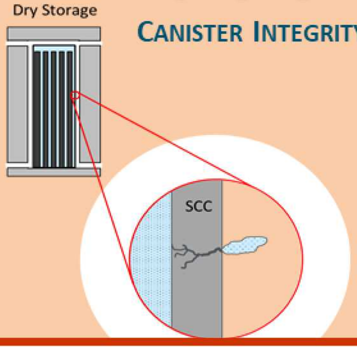
THERMAL BEHAVIOR

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



SPENT FUEL TRIATHLON AND NCT DROP TESTS:
QUANTIFICATION OF NORMAL TRANSPORT SHOCKS & VIBRATIONS

CANISTER INTEGRITY



Atmospheric Stress Corrosion Cracking:

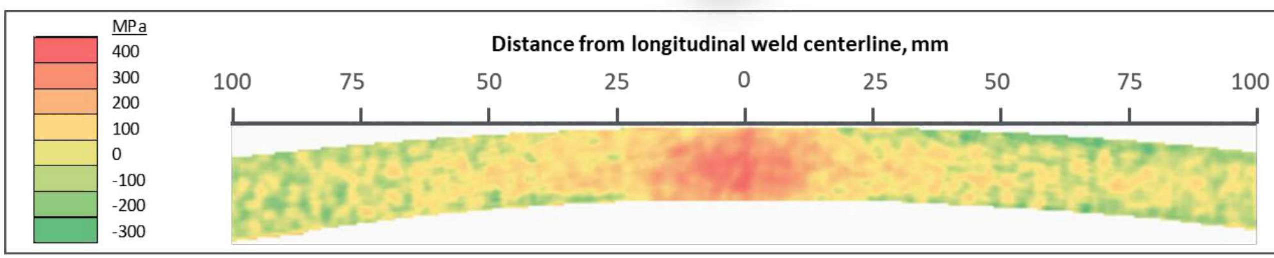
SCC Requires 3 Concurrent Conditions

Photo of canister weld. Photo: SNL

Dust on canister surface at Calvert Cliffs (EPRI 2014)

AT SOME ISFSI SITES, AN AGGRESSIVE ENVIRONMENT (CHLORIDE-RICH SALT AEROSOLS) WILL BE PRESENT, AND ALL THREE CRITERIA WILL BE MET.

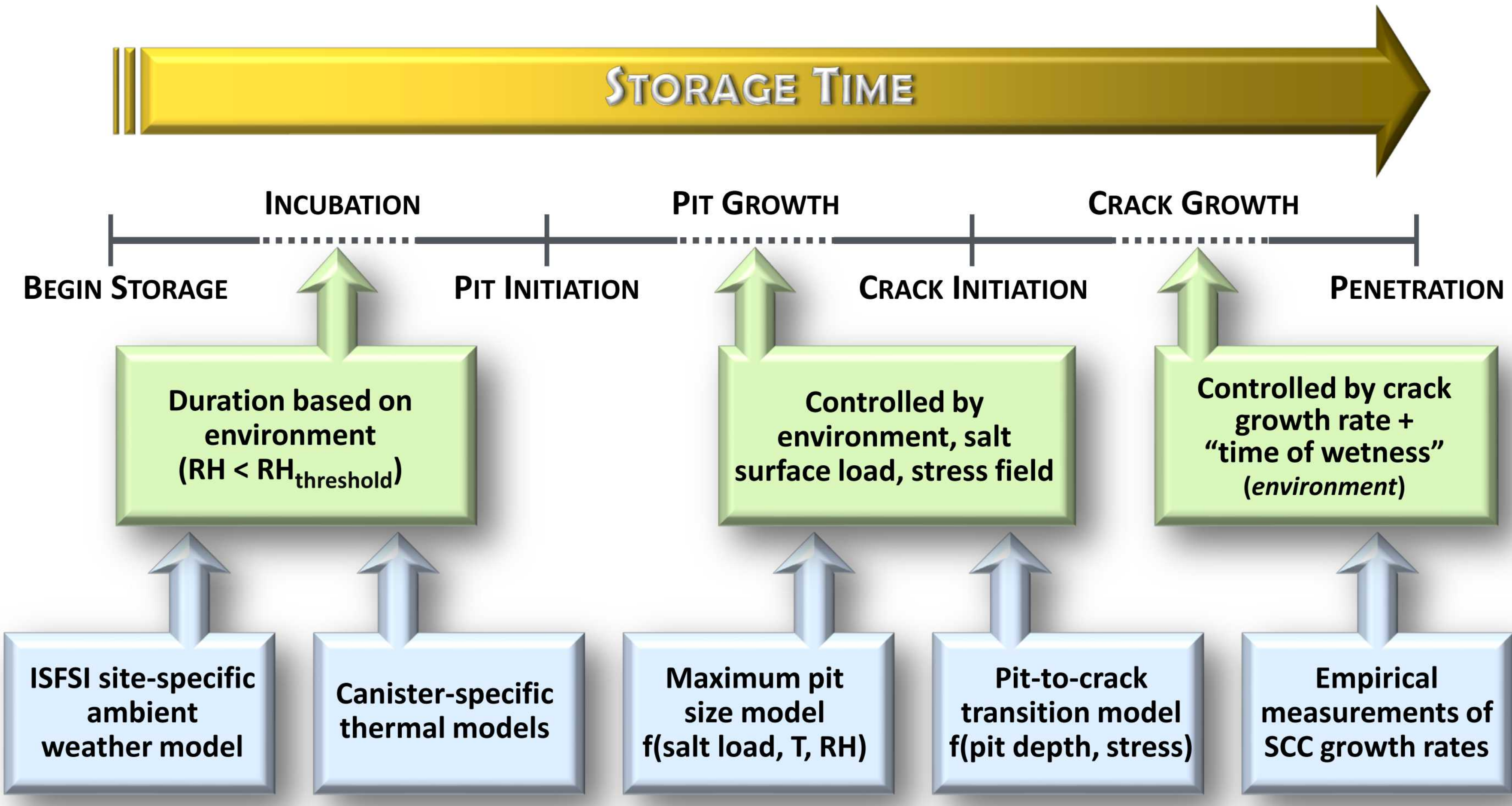
Weld residual stresses measured on SNL mockup



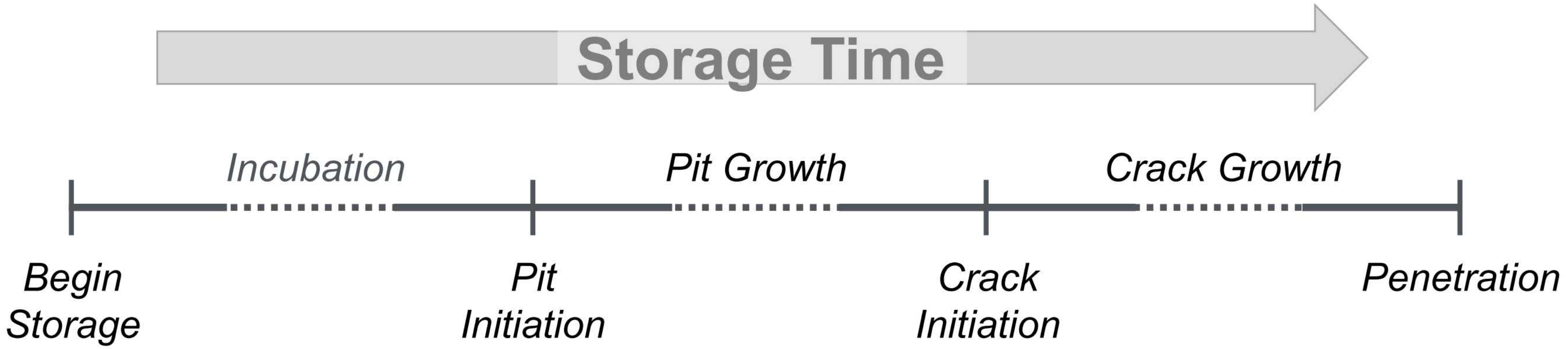
Understanding Canister Performance:

Probabilistic Modeling of Canister SCC

SNL Probabilistic SCC model divides timeline for canister failure into three periods and develops models for the dominant processes in each.



Understanding Canister SCC:
Surface Environment R&D



SNL — Surface Environment, Brine Stability

Expected salt/brine compositions

Determines corrosiveness, deliquescence properties of salts

Stability of salts and brines both before…

Impacts temperature and timing of deliquescence

…and after initiation of corrosion

Impacts brine layer properties (composition, thickness), potentially causes brine dry-out

Sampling/analysis of salts collected from in-service SNF dry storage canisters

Focus of coastal sites, with high chloride aerosols

Prior to deliquescence

Experimental evaluation of ammonium salt stability

After deliquescence

Experimental evaluation of sea-salt ($MgCl_2$) brine stability

Effect of cathodic reactions:

Hydroxide production at the cathode can affect brine composition, stability

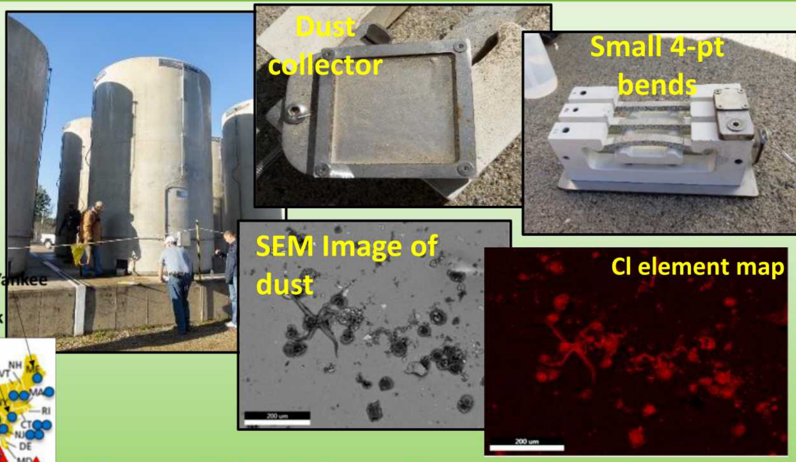
Incorporation of brine components into corrosion products

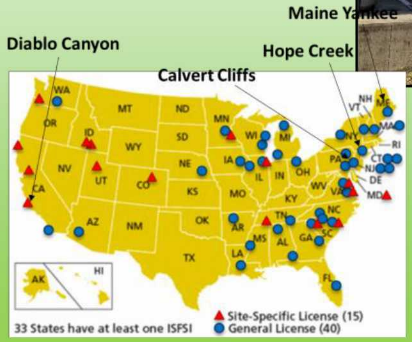
Chloride sequestration by iron oxyhydroxides

Canister Surface Environment:

Determine Brine Compositions and Evolution with Time

Sampling and analysis of dust and salts on in-service dry storage canisters

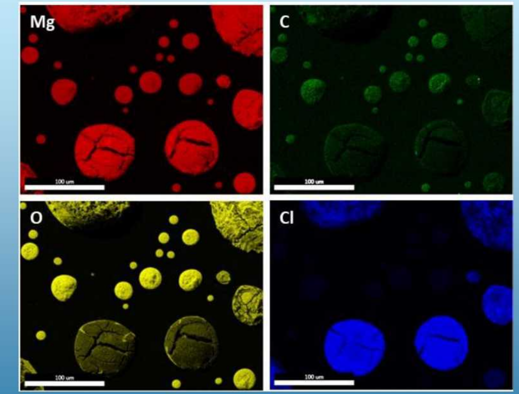




Three additional sites will be sampled in the next year.

Modeling and experimental evaluation of brine compositions/evolution on heated canister surfaces

EDS element maps: depletion of Cl^- in $MgCl_2$ droplets with exposure time



Ongoing efforts to understand effects of atmospheric exchange reactions and corrosion reactions on brine stability

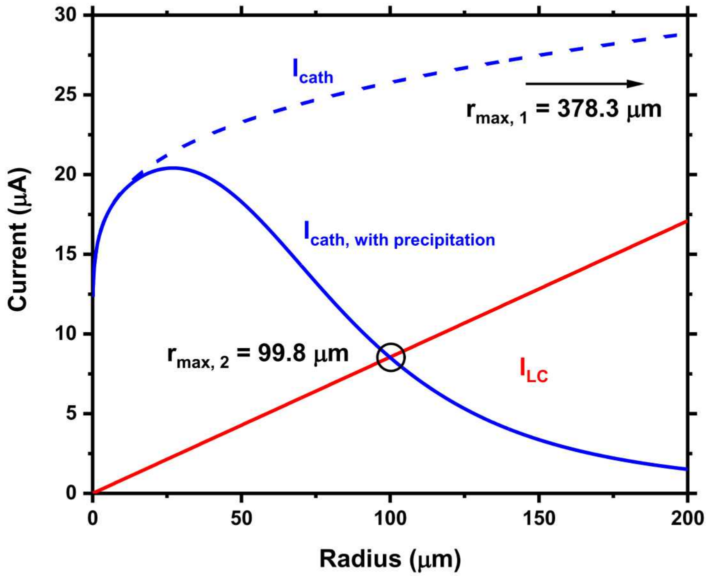
Determination of realistic environments for corrosion testing

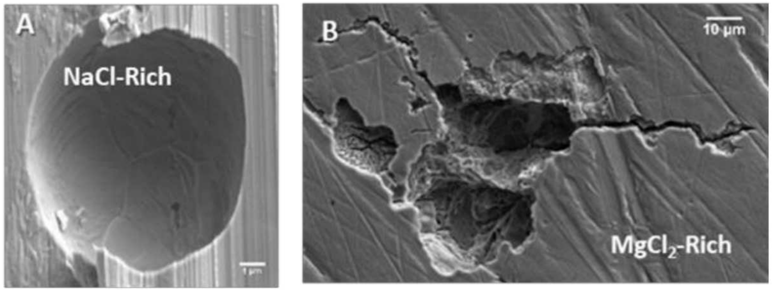
- **Diurnal cycles—**daily changes in temperature and relative humidity on canister surfaces will potentially affect corrosion rates, distributions, and morphologies. Realistic cycles have been developed for testing.
- **Chemistry—**corrosion experiments to date used sea-salts; actual field data show more complex salt mixtures at most sites; may be more benign or more aggressive. Realistic brine compositions have been developed.
- **Inert dust particles—**dust is dominantly inert mineral grains, which may affect corrosion via several processes. Dust particle size distributions were evaluated at four sites, representative particles sizes chosen and purchased. Coordinating with SNL aerosol group for dust deposition and corrosion testing.

Corrosion Experimental Work: Damage Distribution and Rates

Pitting, Pit-to-Crack, and CGR

- ***Pitting:***
  - Determine as a function of canister relevant environment and material properties
- ***Pit-to-crack transition:***
  - Pit morphology effects on local stresses and crack initiation
  - Microstructural and residual stress effects on pit-to-crack
  - Environment dependence





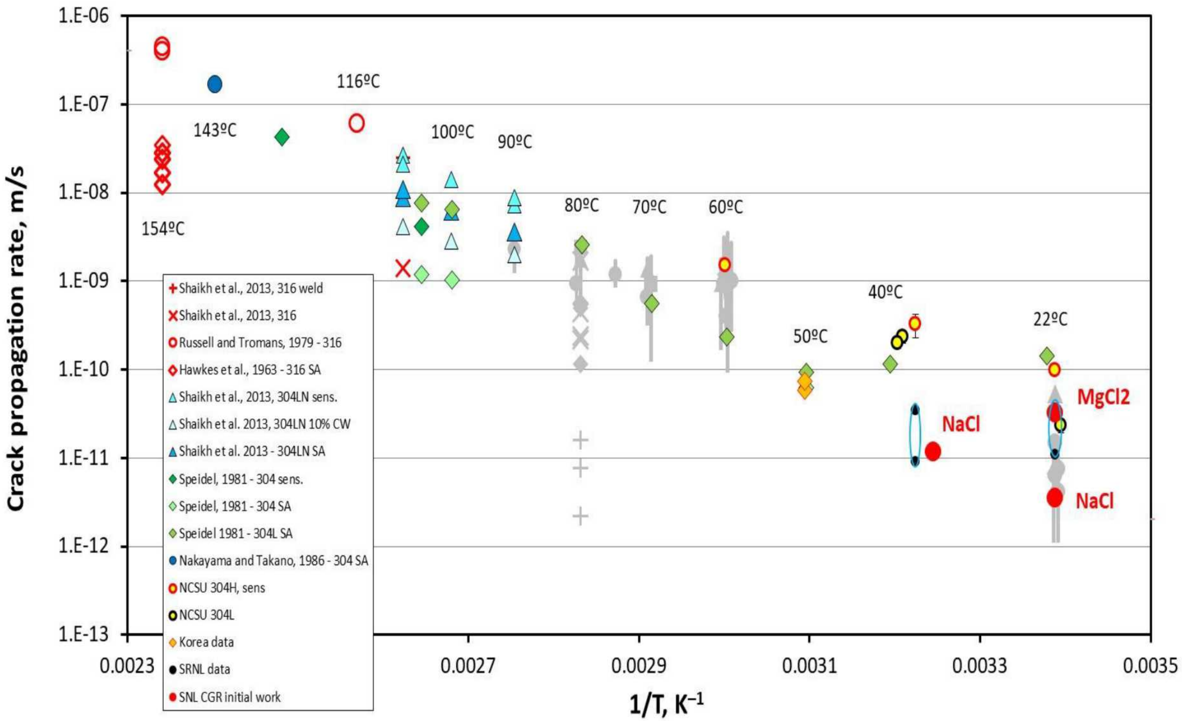
Example: Exposure environment influences max pit size and morphology, thus also possibly affects propensity for sustained crack growth

Corrosion Experimental Work: Damage Distribution and Rates

Pitting, Pit-to-Crack, and CGR

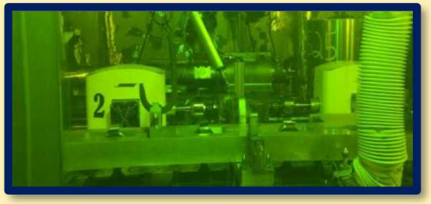
Crack growth rate (CGR):

- Initial: Obtain CGR as a function of full immersion environments
  - Strain rate dependence, K dependence
- Future: Obtain CGR as a function of canister relevant conditions
  - Atmospheric environment dependence
  - Material properties



Example: Initial CGR testing (solid red points) show agreement with historical data, but may also allude to influence of environment on CGR (saturated NaCl vs. $MgCl_2$)

How the Projects Fit Together



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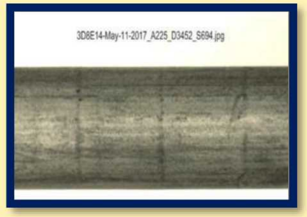

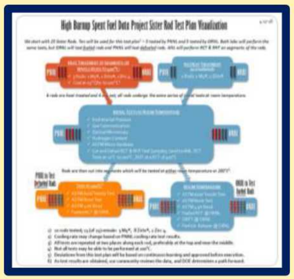

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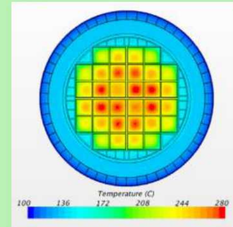

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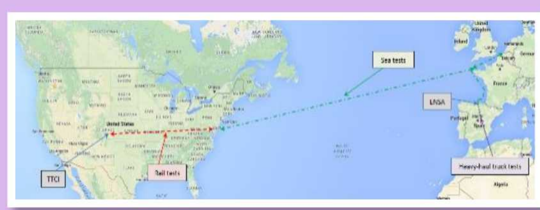

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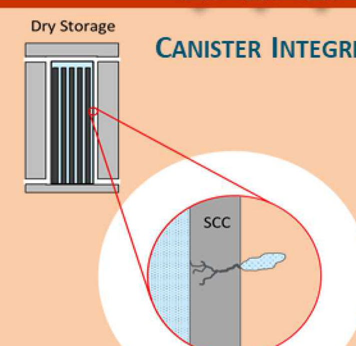
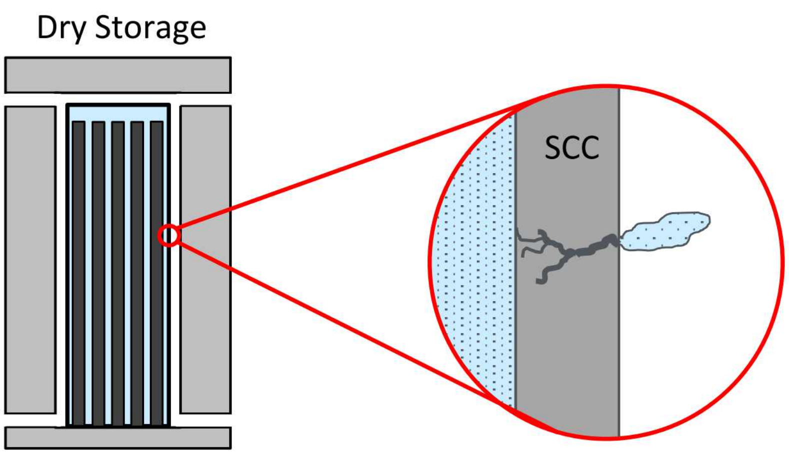
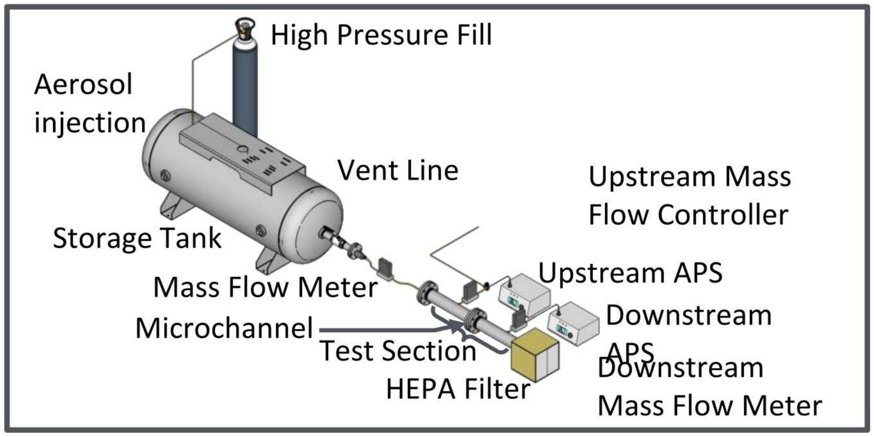


What is the Consequence of a Through-Wall Crack?

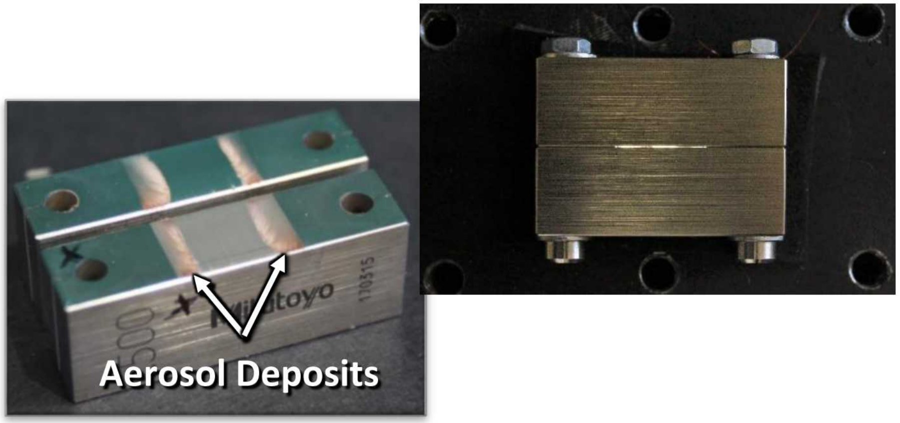


Study system physics with <u>simplified</u> conditions

- Start with slot orifices with SCC-like dimensions
- Non-radioactive surrogates (CeO_2)
- Measure flow rates and pressure drop during blowdown
- Quantify particle density and size distribution both upstream and downstream of “crack”
- *Incorporate knowledge from mechanical testing, such as respirable fraction, overall robustness of fuel rods, and external loads.*



SCC flow test setup



Slot orifice constructed from modified gage blocks after aerosol flow test

Utilize Respirable Fraction Data from Sibling Pin Work

Sibling pin respirable fraction work will be used to obtain more realistic particles for crack consequence testing.

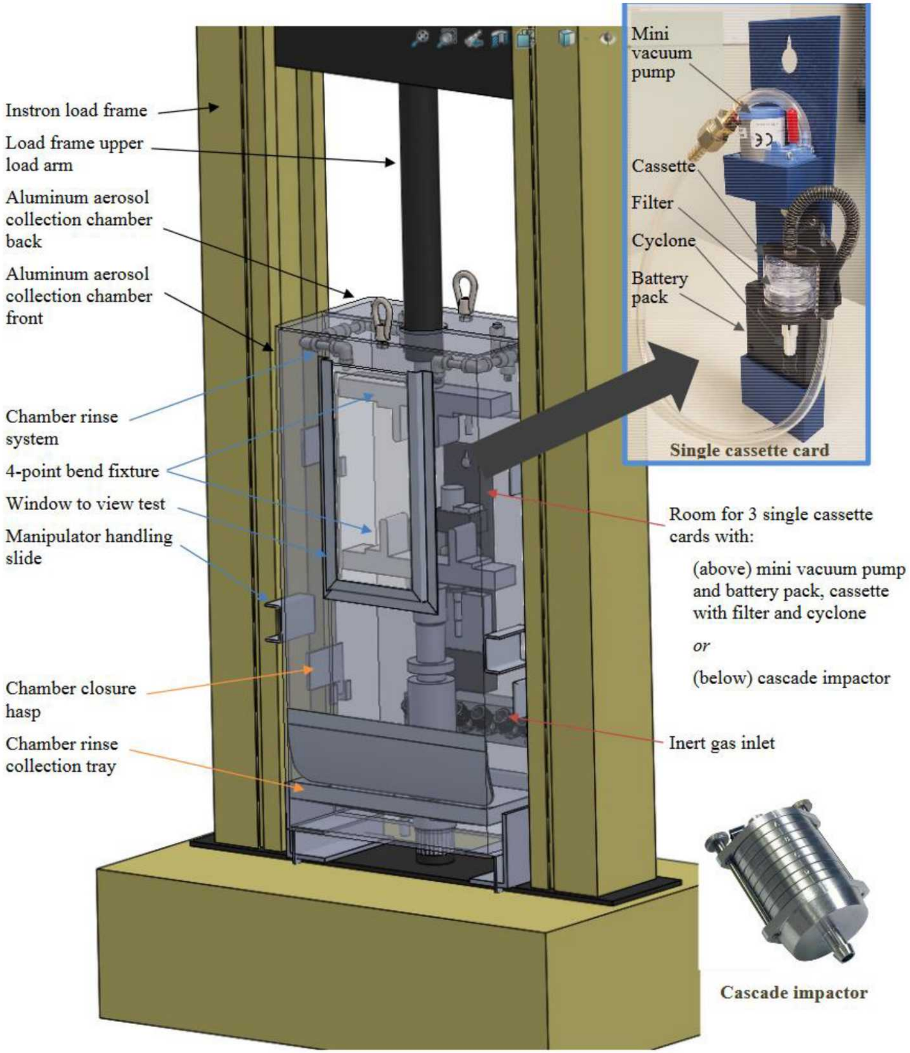


Figure 9. Illustration of the Load Frame Aerosol Collection Chamber with One Cassette Sampling Card Shown.

R&D Focus for SFWST Storage and Transportation

Develop the technical basis for

- Extended storage of used nuclear fuel
  - Will get data on 10-year stored fuel
  - Understanding thermal environment and the mechanical integrity of fuel
  - Understanding canister corrosion, identification of corrosion, and developing mitigation techniques.
- Fuel retrievability and transportation after extended storage
  - Quantifying external loads the fuel and hardware experiences during transportation and comparing that to the mechanical integrity data
- Transportation of high-burnup used nuclear fuel
  - Quantifying external loads the fuel experiences during transportation and comparing that to the demo high-burnup fuel mechanical integrity data

Questions?

Clean. **Reliable. Nuclear.**