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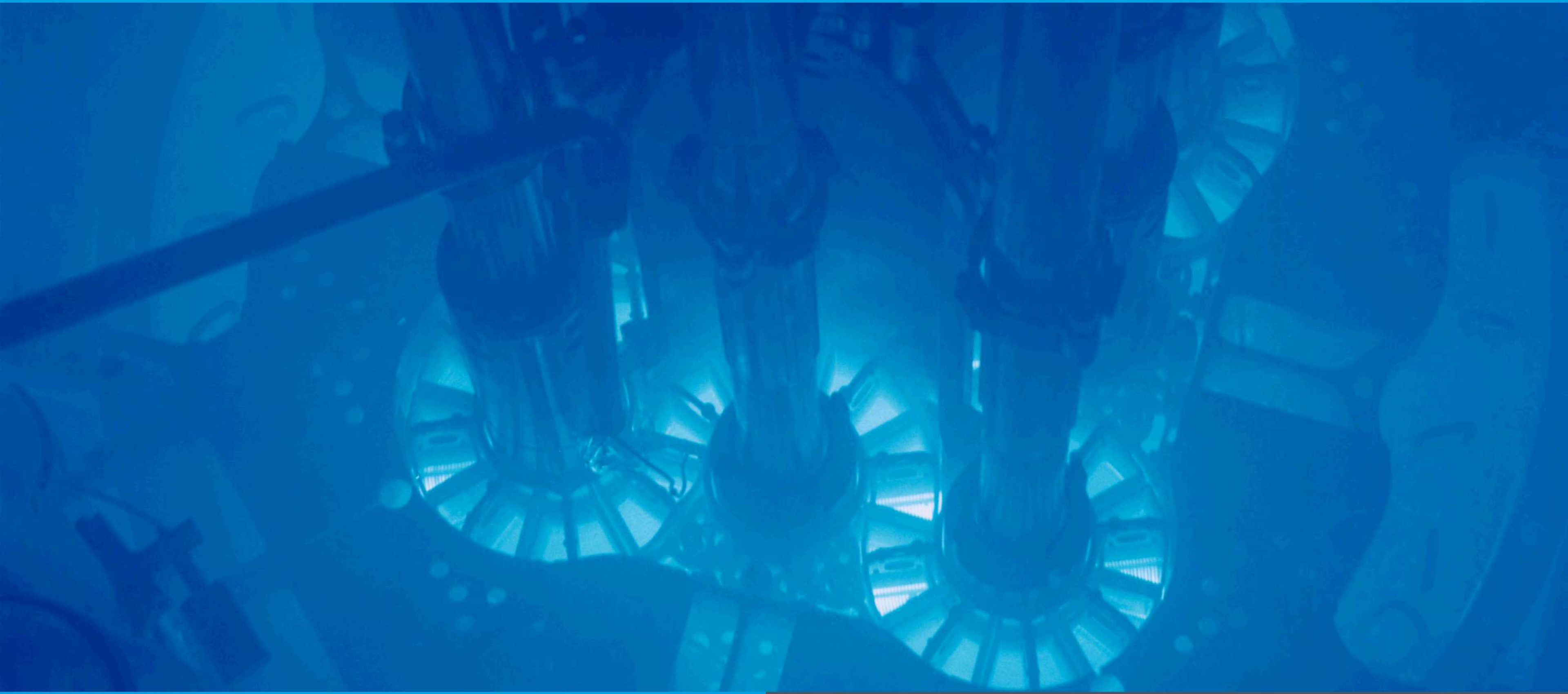

Making the Case: Demonstrating the Integrity of PWR Spent Nuclear Fuel During Long-term Storage and Subsequent Transportation

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DOE/NRC Collaboration and Communication Meeting

NRC White Flint Offices

November 20, 2019

SAND2019-xxxx PE

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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

SSJ1

Thermal Profiles:

The TN-32B Research Project Cask Bounds Most Cask Loadings

	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

Slide 3

SSJ1 the FSAR thermal numers don't match in this and the next slide.
Saltzstein, Sylvia J, 8/1/2019

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 4

SSJ2 Why the question mark? after gaps?
Saltzstein, Sylvia J, 8/1/2019

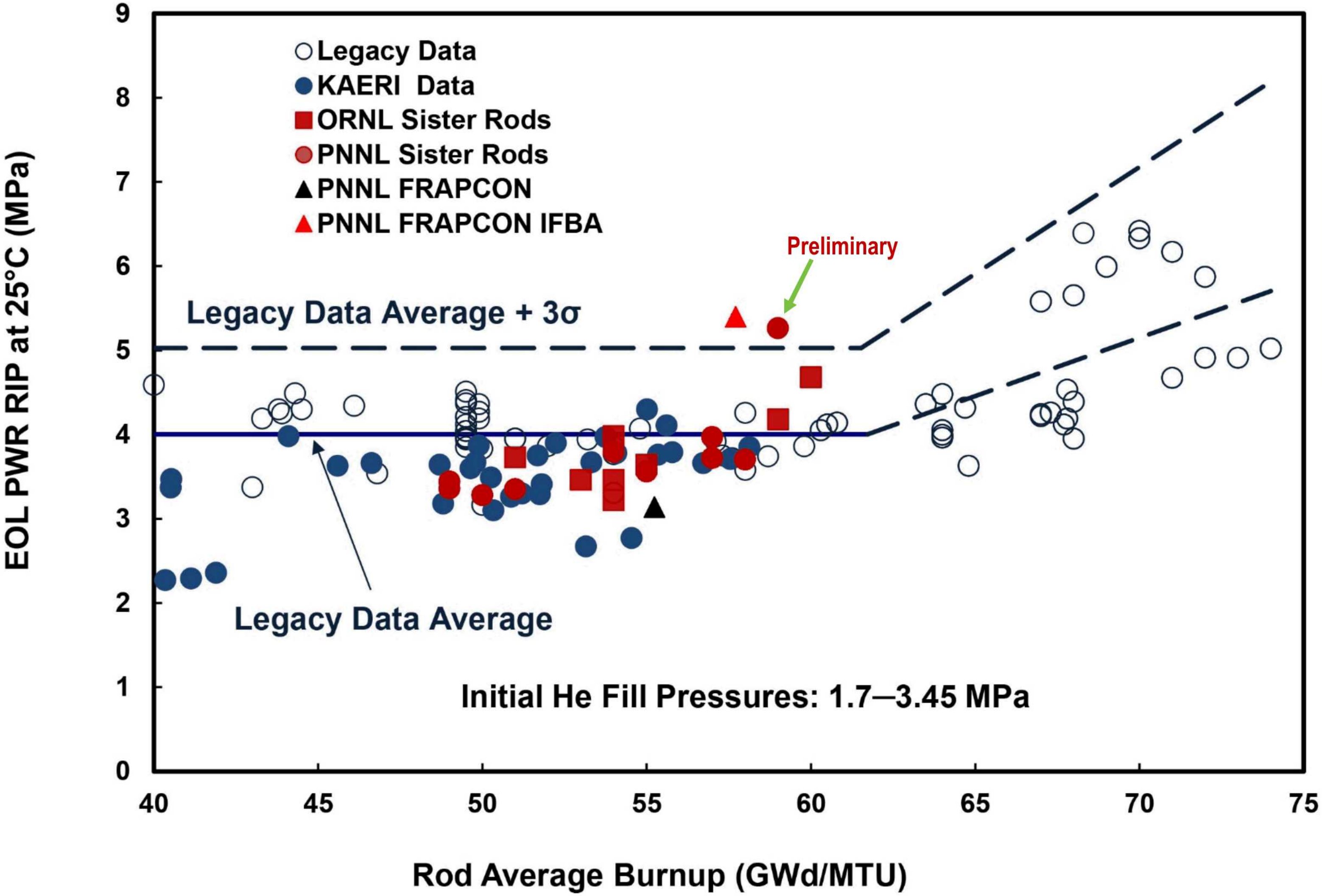
SSJ3 Thisi s for the Demo cask.
Saltzstein, Sylvia J, 8/1/2019

SSJ4 aluminum basket will expand and close gaps, but we don't know by how much.
Saltzstein, Sylvia J, 8/1/2019

SSJ5

Stress Profiles:

When Temperature is Lower, Rod Internal Pressure is Lower (< 5 MPa at 25° C)



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

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

Slide 5

SSJ5 The newer fuels get higher burnup, but the rods are smaller and the inital pressure is lower to begin with.

Saltzstein, Sylvia J, 8/1/2019

Stress Profiles:
Modeled Hoop Stress from Rod Internal Pressure

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

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

Table 3. Maximum Plenum Temperature (all fuel types)

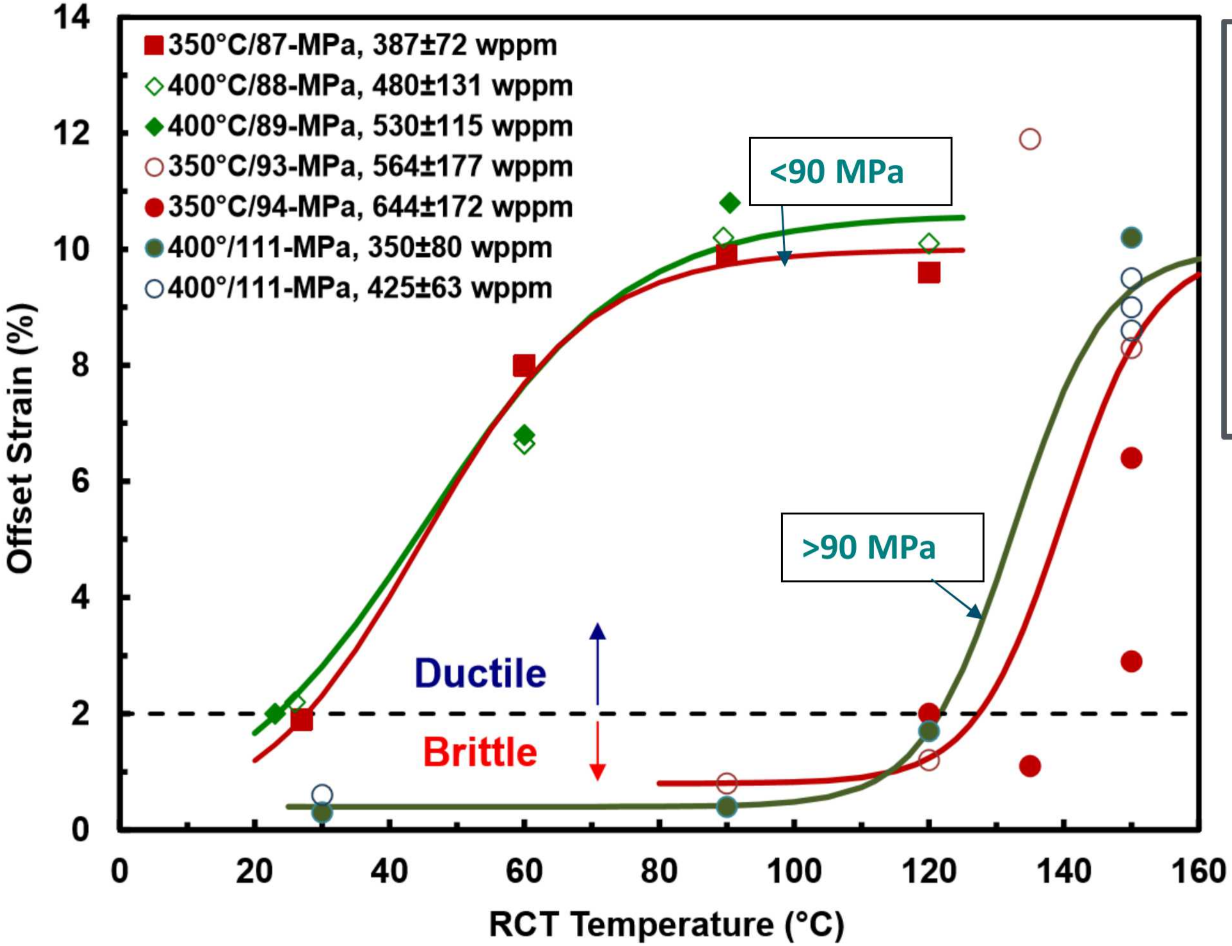
Profile	Temperature (˚C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

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

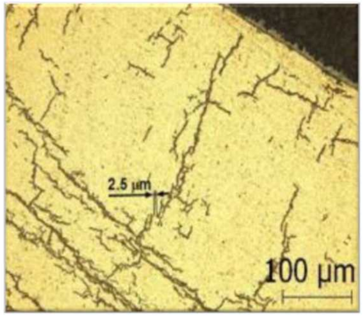
Stress Profiles:

Ductile-Brittle Transition Temperature using Ring Compression Tests (RCT)

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 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.

Mechanical Properties: Summary

The lower PCTs mean:

- Less hydrogen is dissolved in the cladding during the drying process.
  - This means that less hydrogen is available to precipitate into a radial orientation during thermal stabilization
- The RIP is lower.
  - Lower RIP results in lower cladding hoop stress and contributes to less radial hydride formation during the drying process.
- Industry loading of high burnup fuel has margin relative to the 400° C regulatory guidance.

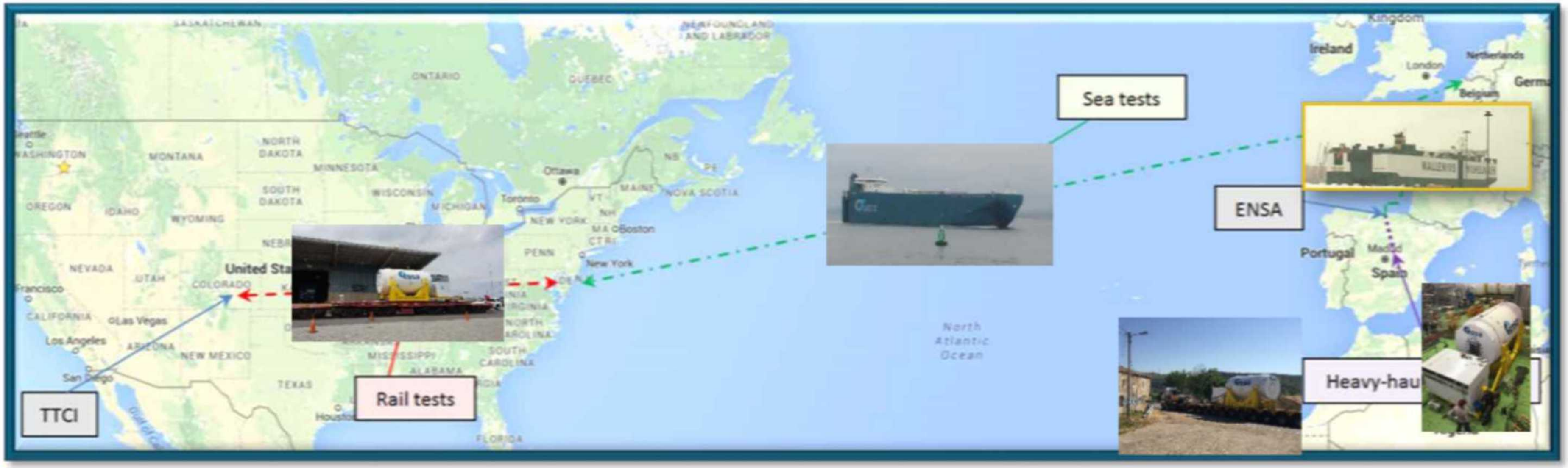
Benchmarking of the PCT data from the Research Project Cask supports the ability to model other dry storage systems without having to perform testing for each specific vertical design.

What are Realistic Mechanical Loads?

- most mechanical loads occur during transportation

Mechanical Loading:

Multimodal Transportation and Handling Tests



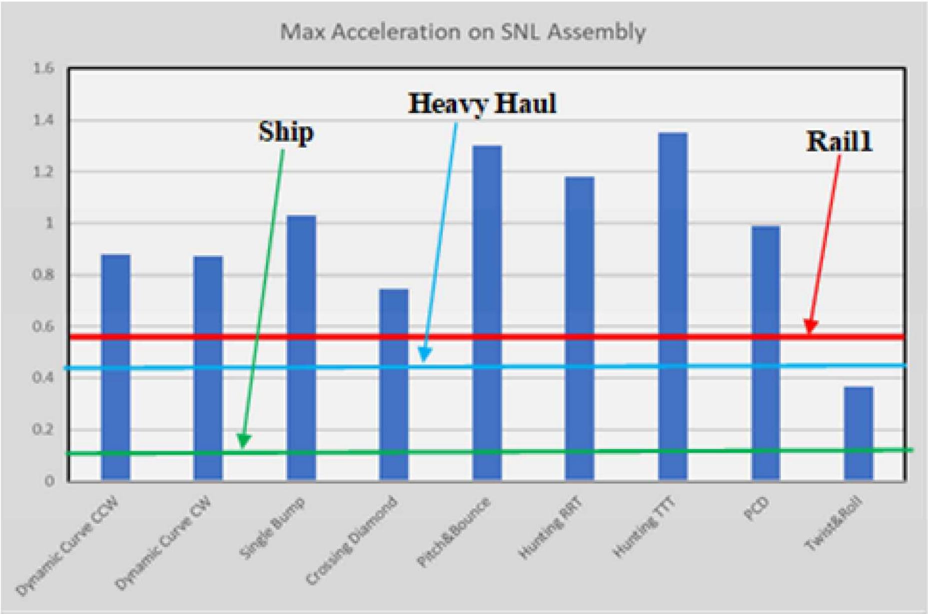
Photos provided by Steve Ross, PNNL

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**

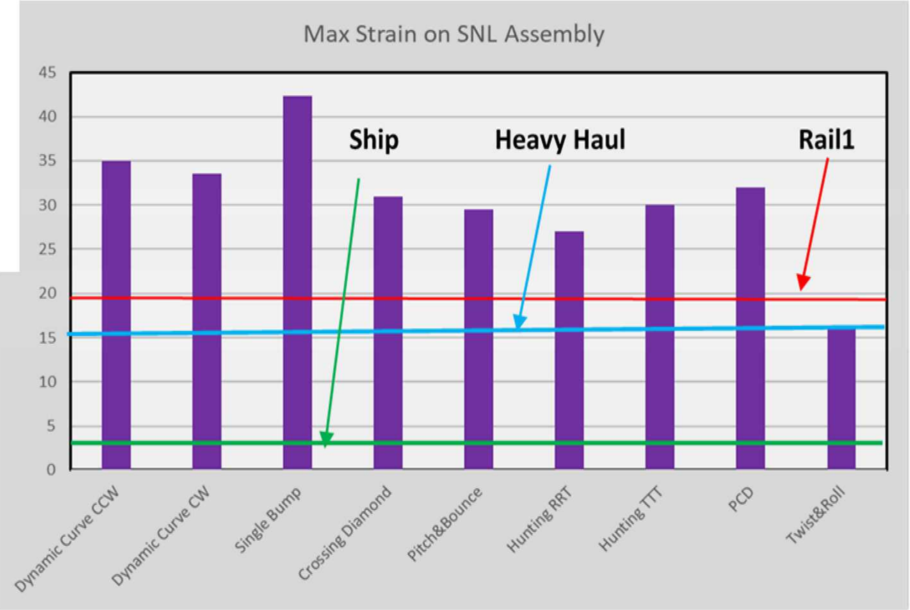
Data was collected throughout all legs of the transport as well as the transfers between legs.

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:

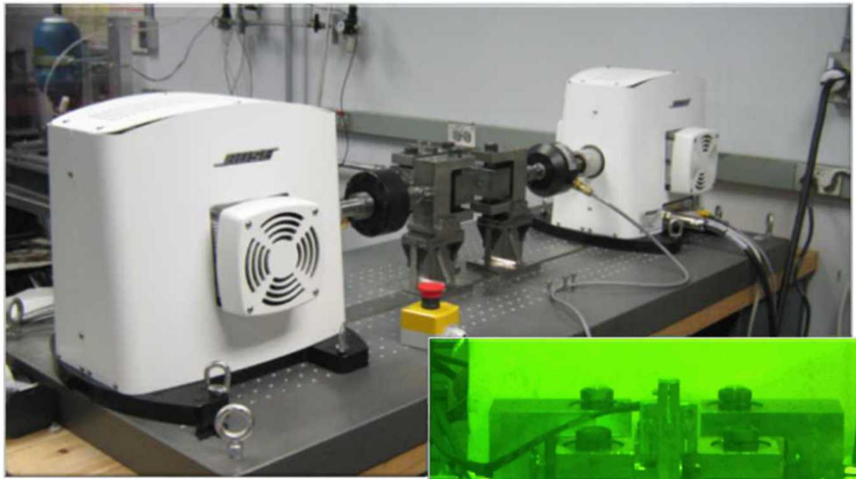
Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) tests fatigue to failure

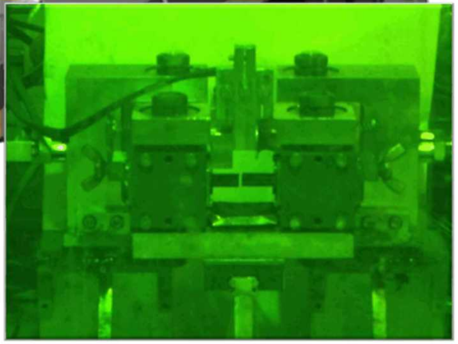
Goal: To determine the number of cycles to fatigue failure as a function of rod curvature and cladding stress and strain

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

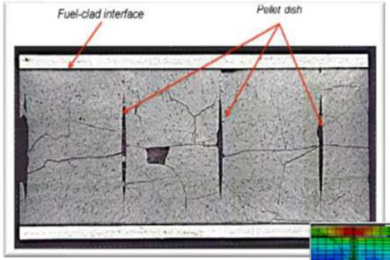
  Fatigue life depends on the level of loading
- Pellet-clad and pellet-pellet bonding provides additional stiffness

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.

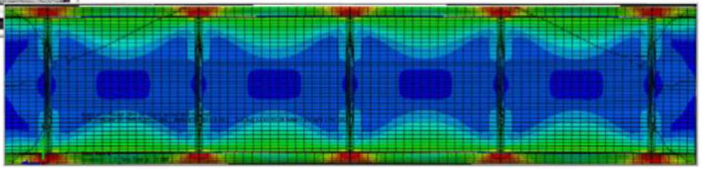




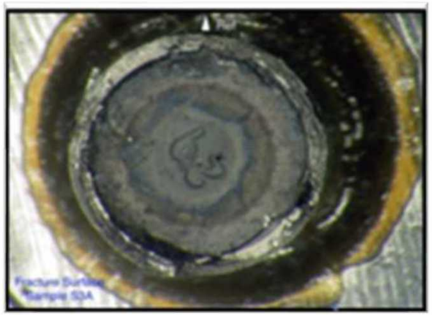
CIRFT tester out of the hot cell (above) and in the hot cell (right) testing High-Burnup Fuel samples.



Pellet Clad Bond and resultant stress distribution



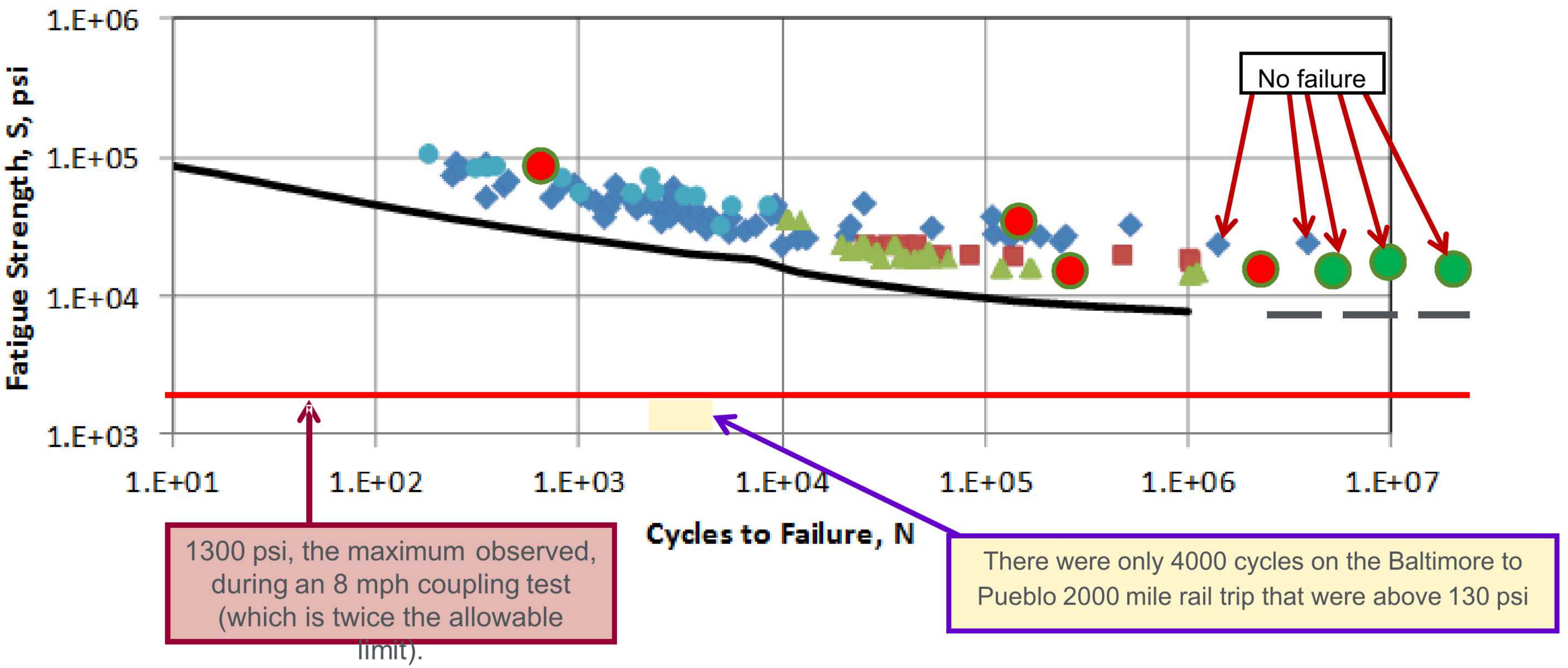
Images courtesy of ORNL.



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)

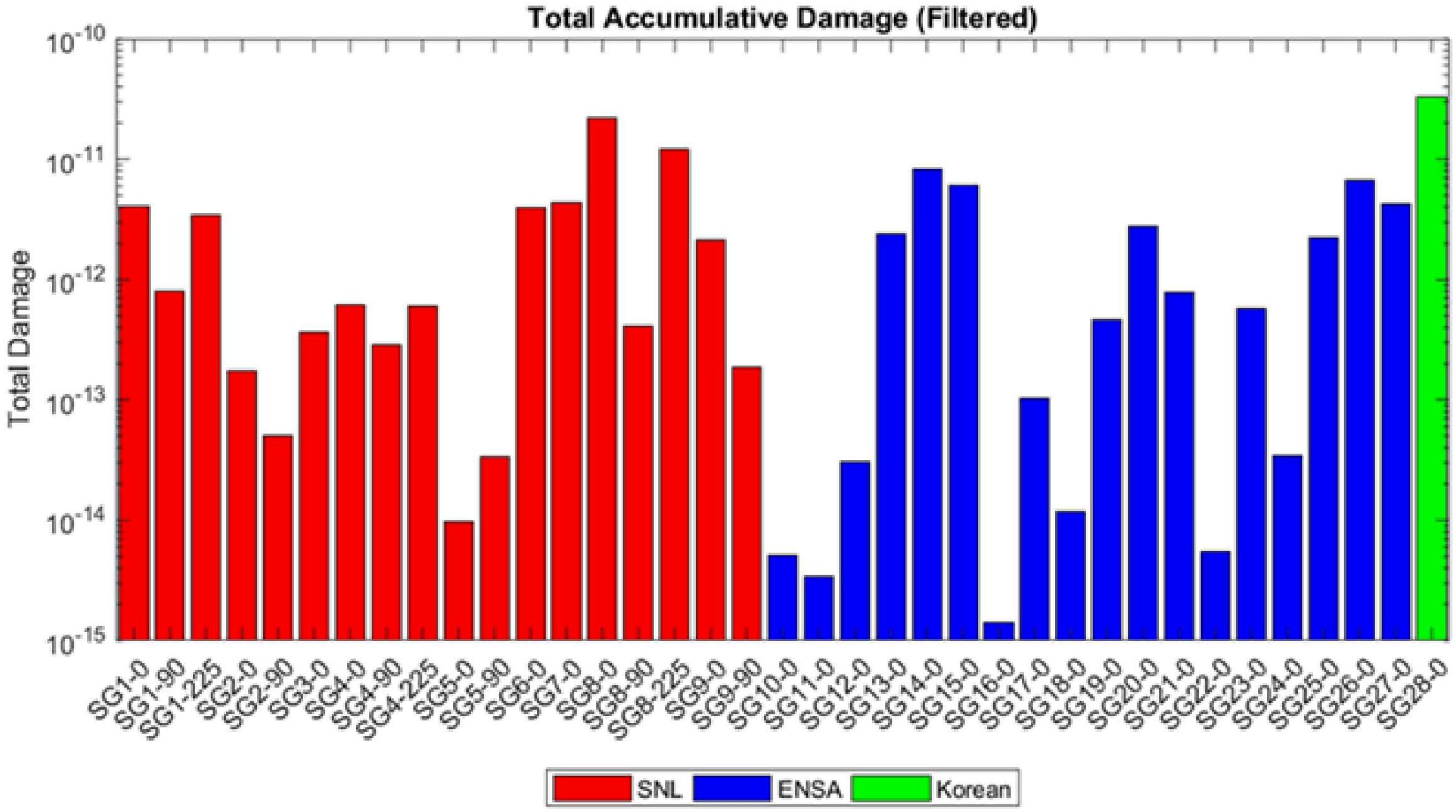
J-A Wang et. al. Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications, NUREG/CR-7198/R1 ORNL/TM-2016/689, Oak Ridge National Laboratory, January 2017.

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.

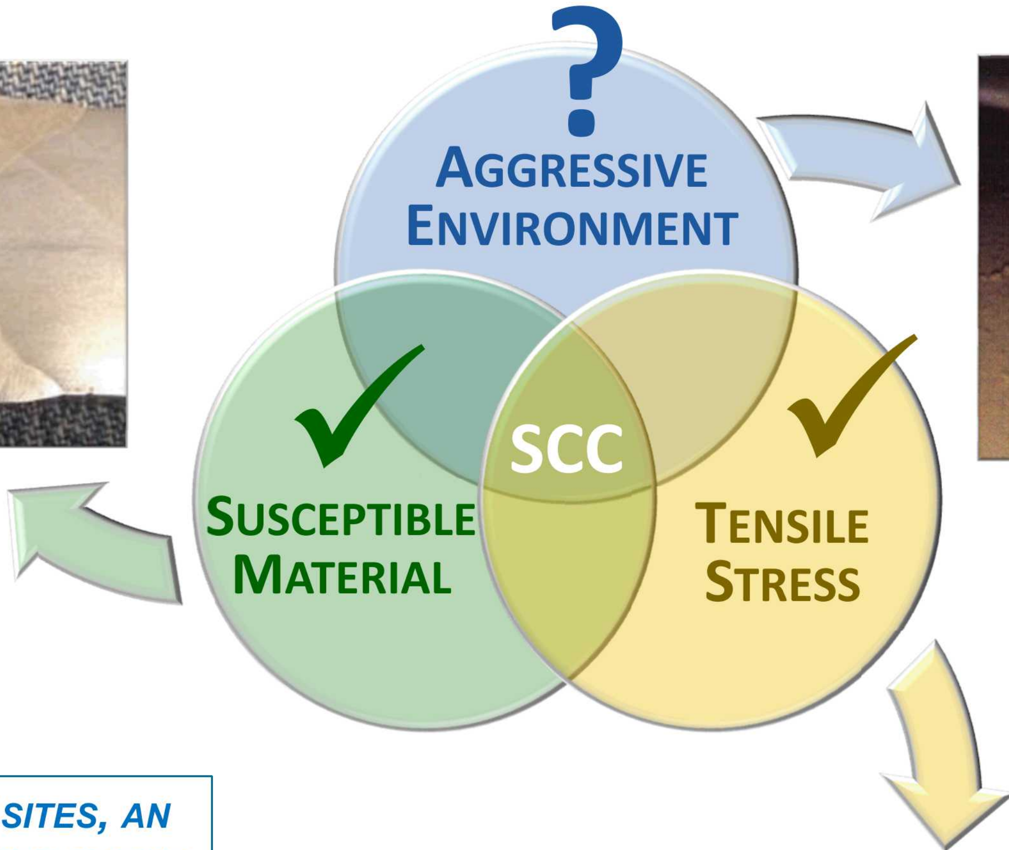
Klymyshyn N.A.et al. 2018. Modeling and Analysis of the ENSA/DOE Multimodal Transportation Campaign. 2018. PNNL-28088. Richland, WA: Pacific Northwest National Laboratory.

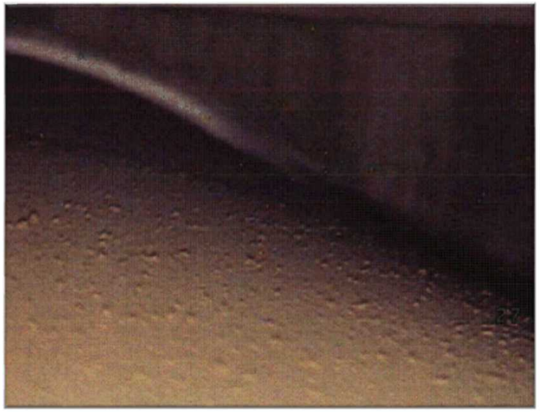
Developing a Model to Assess Risks in Canister Integrity

Atmospheric Stress Corrosion Cracking:

SCC Requires 3 Concurrent Conditions

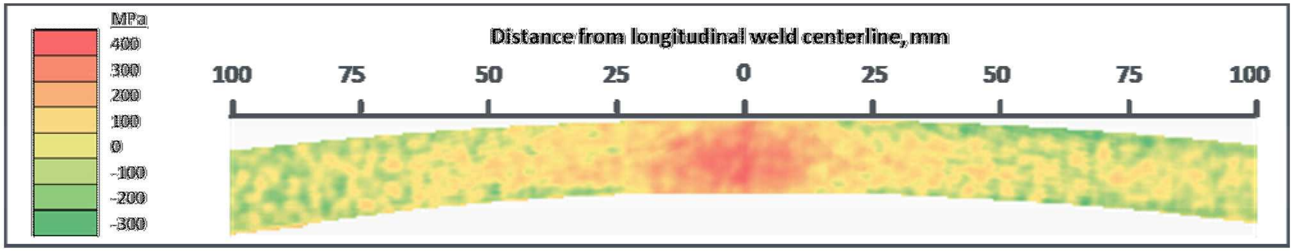
Photo of canister weld. Photo: SNL





Dust on canister surface at Calvert Cliffs (EPRI 2014)

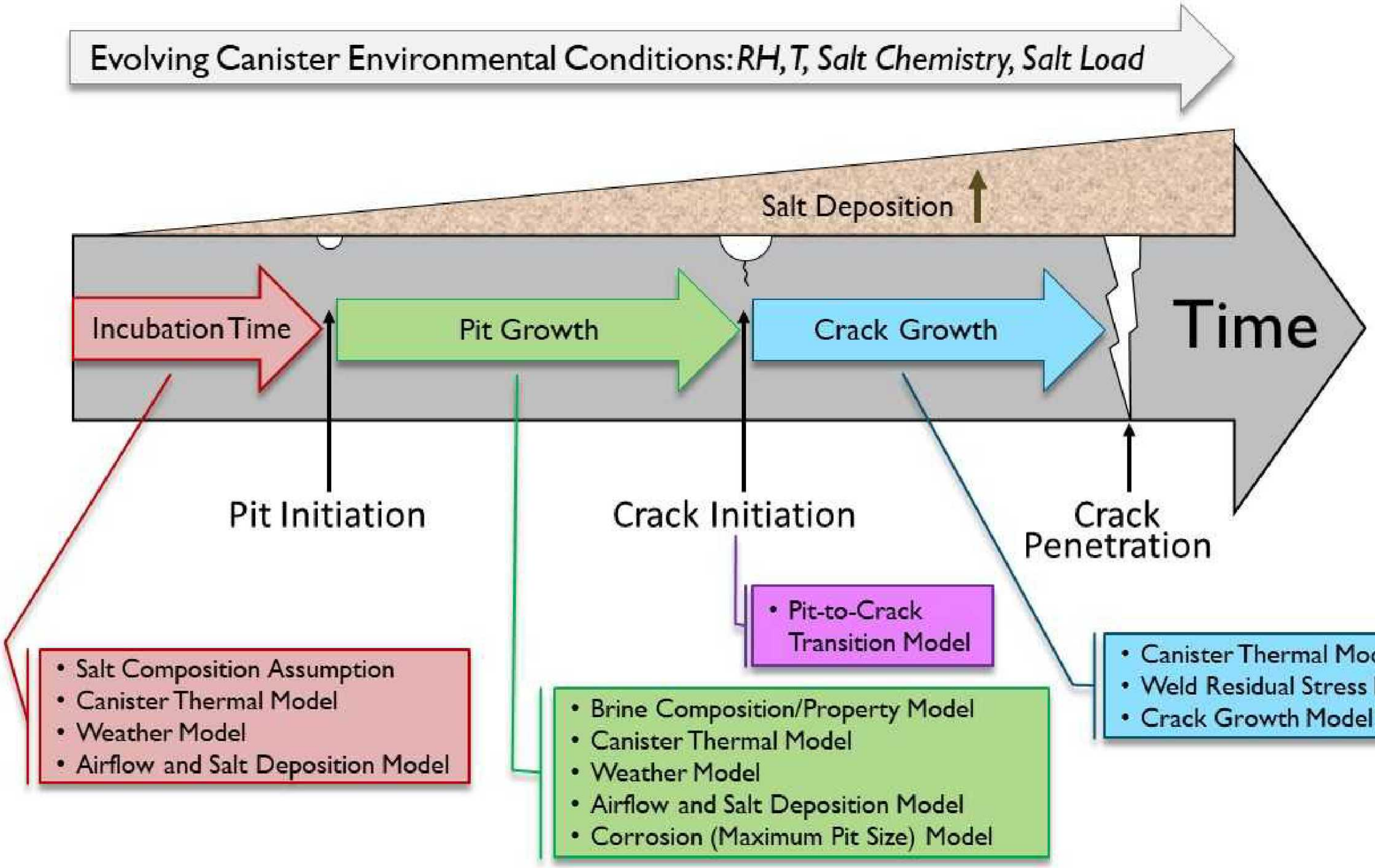
Weld residual stresses measured on SNL mockup



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

Atmospheric SCC of Dry Storage Canisters:

SNL Integrated Mechanistic/Probabilistic Model for Canister SCC

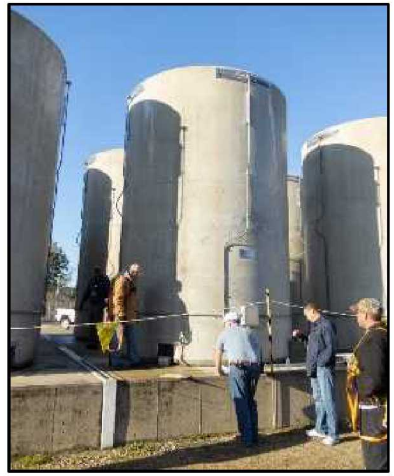


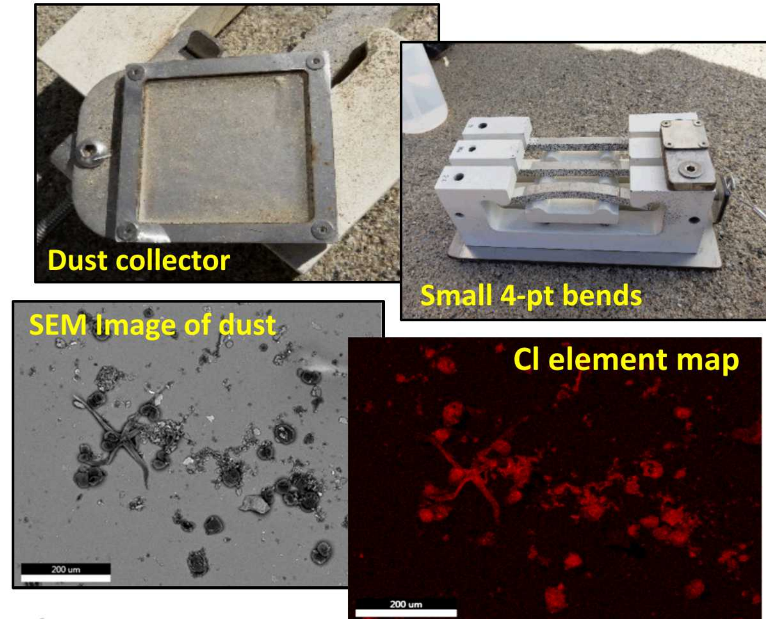
Goal: Improve ability to predict timing and location of potential canister penetration by SCC cracks

Canister Surface Environment:
Determine Brine Compositions and Evolution with Time

1) Dust sampling: Maine Yankee ISFSI, Oct. 2019

- Samples placed in 4 overpacks in 2017
- 8 Dust collectors sampled and replaced
- Corrosion test specimens examined (different loads and surface finishes)





2) Experimental Evaluation of Brine Stability and Evolution

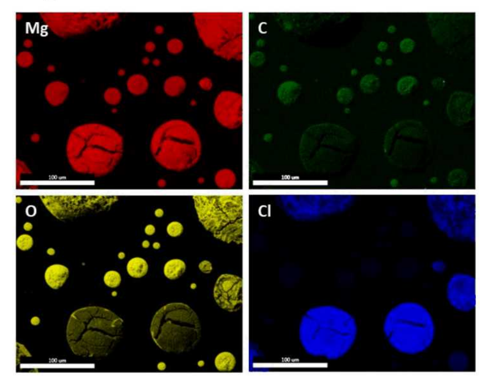
Mg-chloride brine stability at elevated temperatures:

- Experimental testing indicates chloride loss, conversion to less-deliquescent salts (dry-out?)
- Mg-hydroxychlorides (observed experimentally)
- Reactions controls deliquescence RH, brine composition & properties

Current Experiments in the Lab:

- Degassing tests at higher air flow and realistic humidities for longer duration
- *Characterization of Mg-hydroxychlorides*

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



SNL Corrosion Studies

Pitting, pit-to-crack transition, and crack growth

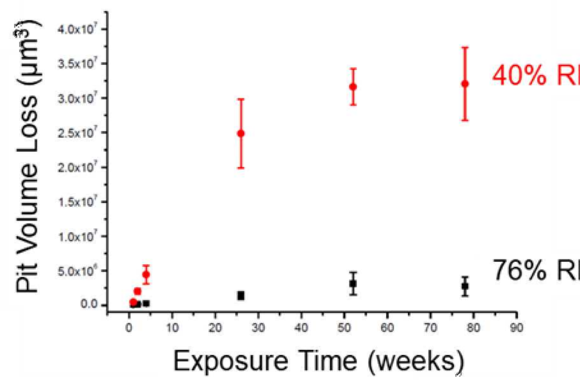
PRIMARY FOCUSES:

- Determine the relationship between surface environment and damage distributions/rates
- Determine the effects of material condition (microstructure, stress) on corrosion distributions/rates

PITTING EXPERIMENTS: LONG TERM EXPOSURE IN CANISTER-RELEVANT CONDITIONS

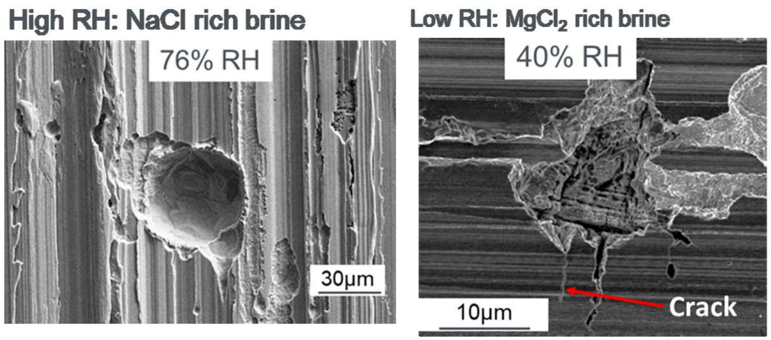
- Generating statistical pitting damage sets as a function of environment and material properties

Statistical Pitting Damage Sets



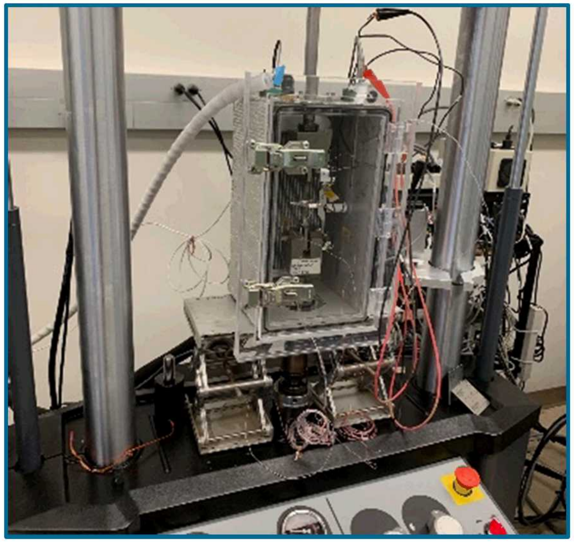
- Material condition and environment govern pit morphology, possibly increasing cracking susceptibility

Pitting *f*(environment)

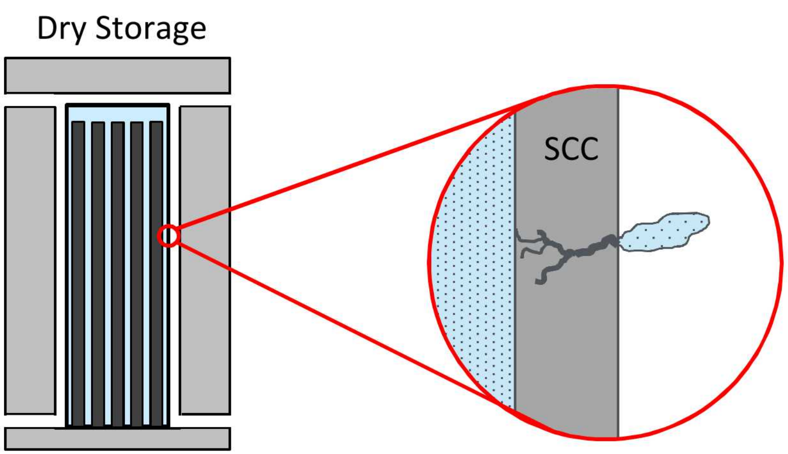


SCC TESTING:

- High-fidelity fracture mechanics testing of pit-to-crack transition and crack growth rate
- Development and interpretation requires knowledge of:
  - Brine Evolution
  - Corrosion damage *f*(environment and material condition)

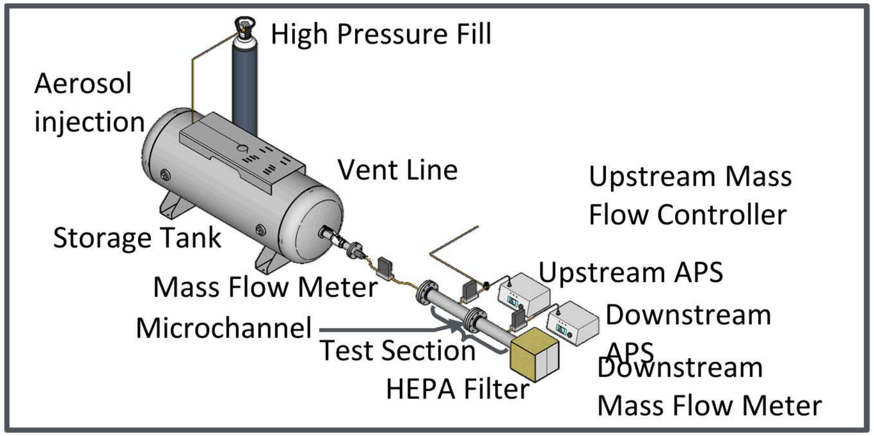


What is the Consequence of a Through-Wall Crack?

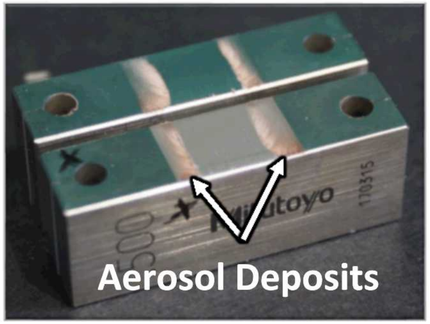


Study system physics with simplified conditions

- 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

Conclusions

- Models can accurately predict cask and component temperatures when accurate inputs are provided.
  - Future work will benchmark models to horizontal dry storage systems data.
- Measured PCT (229ºC) from the demonstration cask were far below the regulatory threshold of 400ºC.
  - Limits amount of hydrogen that is available to reorient in the radial position during drying
  - Reduces the rod internal pressure and the hoop stress
- Ring Compression Tests show that cladding operating in representative storage environments will behave in a ductile fashion.
  - Upper bound tests at 90 MPa and 400ºC were well above the demonstration cask values of 50 MPa and 229ºC .
- Estimated stresses from measured mechanical loads are far below yield stress levels and fatigue limits of high burnup spent nuclear fuel.
- Canister Stress Corrosion Cracking is a risk, so consequence needs to be determined.

With the data that is currently available and using the integrated approach, cladding integrity will not be challenged during extended storage and normal conditions of transport.

Yet, extended storage is not a final solution. Deep Geologic Disposal is still required.

Conclusions

- Models can accurately predict cask and component temperatures when accurate inputs are provided.
  - Future work will benchmark models to horizontal dry storage systems data.
- Measured PCT (229ºC) from the demonstration cask were far below the regulatory threshold of 400ºC.
  - Limits amount of hydrogen that is available to reorient in the radial position during drying
  - Since the PCT is lower, the rod internal pressure and associated hoop stress are lower
- Ring Compression Tests show that cladding operating in representative storage environments will behave in a ductile fashion.
  - Upper bound tests at 90 MPa and 400ºC were well above the demonstration cask values of 50 MPa and 229ºC .
- Estimated stresses from measured mechanical loads are far below yield stress levels and fatigue limits of high burnup spent nuclear fuel.

With the data that is currently available and using the integrated approach, cladding integrity will not be challenged during extended storage and normal conditions of transport.

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Questions?

Clean. **Reliable. Nuclear.**