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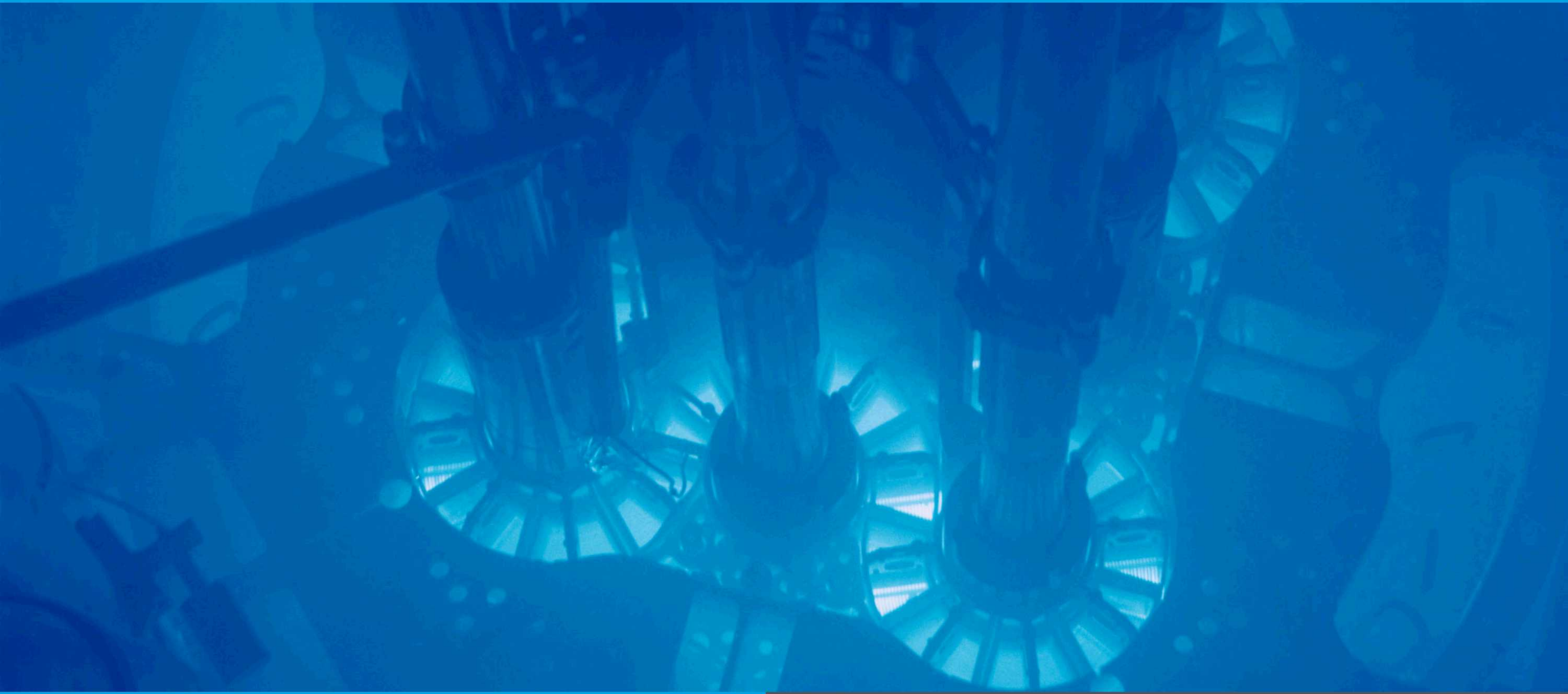
SAND2019-9116C ar.

Spent Fuel and Waste Science and Technology (SFWST)



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

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PATRAM 2019

New Orleans, Louisiana
August 4-9, 2019

SAND2019-8750 C

Campaign Strategic Focus: Storage and Transportation R&D

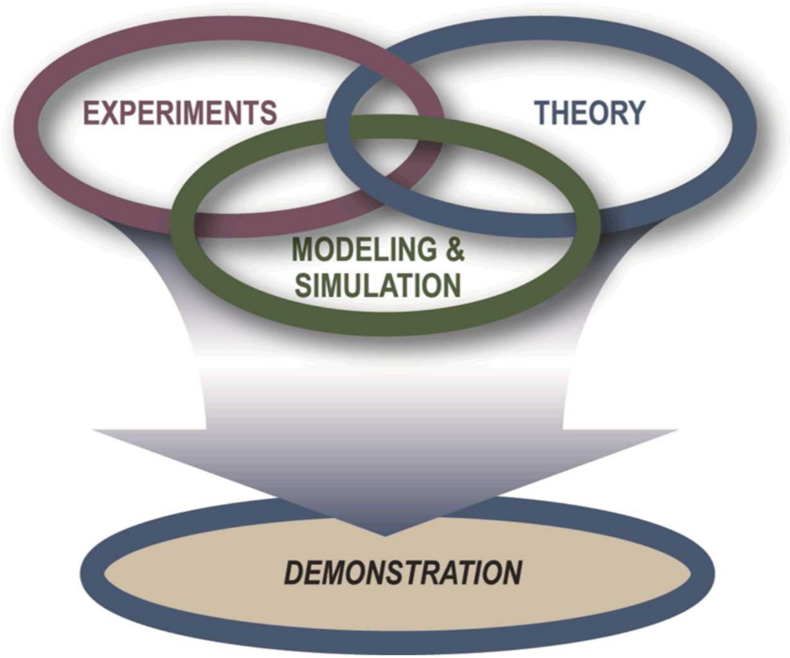
- Prepare for extended storage and eventual large-scale transport of spent nuclear fuel and high-level waste
- Support the technical basis for evaluating:
  - Extended storage of spent nuclear fuel
  - Fuel retrievability and transportation after extended storage
  - Transportation of high-burnup spent nuclear fuel

Presentation Objective

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

Collaboration Leverages Research Dollars –
Enables Diversity of Perspectives, Skills, & Ideas

Technical Direction



Partnerships

- **Industry**
  - Utilities – EPRI, 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**
  - More than 18 universities, numerous students and professors are involved ($27M)
- **Nuclear Regulatory Commission**
  - Jointly fund research when appropriate
  - Continue some testing NRC began
- **International – ESCP**
  - Extended Storage Collaboration Program

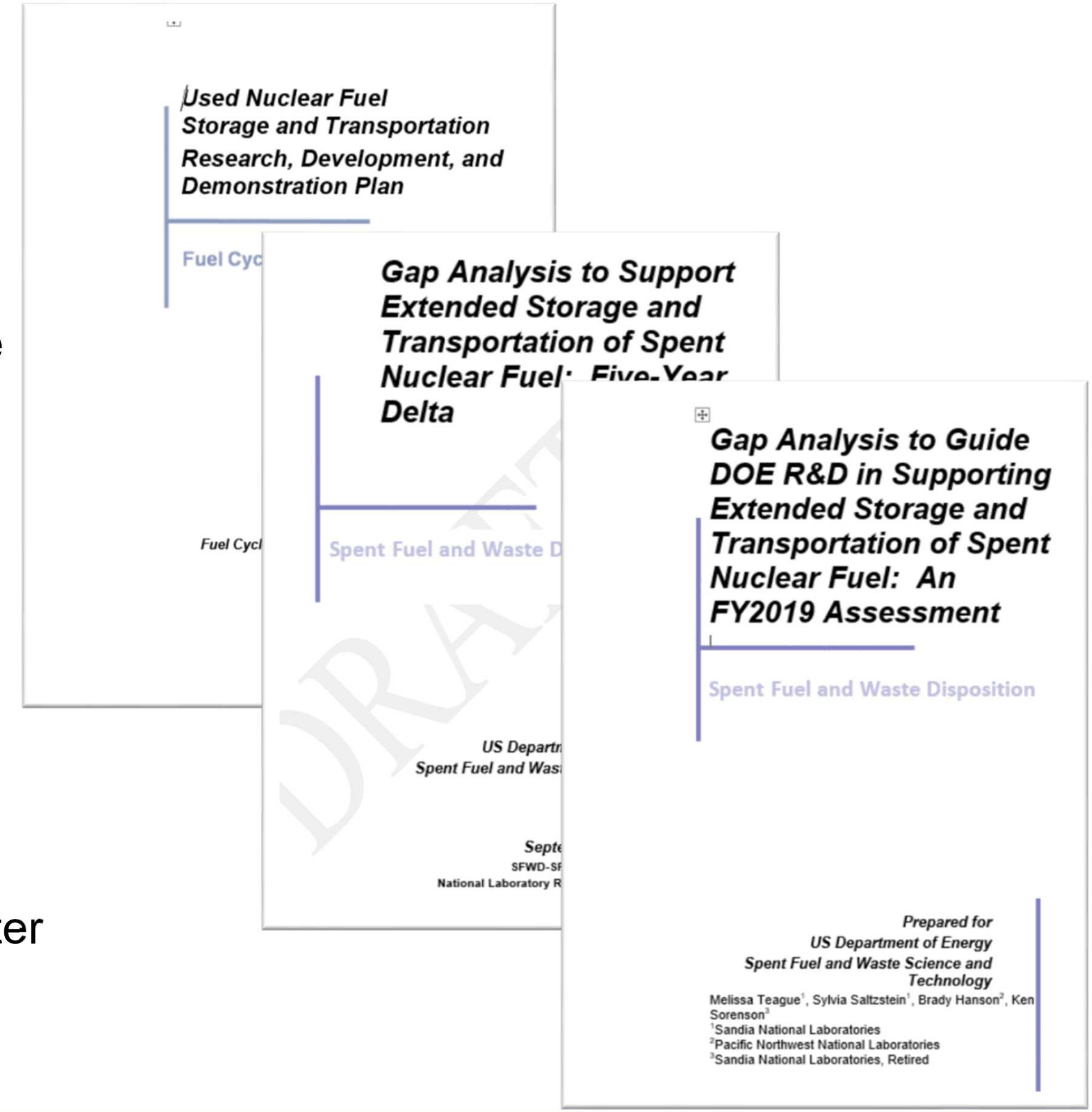
SJS4

R&D Guided by Peer-Reviewed Gap Analyses

Guides how we allocate our budget

Identifies R&D priorities

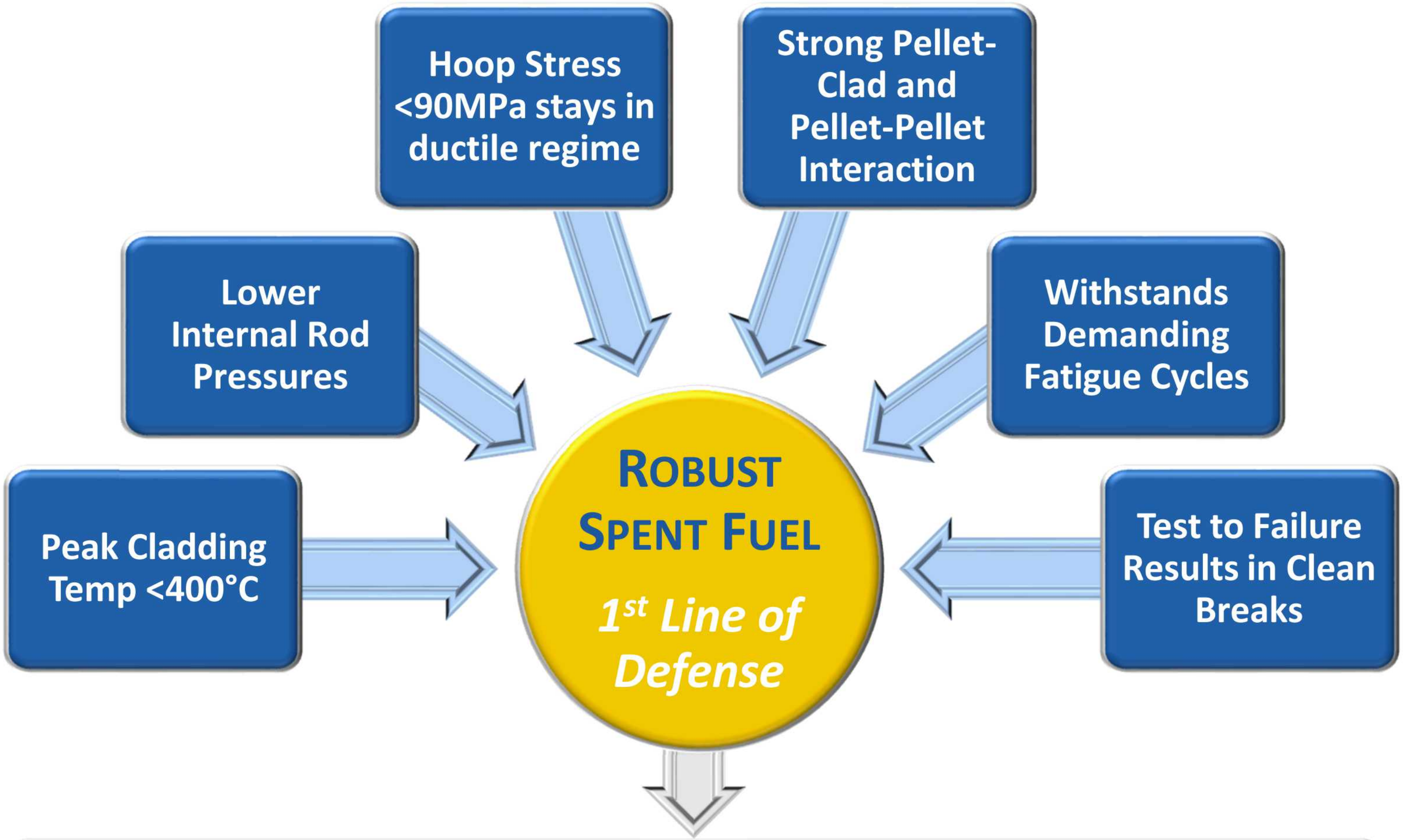
- 2012
  - Thermal Profiles
  - Stress Profiles
  - H2 Effects: hydride reorientation and embrittlement
- 2017
  - Thermal Profiles
  - Stress Profiles
- 2019
  - Thermal Profiles
  - Stress Profiles
  - Atmospheric Canister Corrosion



Slide 4

SJS4 May want to state that this document was used to direct how we spent the FY18 appropriation.
Ho Family, 4/16/2018

Focused R&D Plan has Allowed the Program to Show Robustness of the Fuel and the DPC System



Realistic stresses fuel experiences due to vibration and shock during normal transportation is below yield and fatigue limits for cladding

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	328°C	348°C

Photo courtesy of Dominion Energy

Slide 7

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 8

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

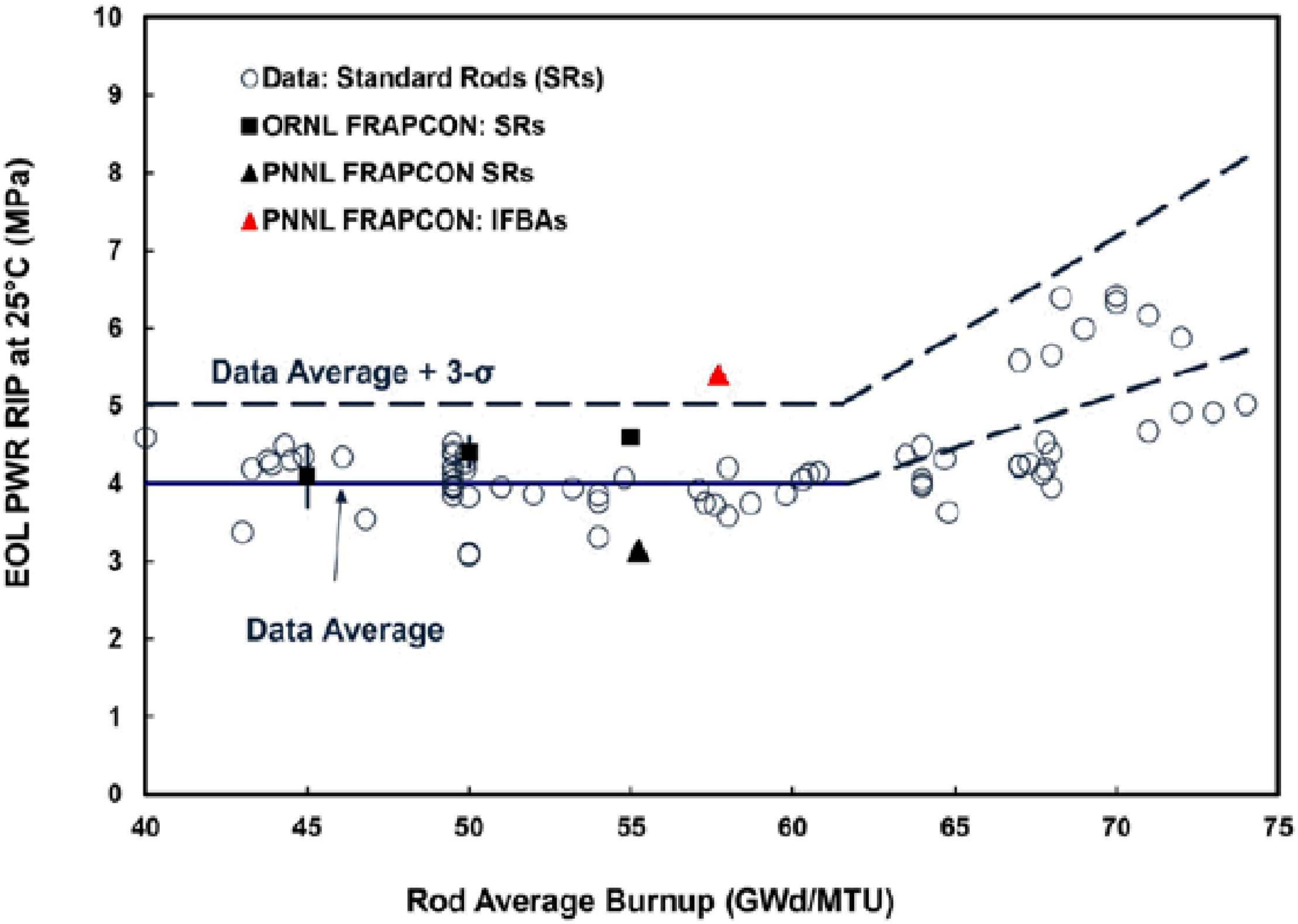
SSJ3 Thisi s for the Demo cask.
Saltzstein, Sylvia J, 8/1/2019

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)



Demo Sibling Pin Rod Internal Pressure measurements are consistent with this data.

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

Slide 9

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

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)

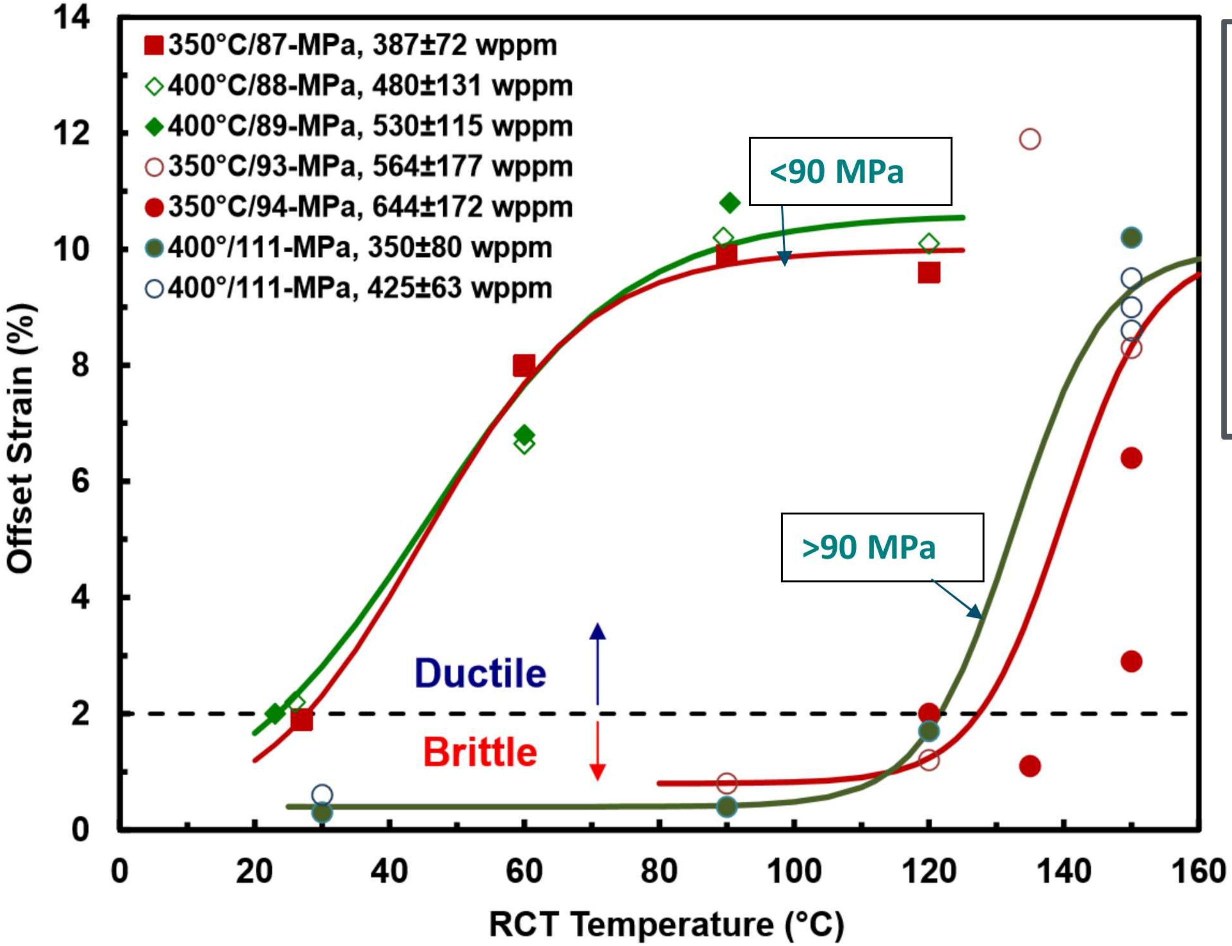
Profile	Temperature (˚C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

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

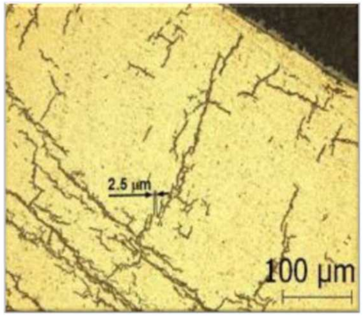
Stress Profiles:

Ductile-Brittle Transition Temperature using Ring Compression Tests

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 thereby reducing the ductile-to-brittle transition effects on the cladding.
- 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?

Mechanical Loading:
Multimodal Transportation and Handling Tests

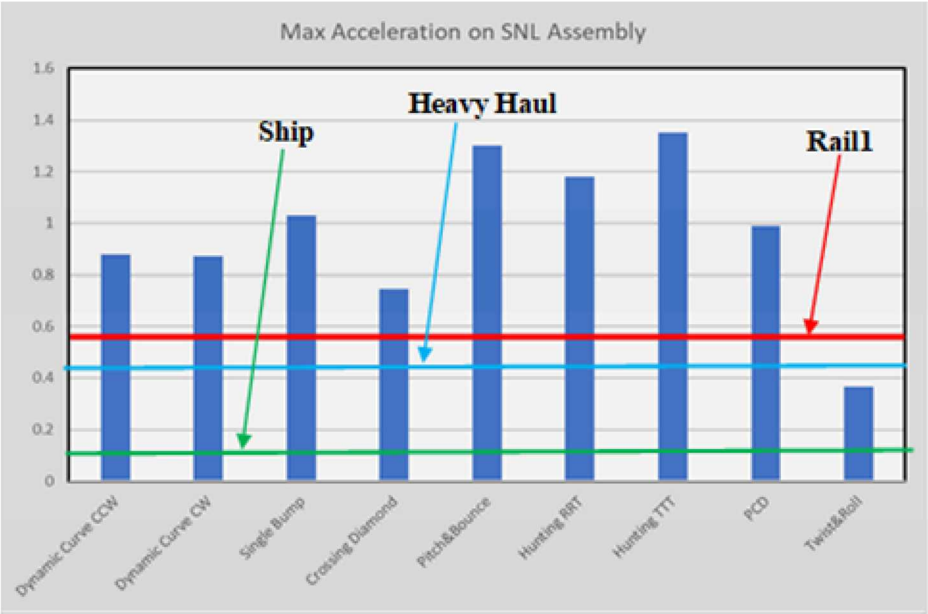
Photos provided by Steve Ross, PNNL

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**

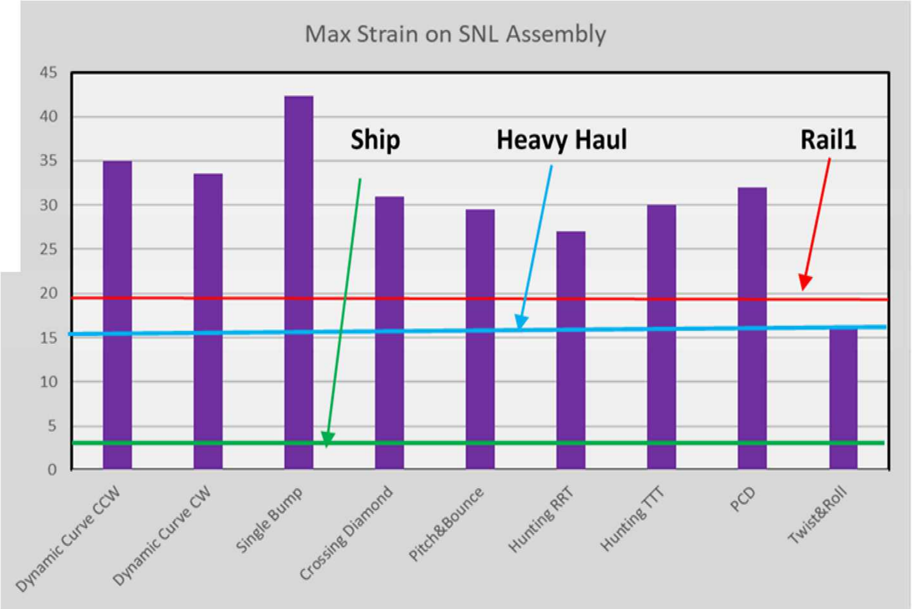
Data was collected throughout all legs of the transport as well as the transfers between legs.

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:

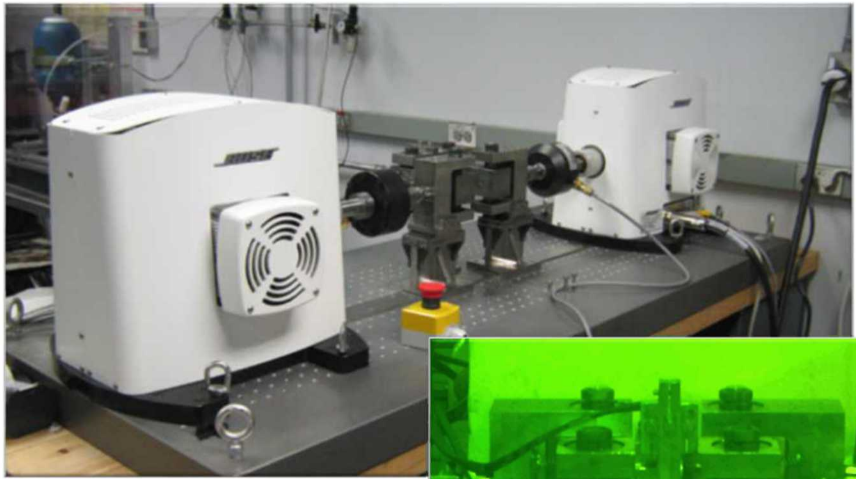
Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) tests fatigue to failure

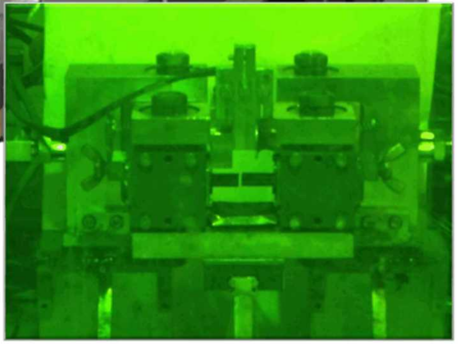
Goal: Determine the load, curvature, # of cycles for failure

- Both static bending and cyclic fatigue
  - Developed at ORNL under an NRC program
- Fatigue life depends on the level of loading

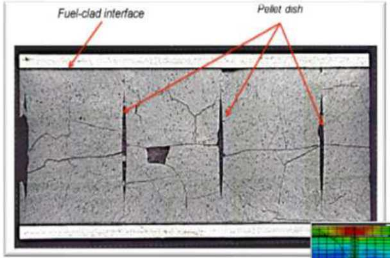
- Pellet-clad and pellet-pellet bonding provides additional stiffness

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.

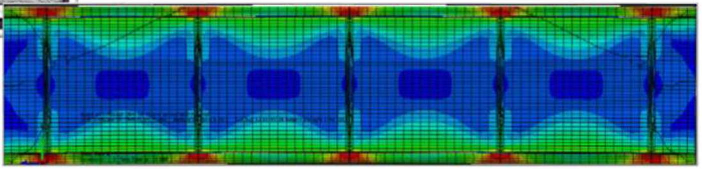


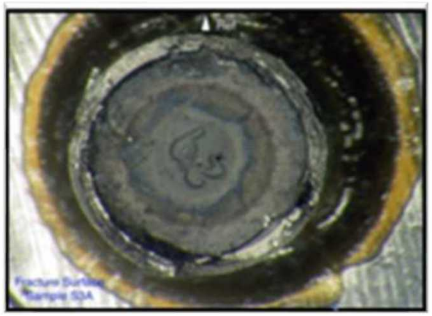


CIRFT tester out of the hot cell (above) and in the hot cell (right) testing High-Burnup Fuel samples.



Pellet Clad Bond and resultant stress distribution



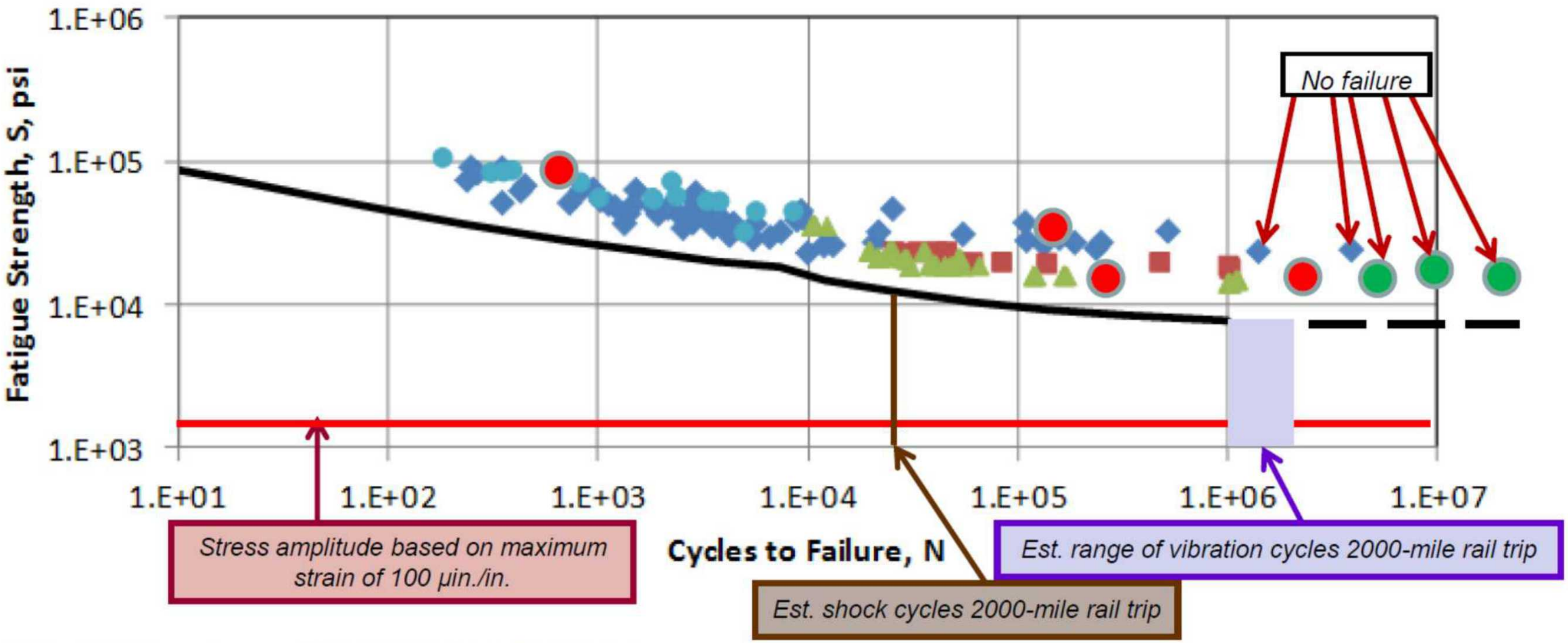


Most rods break cleanly between two pellets.

Images courtesy of ORNL.

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)

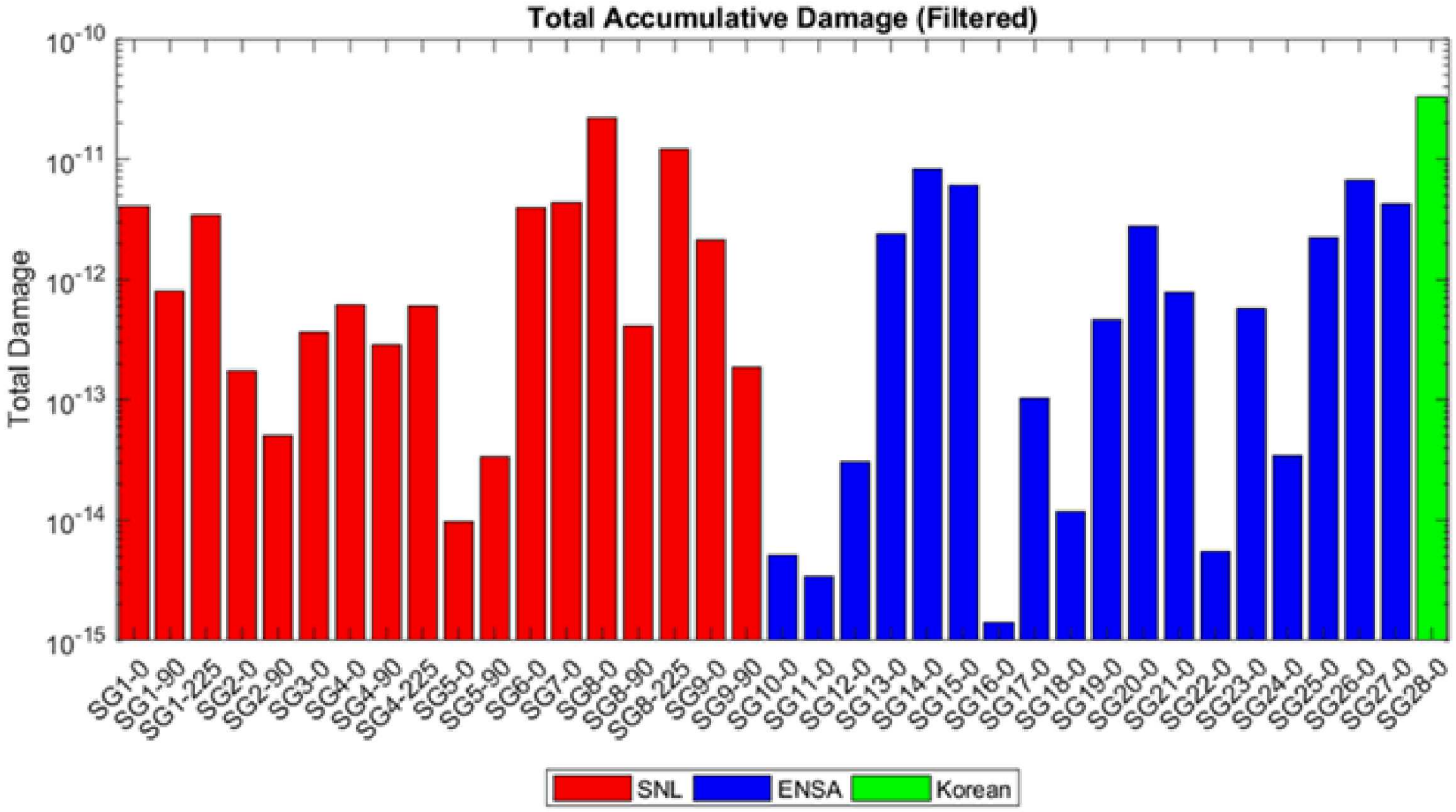
Data plot courtesy of Ken Geelhood, PNNL
The large circles are ORNL HBR data

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.

- **Large red and green circles represent CIRFT data.**
- **Horizontal red line represents highest recorded stress value from the muiltimodal 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)



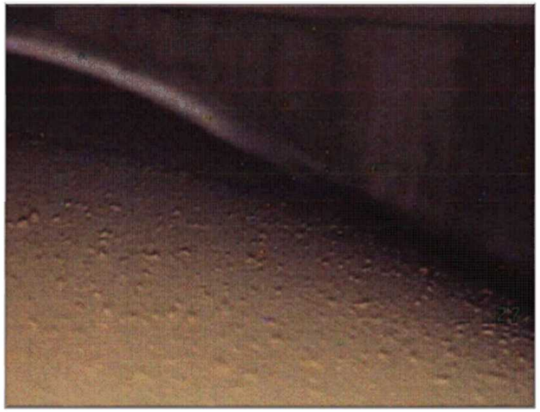
Damage Fraction of 1 represents failure. Strain data is 12 orders of magnitude below fatigue failure. Accumulated fatigue damage is approximately zero.

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 do Loadings Relate to Canister Integrity?

Atmospheric Canister Corrosion:

Stress Corrosion Cracking (SCC) Requiring 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

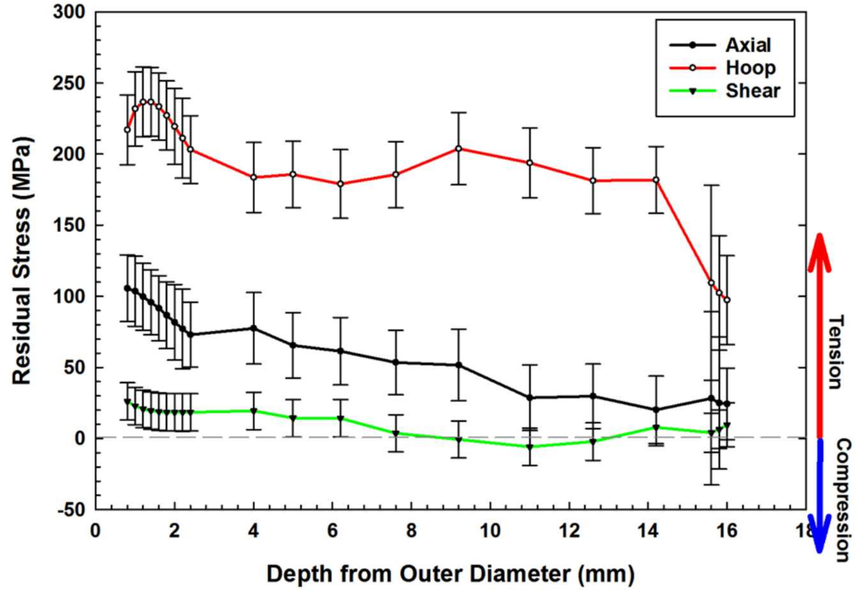
Atmospheric Canister Corrosion:

There is Tensile stress through the canister wall at the weld and Heat Affected Zone

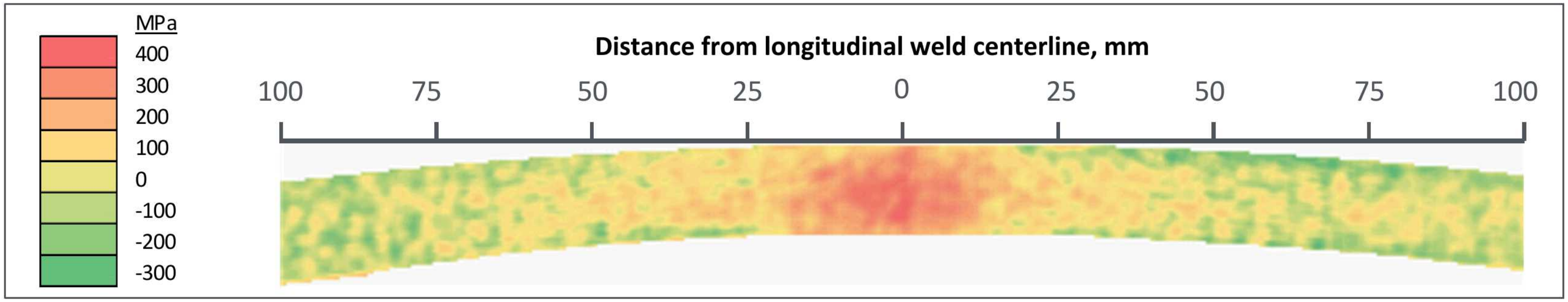
Canister Mockup Weld Residual Stress Measurement Results

- DHD and contour mapping results are consistent.
- High *through-wall* tensile stresses measured in all weld types and in all HAZ. Highest tensile stresses are parallel to welds, but tensile stresses also occur perpendicular to welds.
- Highest tensile stresses (up to 600 MPa) measured at simulated weld repairs.

Residual stresses measured by deep-hole drilling (DHD) method, circumferential weld HAZ



Residual stresses measured by contour method, longitudinal weld



Enos D. and Bryan C., 2016. *Final Report: Characterization of Canister Mockup Weld Residual Stresses*, FCRD-UFD-2016-000064, U.S. DOE

Atmospheric Canister Corrosion:

We need to understand brine evolution under relevant temperatures and humidities.

DOE/EPRI sampling efforts at Calvert Cliffs, Hope Creek, Diablo Canyon, and Maine Yankee. Potentially corrosive chloride salts found in some areas. Need additional sampling to determine:

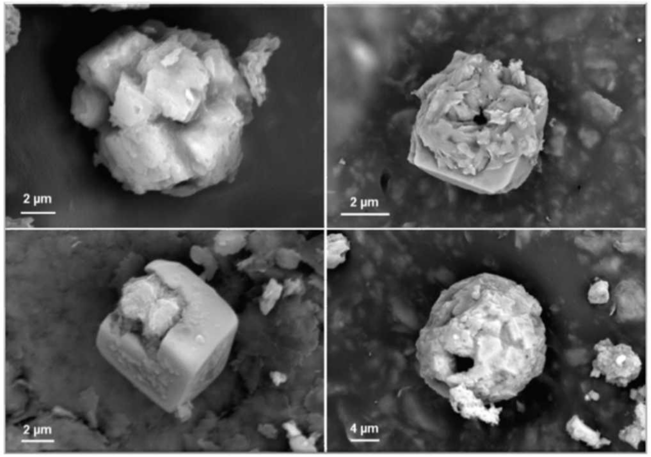
(1) deposited salt compositions as a function of geographical location;

(2) salt loads and compositions as a function of canister surface location and surface temperatures.

Dust Sampling at the Diablo Canyon ISFSI

Photos: Bryan, SNL

Sea-salt aerosols found in canister surface dusts.



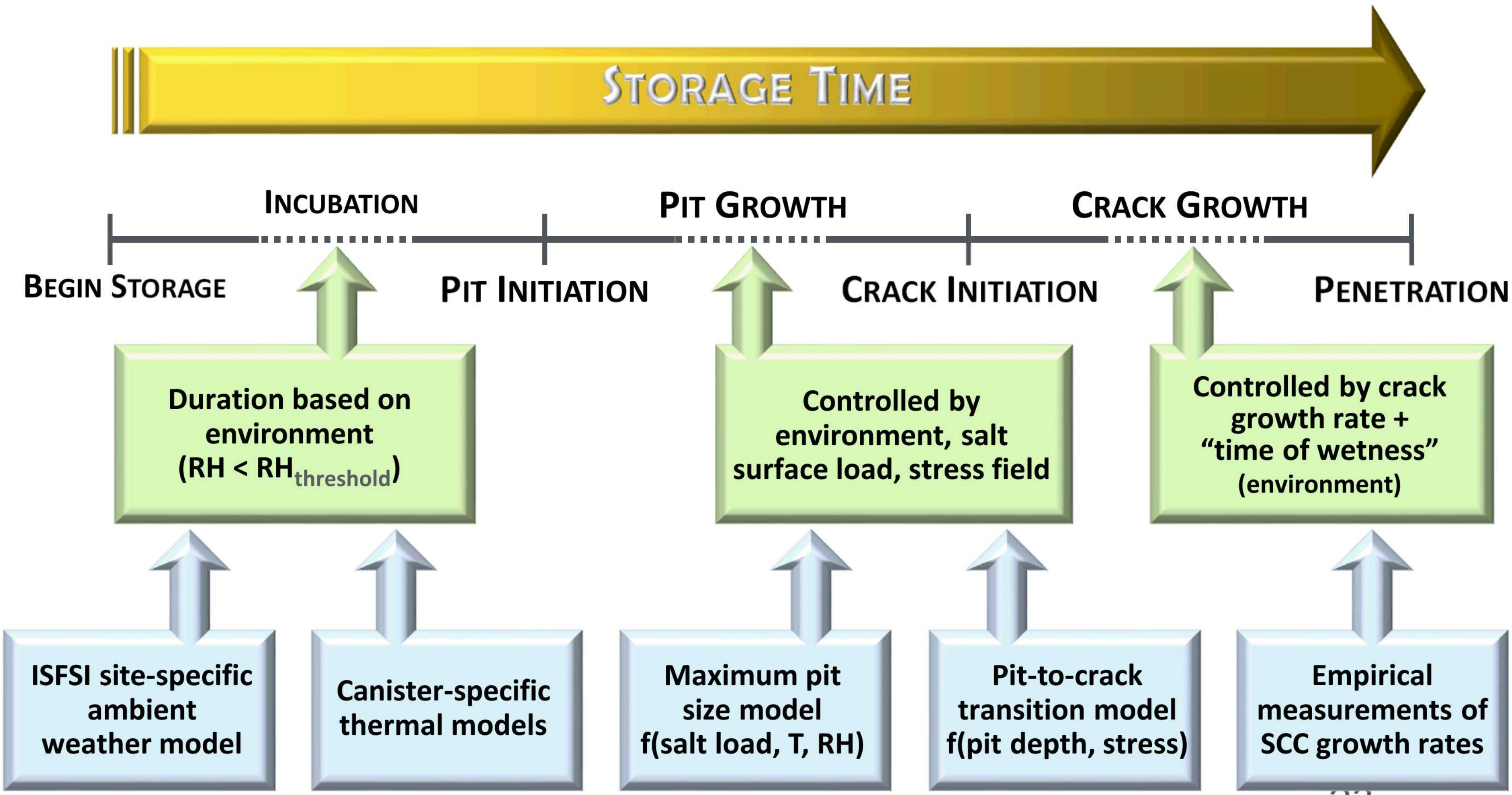
Are deliquescent brines stable on the heated canister surface?

Previous Work Ammonium- and chloride-containing brines are not stable on heated surfaces, rapidly degassing until one or the other component is consumed. This makes presence of chloride-rich brines at inland sites with ammonium-rich continental salts unlikely.

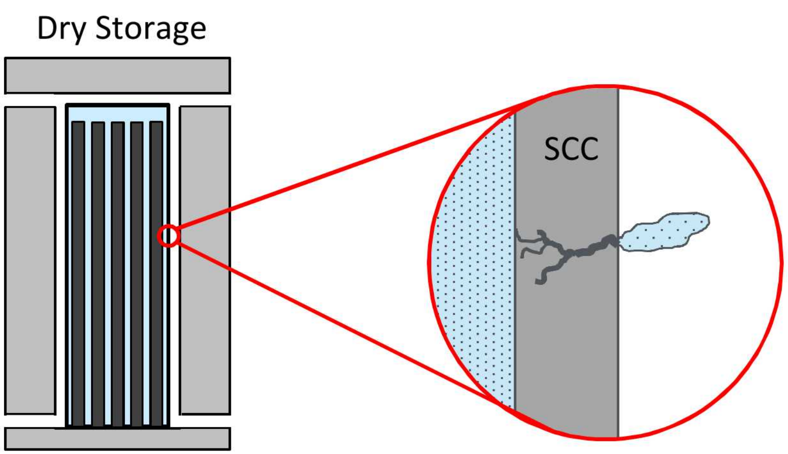
Current Work Evaluating the stability of brines formed by sea-salt deliquescence at relevant temperatures and humidities.

Atmospheric Canister Corrosion:
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.

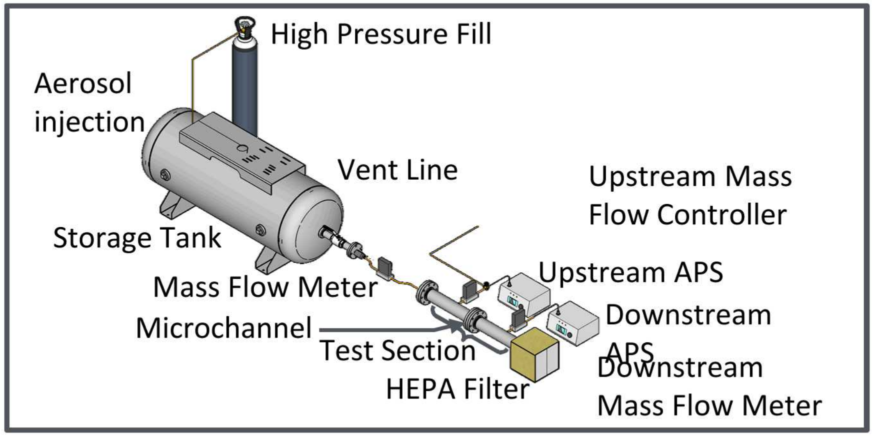


What is the Consequence of a Through-Wall Crack?

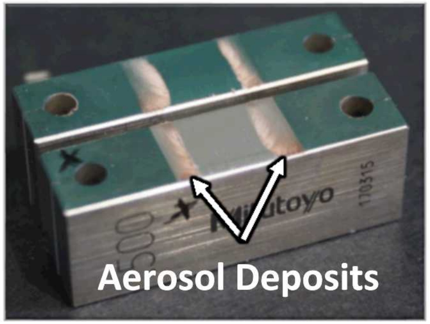


Study system physics with simplified conditions

- 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.

References (available in the paper)

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Questions?

Clean. Reliable. **Nuclear.**