DOE Spent Fuel Research for Storage & Transportation

Ned Larson

NWTRB Winter 2022 Meeting
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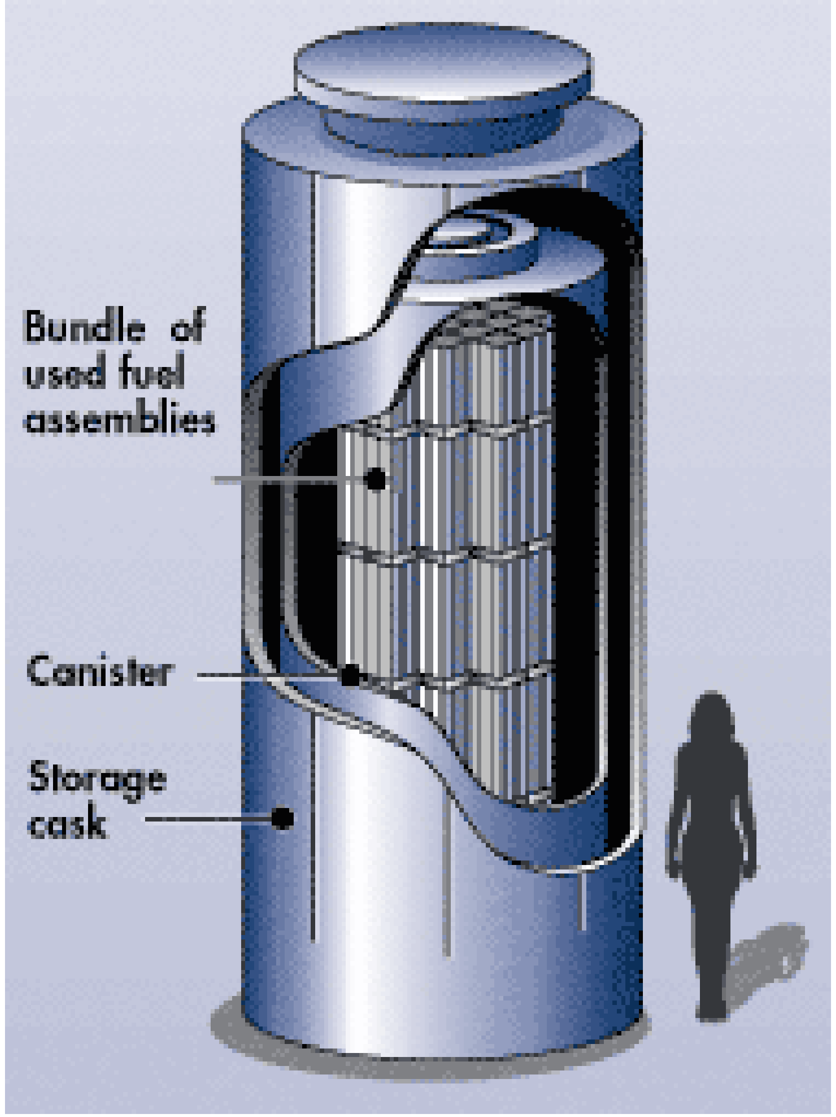
Disclaimer

This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

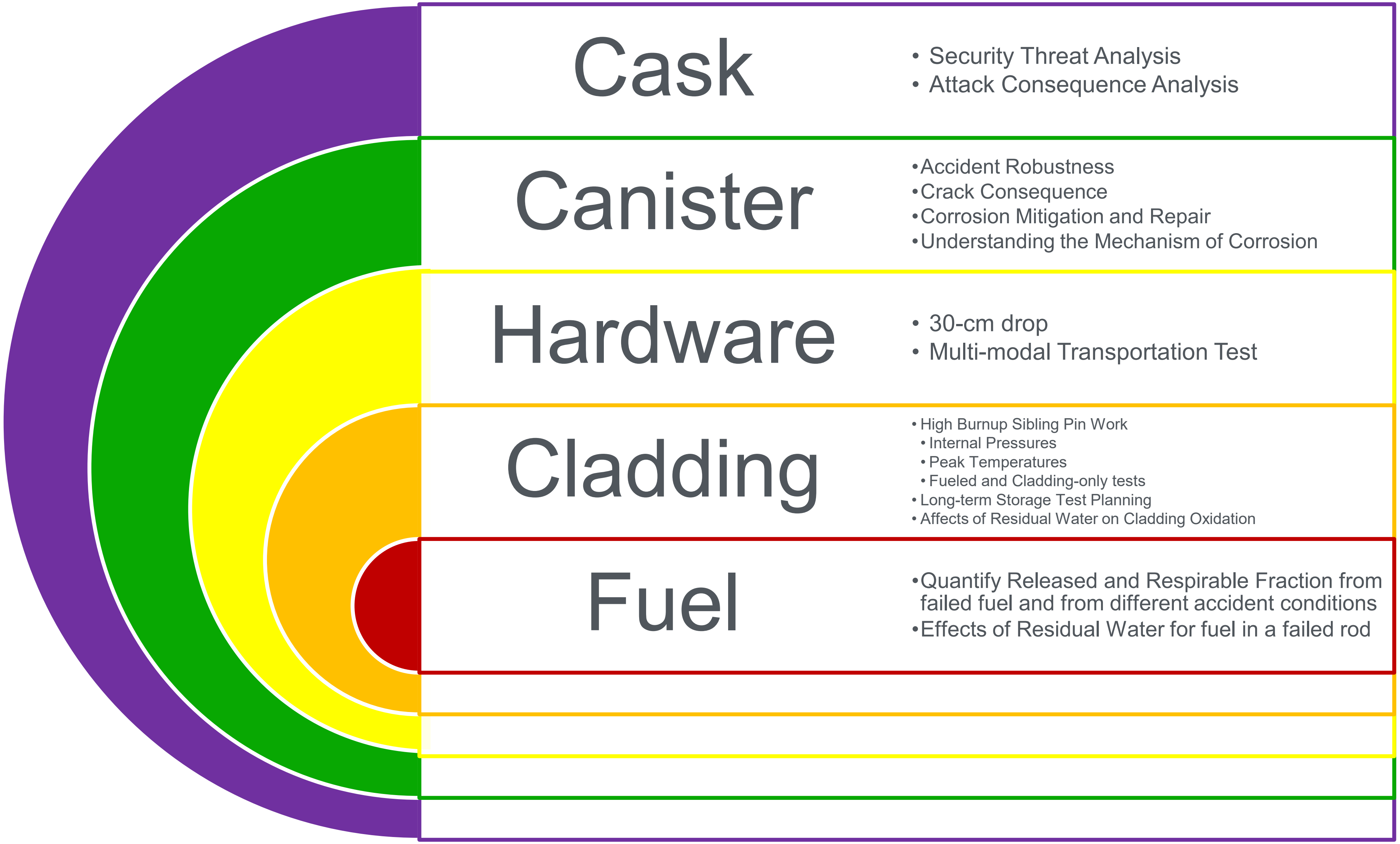
This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

General Priority For Spent Fuel R&D



- NRC is responsible for approving cask systems for containment of spent fuel for storage and transportation
- DOE has every belief that the NRC has done and continues to do a good job in issuing Certificates of Compliance for the cask systems
- DOE is not redoing the work that the NRC has already completed.
- DOE is not testing the cask systems
- DOE is testing how everything behaves inside the cask/canister

Ensuring Spent Fuel Long-Term Defense in Depth



Cask

- Security Threat Analysis
- Attack Consequence Analysis

Canister

- Accident Robustness
- Crack Consequence
- Corrosion Mitigation and Repair
- Understanding the Mechanism of Corrosion

Hardware

- 30-cm drop
- Multi-modal Transportation Test

Cladding

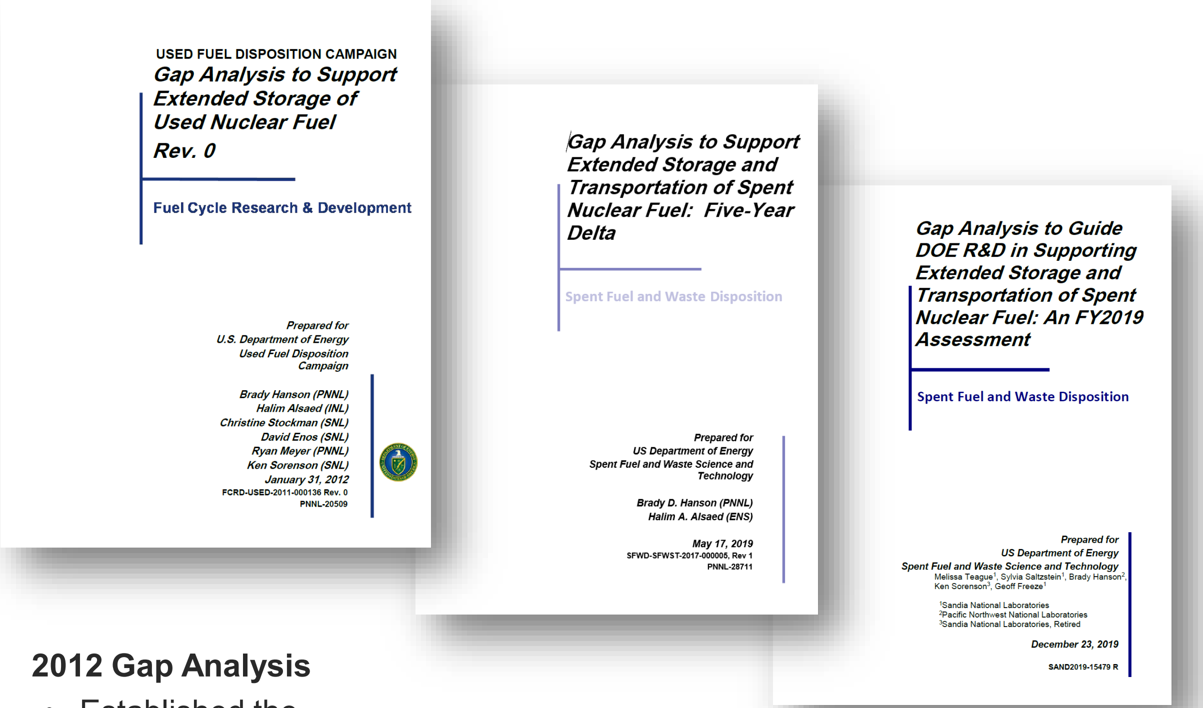
- High Burnup Sibling Pin Work
  - Internal Pressures
  - Peak Temperatures
  - Fueled and Cladding-only tests
- Long-term Storage Test Planning
- Affects of Residual Water on Cladding Oxidation

Fuel

- Quantify Released and Respirable Fraction from failed fuel and from different accident conditions
- Effects of Residual Water for fuel in a failed rod

Planning Long-Term

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



USED FUEL DISPOSITION CAMPAIGN

Gap Analysis to Support Extended Storage of Used Nuclear Fuel

Rev. 0

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign

Brady Hanson (PNNL)
Halim Alsaed (INL)
Christine Stockman (SNL)
David Enos (SNL)
Ryan Meyer (PNNL)
Ken Sorenson (SNL)
January 31, 2012
FCRD-USED-2011-000136 Rev. 0
PNNL-20509

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

[1]Sandia National Laboratories
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[3]Sandia National Laboratories, Retired

December 23, 2019

SAND2019-15479 R

2012 Gap Analysis

- Established the structure and process
- Identified Technical Categories
- Ranked R&D Gaps for R&D Funding priority.

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

Current R&D Priorities

Priority 1

- Thermal Profiles
- Stress Profiles
- Welded Canister – Atmospheric Corrosion

Priority 2

- Drying Issues

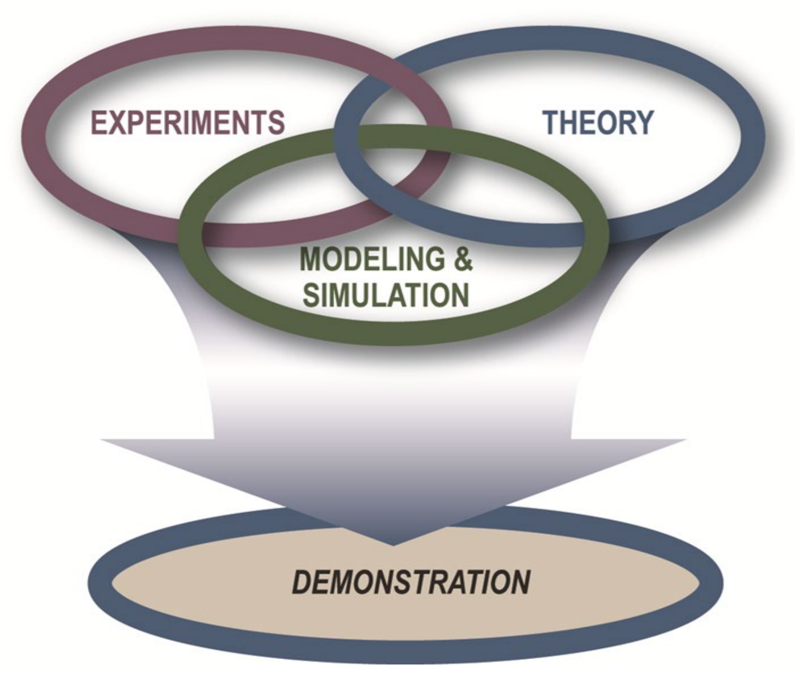
Priority 3

- External Monitoring
- Cladding – H_2 Effects
- Consequence of Canister Failure
- Fuel Transfer Options

DOE ranking and priorities may differ from those of industry and NRC to follow an approach that includes maintaining options for final disposition (e.g., reprocessing, geologic disposal, etc.)

Collaboration Leverages Research Dollars – Enables Diversity of Perspectives & Ideas

Technical Direction



Partnerships

- **Industry**
  - Utilities – EPRI and NEI
  - Cask manufacturers
  - Fuel suppliers
  - Rail and trucking companies
- **National Laboratories**
  - 11 National Labs
  - Specialized personnel, facilities and equipment are available
- **Small Businesses**
  - $5.2 million and 13 contracts awarded
- **Nuclear Energy University Program (NEUP)**
  - 40 university awards, numerous students and professors are involved ($48M) for Storage &Transportation
- **Nuclear Regulatory Commission**
  - Jointly fund research when appropriate
  - Continue some testing NRC began
- **International – ESCP**
  - Extended Storage Collaboration Program

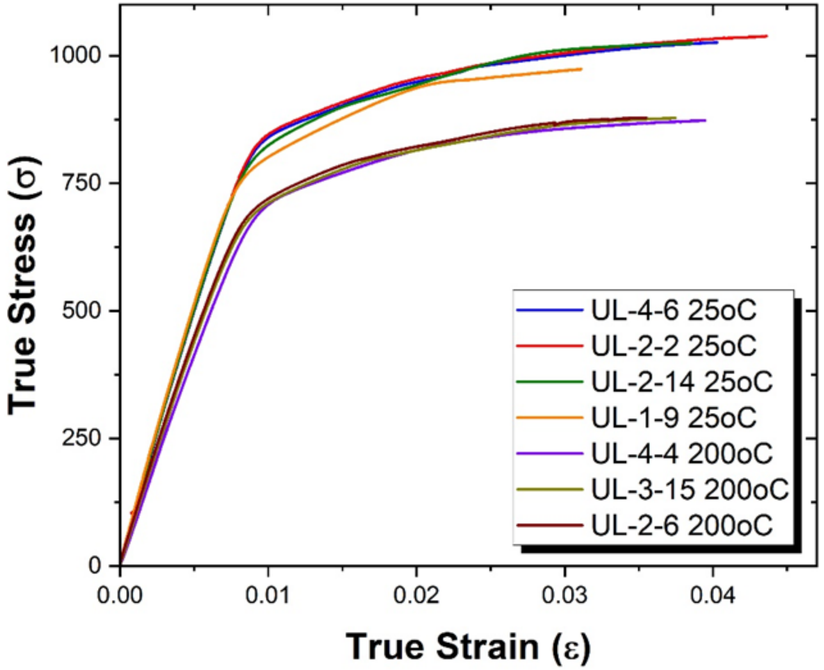
FUEL / CLADDING BEHAVIOR

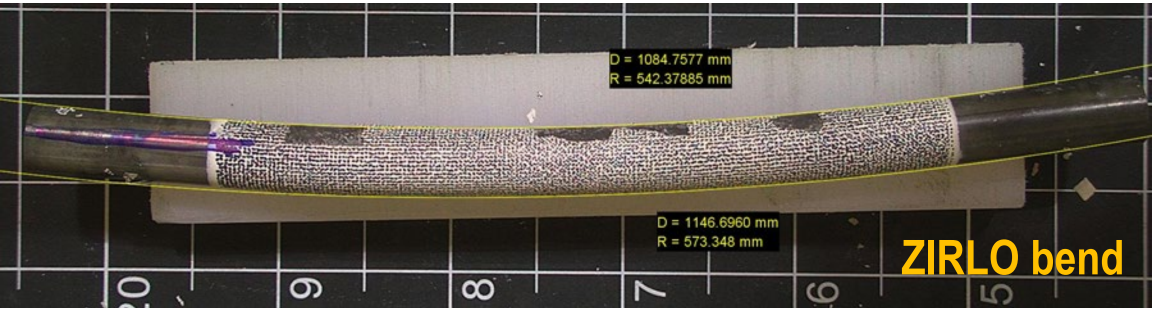
Sibling Rod Testing

Sibling Pin Accomplishments

- Phase 1A (as-received) testing on one ZIRLO® and one M5® rod
- Testing at room temperature and 200˚C
  - Axial tube tensile
  - Burst
  - 4 pt bend
- Results consistent with international database

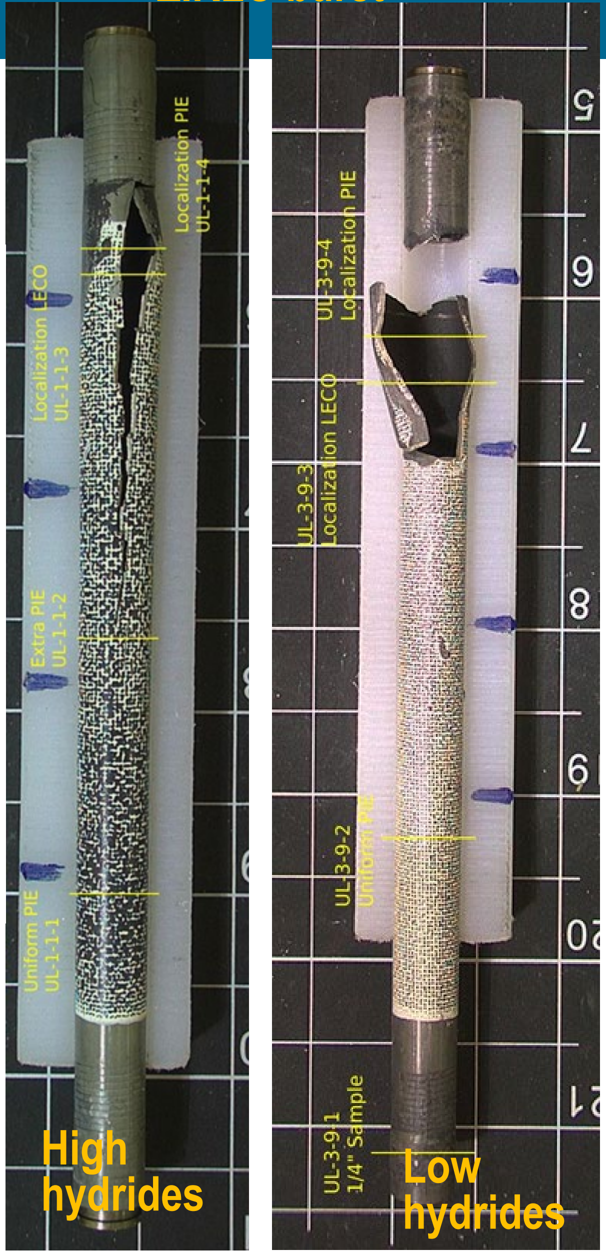
ZIRLO tensile





ZIRLO bend

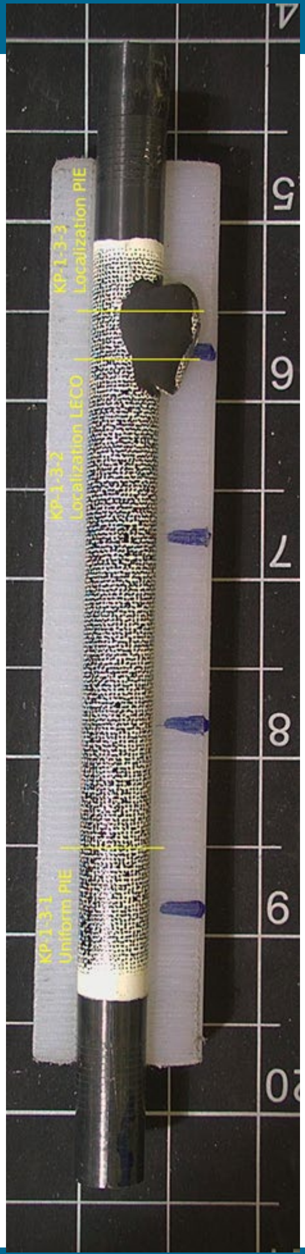
ZIRLO burst



High hydrides

Low hydrides

M5 burst



Sibling Rod Testing - Status

- So far, our hot cell testing has not found anything surprising or out of the ordinary from other published results or from what we expected
- We believe the cladding is sufficiently robust so there will not be any problems storing and transporting spent nuclear fuel from a cladding perspective

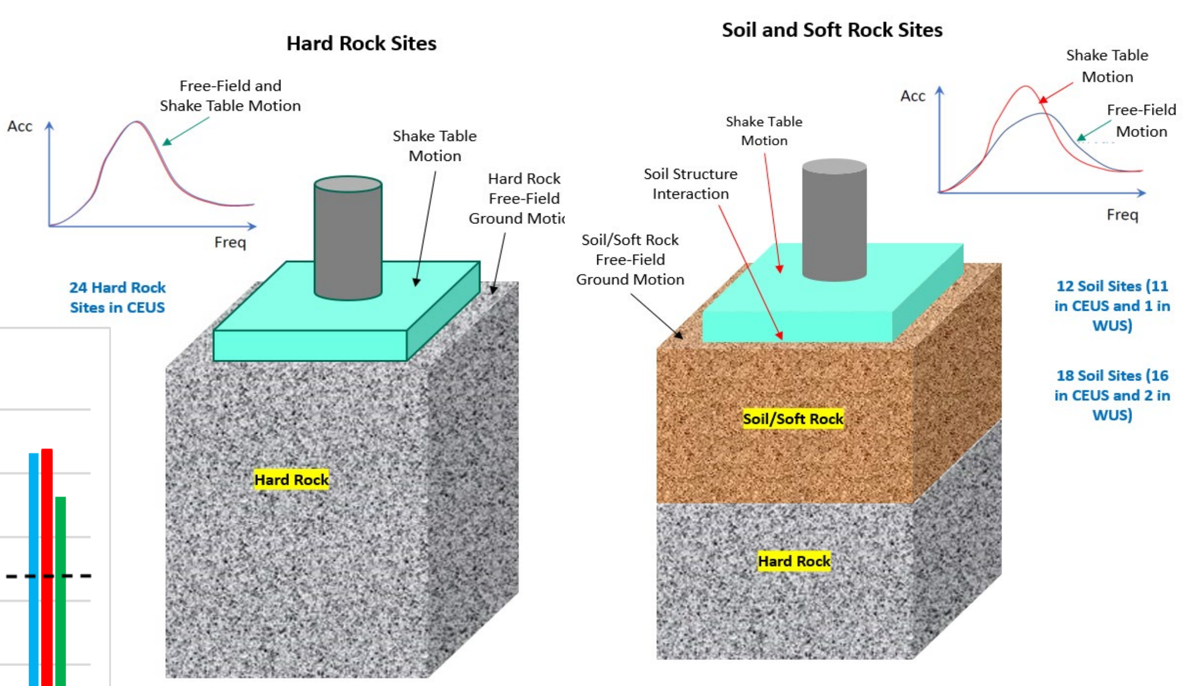
FUEL / CLADDING BEHAVIOR

Seismicity and Applied Stresses

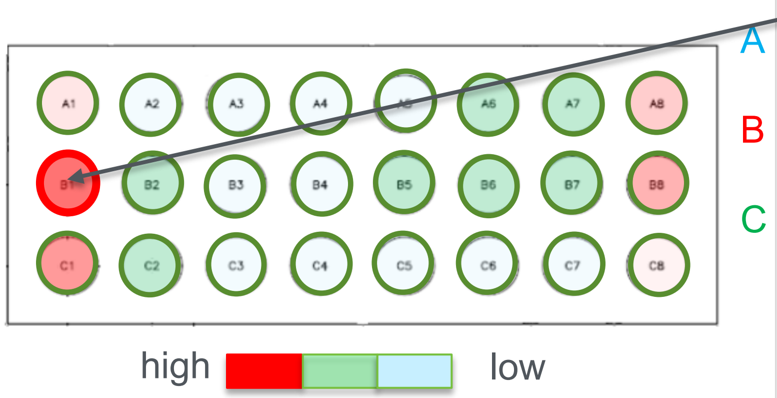
Update on the Seismic Shake Table Test

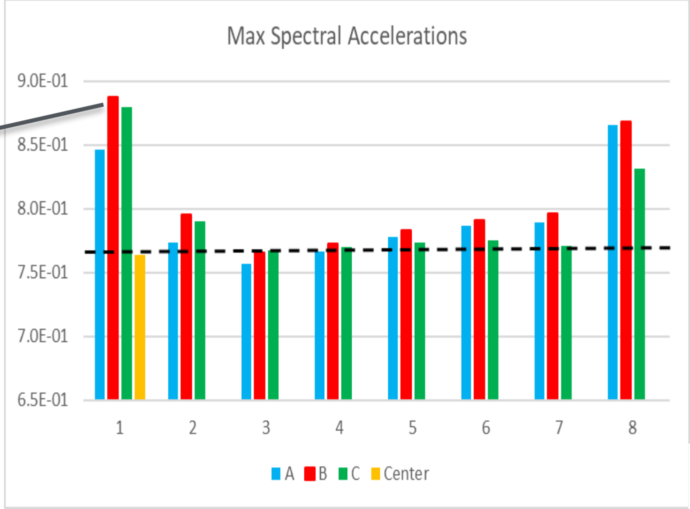
A new methodology was developed to define representative free-field ground motions for hard rock, soft rock, and soil in the Central Eastern U.S. (CEUS) and soft rock and soil in the Western U.S. (WUS).

The soil-structure interaction (SSI) analyses is in progress to account for SSI effects and pad flexibility.



Max Spectral Accelerations at the Different Locations on the Pad

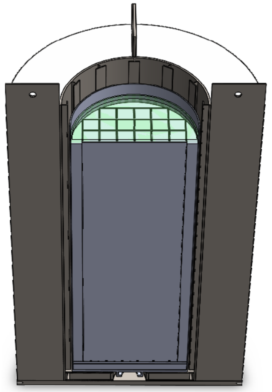




4 surrogate assemblies will be used: 16x16 CE PLUS7, 17x17 Westinghouse (intact); 16x16 Framatome; and 17x17 SNL Westinghouse (slightly damaged).

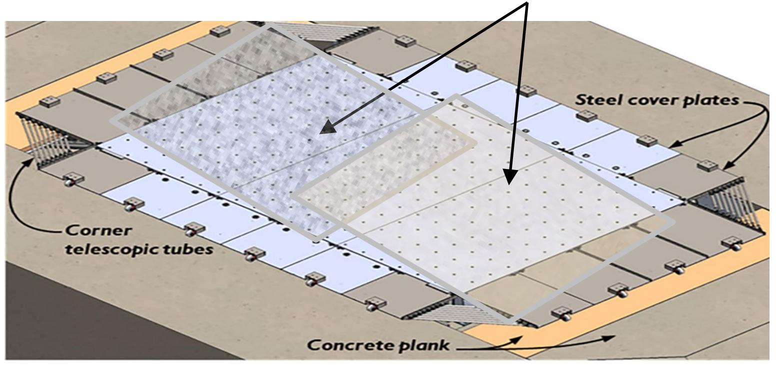
Test unit will be instrumented with ~300 sensors to capture all the important differences in the responses to the seismic excitations.

Test Unit



LHPOST Shake Table

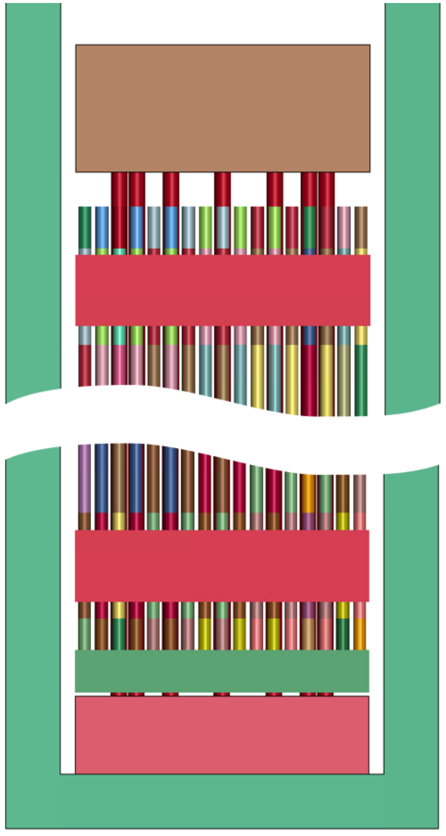
Concrete layers with different finishes to simulate different friction.



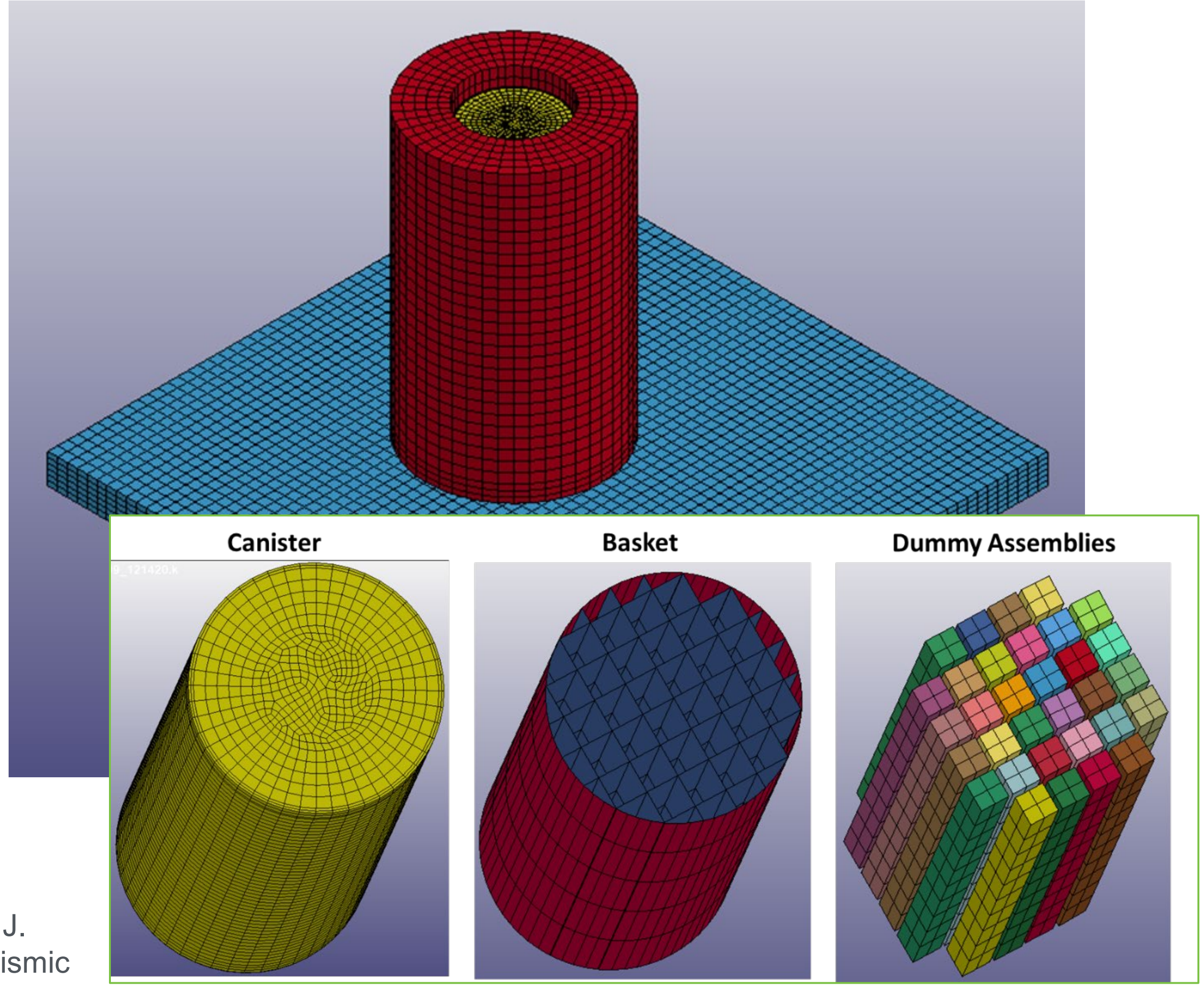
Seismic Test Modeling

PNNL completed preliminary test modeling to inform the test plan.

PNNL is currently preparing pretest predictions for the seismic test and estimating the nonlinear effects of cask system behavior.



Fuel Assembly in Basket Cell

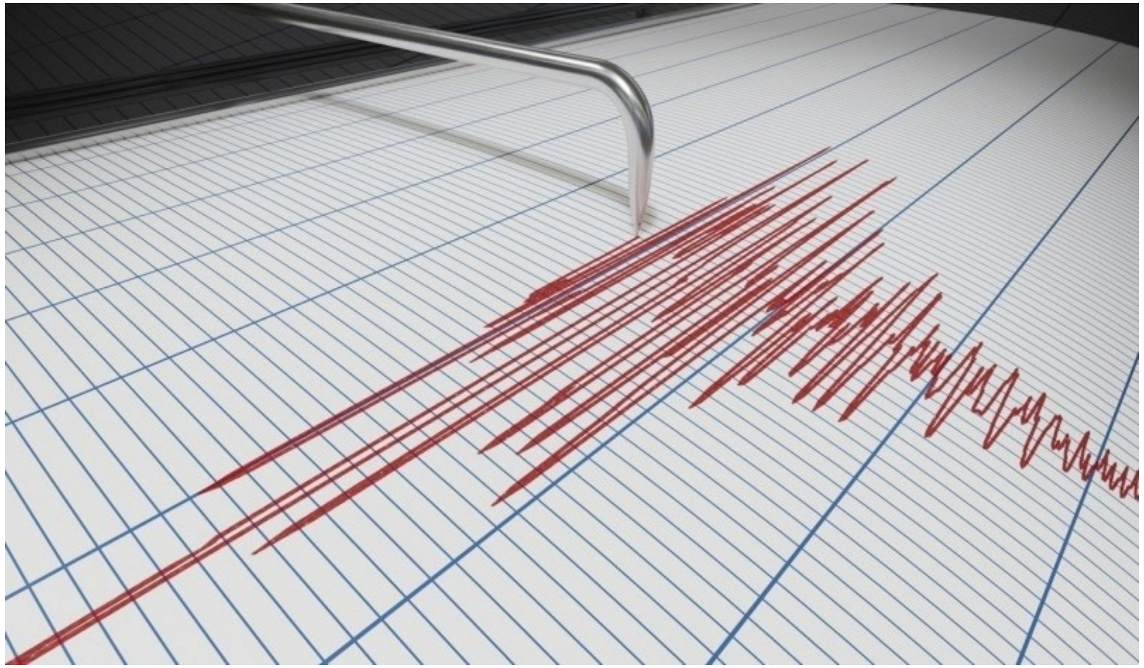


VCC System Model on Shake Table

M3SF-21PN010202014. Klymyshyn N.A., P. Ivanusa, C.J. Spitz, K. Kadooka, C. Mason, B.J. Jensen, and J.A. Bamberger, et al. 2021. Modeling and Analysis for Spent Nuclear Fuel Seismic Testing. PNNL-31878. Richland, WA: Pacific Northwest National Laboratory.

Seismic Testing -Status

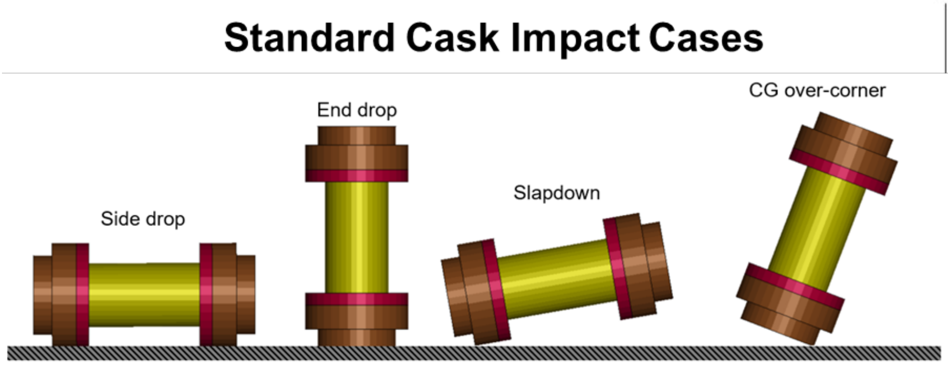
- It is believed that due to the robustness of the cladding, there will not be a problem with a seismic event
- However, we do not know exactly how much the stress the cladding will experience from a seismic event, so we are moving forward with this work.

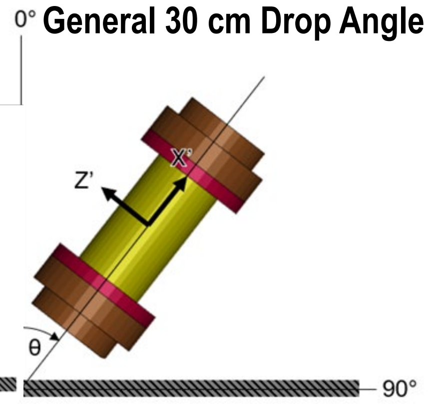


FUEL / CLADDING BEHAVIOR

Drop Test and Applied Stresses

Spent Nuclear Fuel Mechanical Loads in the General 30 cm Package Drop Scenario


Standard Cask Impact Cases


General 30 cm Drop Angle

SFWST test data recorded the **Side Drop** impact response of surrogate SNF. PNNL validated finite element models with the test data and performed a large (2000+ cases) parametric study to estimate the universe of potential SNF loads.

- No cladding yield in any case of the study.
- Up to 200°C: Large margins on cladding yield.
- Up to 300°C: Outliers have tight margins.
- 400°C (Max temperature case): Not evaluated.

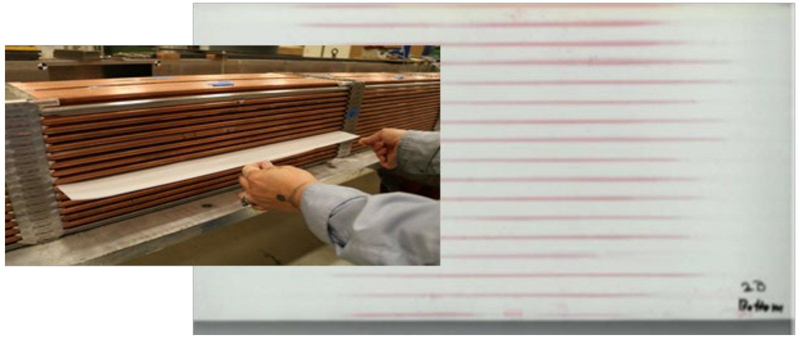
	Parametric Study	# of Parameters
Fuel Assembly	17x3 Reduced PWR Model, 10x10 BWR	2
Cask Mass	As-tested	1
Cask Impact Limiters	As-tested	1
Burnup	10, 36, 62 GWd/MTU	3
Temperature	RT, 100°C, 200°C, 300°C	4
Drop Orientation (angle from vertical)	0°-90° in 10° increments	10
Fuel-Basket Gap	1%, 50%, 99%	3
Grid Crushing	Best Estimate, -20%, +20%	3
Basket Stiffness	Rigid	1
	Total # of Permutations	2,160

M3SF-21PN010202016. Klymyshyn N.A., K. Kadooka, C.J. Spitz, J.F. Fitzpatrick, and P.J. Jensen. 2021. Mechanical Loads on Spent Nuclear Fuel in the General 30 cm Package Drop Scenario. PNNL-32087. Richland, WA: Pacific Northwest National Laboratory.

Drop Test Applied Stresses - Status

- Test data and model predictions both agree that the SNF assemblies are subjected to significantly higher loads in a cask drop event than normal transportation shock and vibration
- Currently there is no reason to expect gross structural damage of the fuel assembly or widespread SNF cladding failure as a result of a 30 cm cask drop.
- The fuel rods will maintain their integrity after being dropped 30 cm more than once
- More work still needs to be done in this area

Rod-to-Rod Contact Pressure

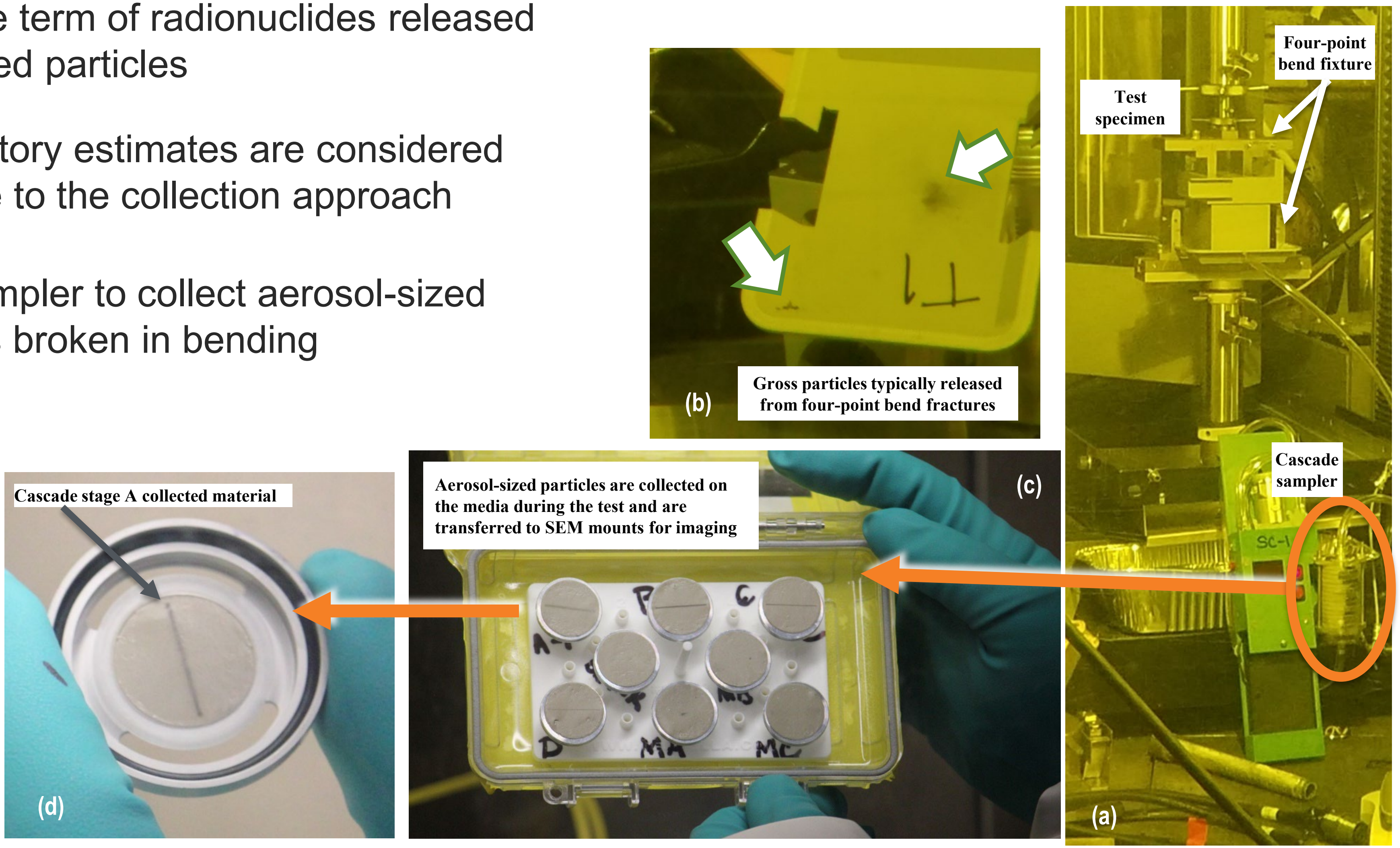


FUEL / CLADDING BEHAVIOR

Aerosol Dispersion

ORNL is collecting and characterizing aerosol sized particles released when a rod is broken in bending

- There is little data on the source term of radionuclides released during rod fracture as aerosolized particles
  - Current test data and inventory estimates are considered extremely conservative due to the collection approach
- This testing uses a cascade sampler to collect aerosol-sized particles released when a rod is broken in bending
- One test has been completed with a total of 4.6 mg dust collected, 0.5 mg of which were collected as respirable-sized particles (<10 μm AED) in the cascade



Gross particles typically released from four-point bend fractures

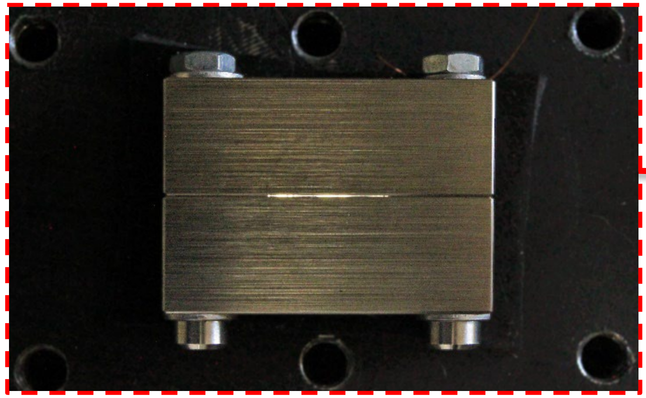
Aerosol-sized particles are collected on the media during the test and are transferred to SEM mounts for imaging

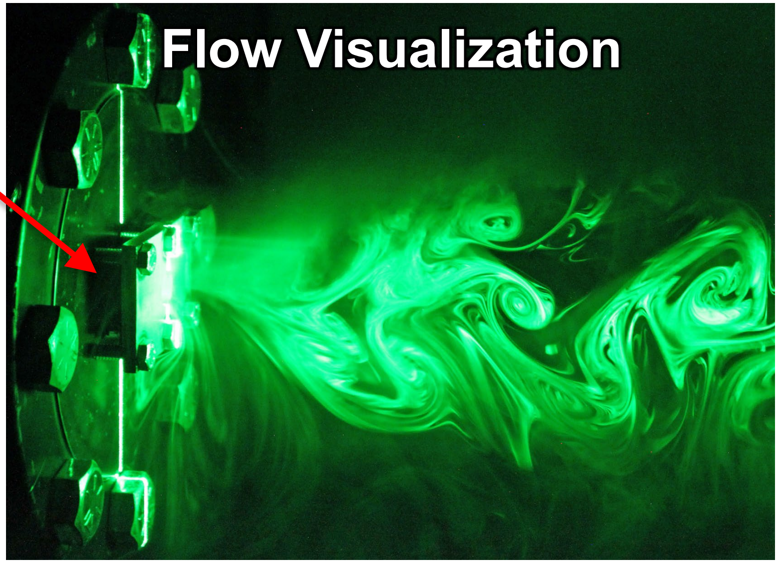
Cascade stage A collected material

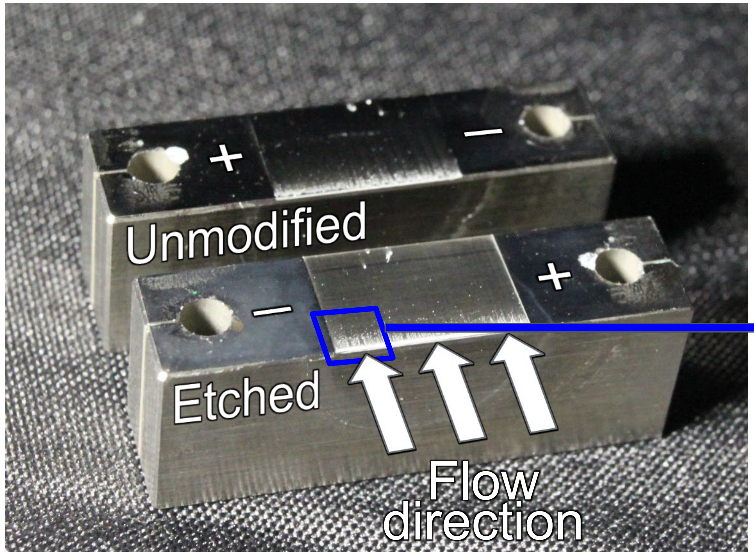
(a) A rod is tested in four-point bending with the aerosol sampler in place. (b) post-test view of larger debris typically collected following a non-aerosol test using four-point bending. (c) the cascade is designed to collect particles having an aerodynamic diameter less than ~15 μm, with each stage (7 stages are used in this sampler design) collecting a specific range of aerodynamic particle diameters. The collected aerosols from test 1, along with a blank, were mounted on SEM mounts for imaging. (d) the sampled material is the black line on the beige collection media. (e) the majority of the aerosol-sized particulate collected during test 1 was in the 10 to 15 micron range.

Transmission of Aerosols Through Cracks

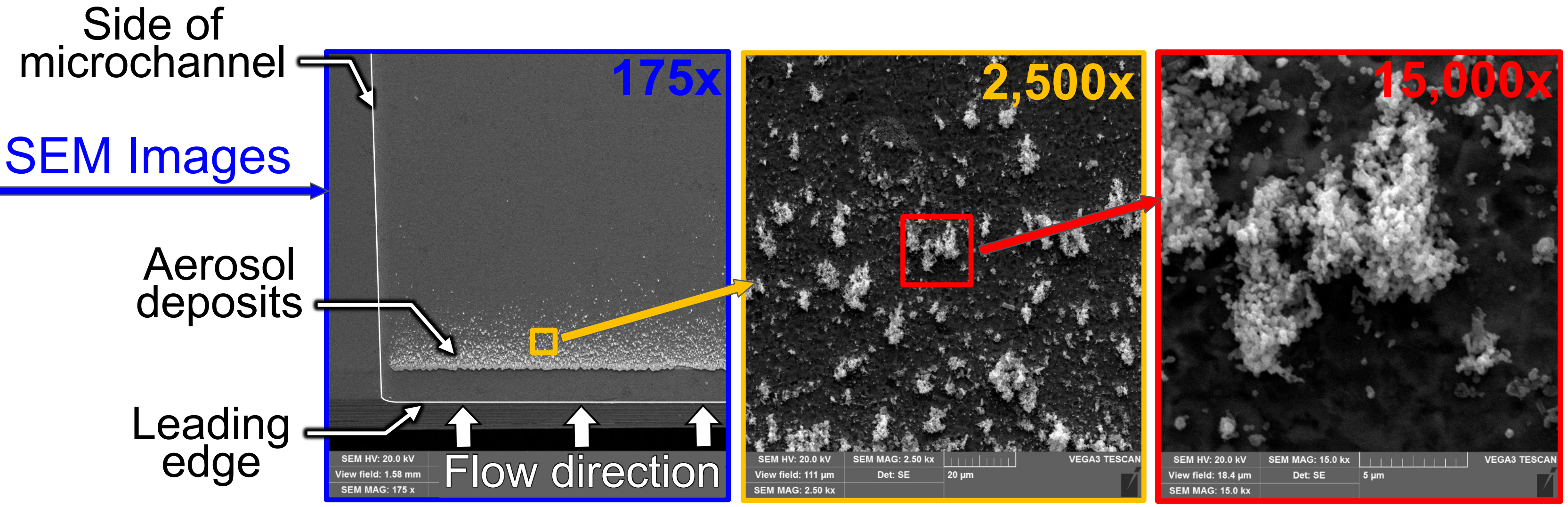
- Tests with linear slot orifice to represent SCC
  - Simplified microchannel
    - Linearly diverging from 13 to 25 μm
  - *Aerosol mass transmission fraction from 0.12 to 0.61*


Assembled Microchannel





Disassembled Microchannel
(Post-Test)



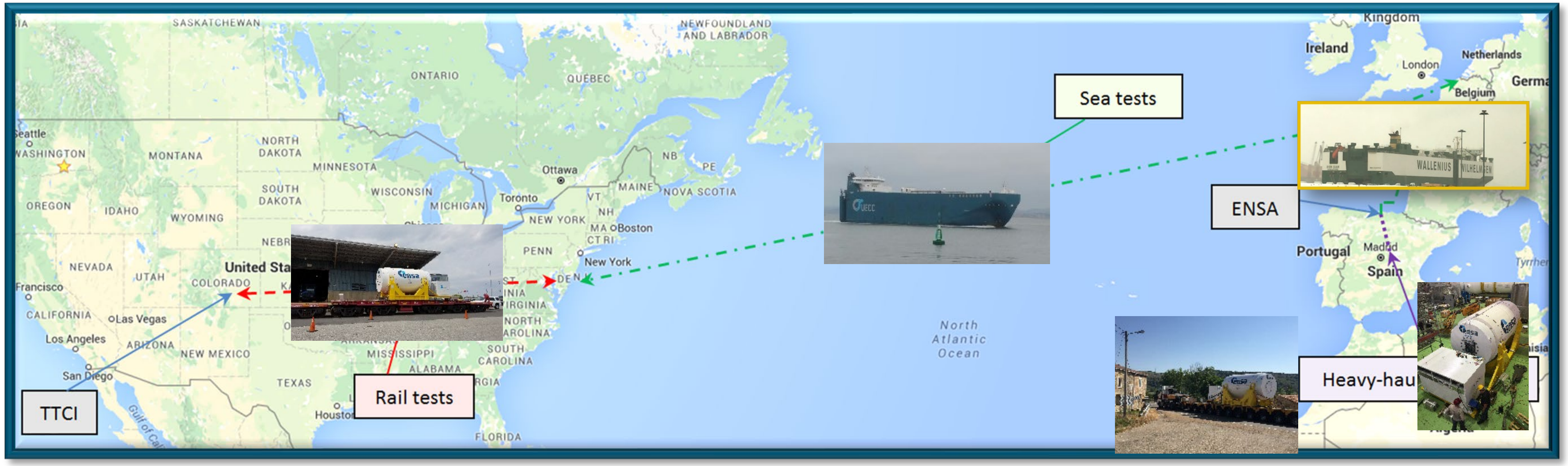
Release of Aerosols “IF” there is a Problem - Status

- Still early in our testing for this issue
- So far, if a rod were to break, and a crack were to occur in the canister, we do not believe that any release of significance would occur.
- More testing and work need to be performed in this area.

FUEL / CLADDING BEHAVIOR

Transportation

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



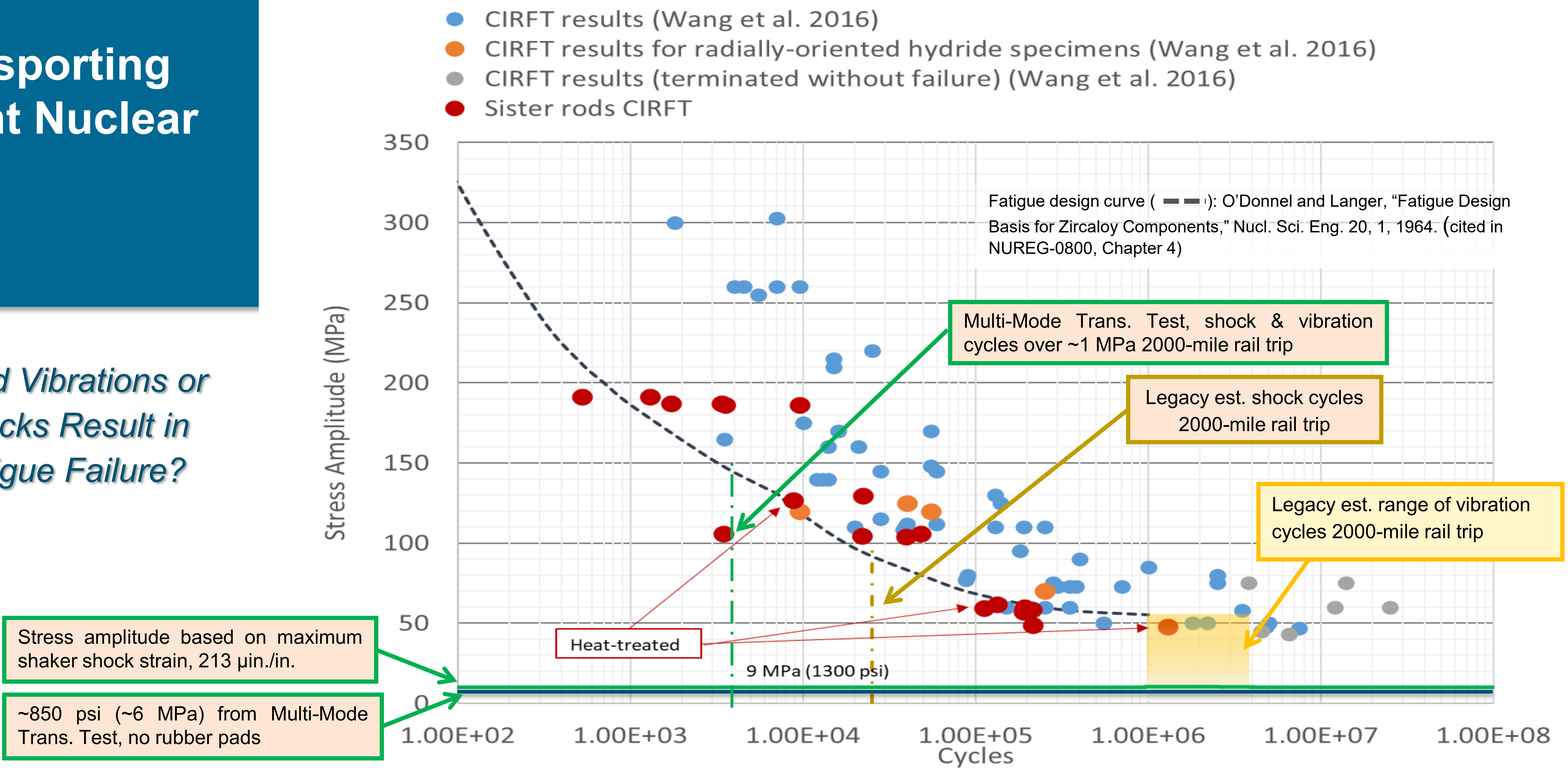
Photos provided by Steve Ross, PNNL

- Transportation was done between June and September of 2017
- 9 Terrabytes of data was collected throughout all legs of the transport as well as the transfers between legs.
- From this test, we conclude that:

For <u>normal conditions of transport</u>, the forces applied to the rods are orders of magnitude below what they can safely withstand. Therefore, transportation under normal circumstances will not be a problem even after long periods of storage.

Transporting Spent Nuclear Fuel

Could Vibrations or Shocks Result in Fatigue Failure?



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)

Multi-Mode Trans. Test, shock & vibration cycles over ~1 MPa 2000-mile rail trip

Legacy est. shock cycles 2000-mile rail trip

Legacy est. range of vibration cycles 2000-mile rail trip

Stress amplitude based on maximum shaker shock strain, 213 µin./in.

~850 psi (~6 MPa) from Multi-Mode Trans. Test, no rubber pads

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

Understanding High Burn-up Cladding Performance – Status

- With the data that are currently available and using the integrated testing approach, cladding integrity will not be challenged during extended storage and normal conditions of transport
- We still have more testing to perform

CANISTER / CASK BEHAVIOR

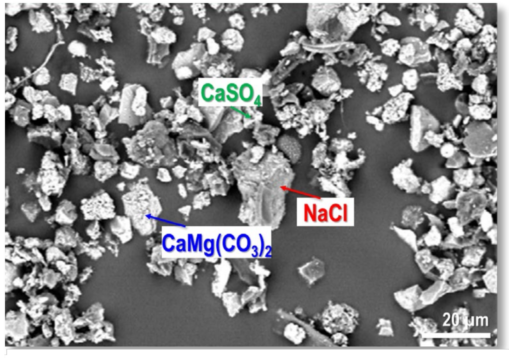
Stress Corrosion Cracking

Stress Corrosion Cracking

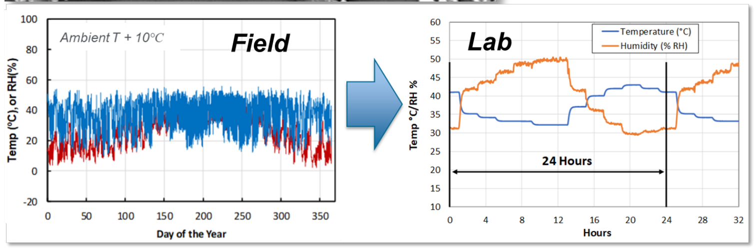
Canister surface environment controls corrosion susceptibility, pit growth, and SCC initiation and growth.

Environment: Site sampling & geochemical modeling provide critical data on canister surface brines ($MgCl_2$ *stability*)

- *Dust from inland ISFSI sites analyzed.*
- *Established realistic environments for corrosion testing.*



Dust and salts analyzed from inland sites



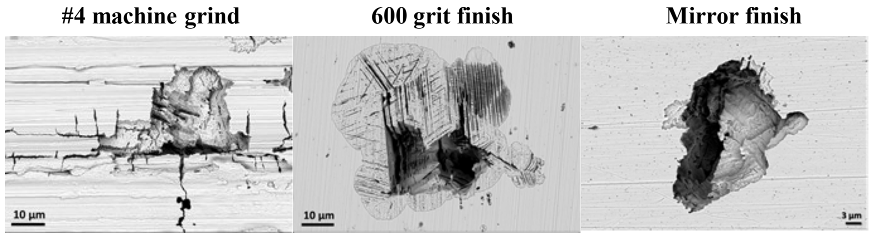
Field to lab cycle

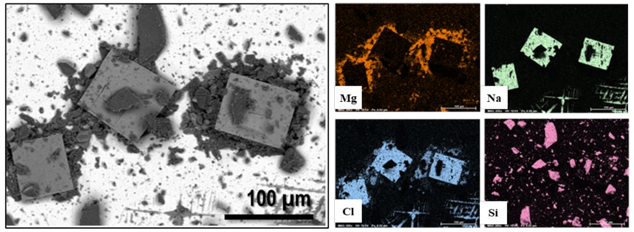
Corrosion Experiments:

Determine environmental& material controls on pitting and SCC initiation.

- *Significant variables : diurnal cycles, NO_3^-/Cl^-, dust.*

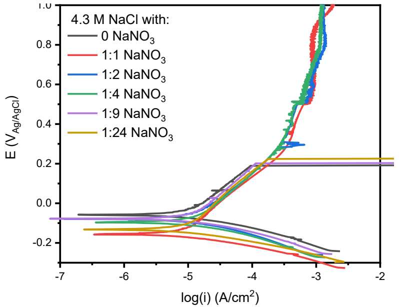
Diurnal Cycles– Corrosion also influenced by surface finish





Dust– Brine morphology & corrosion influenced by dust

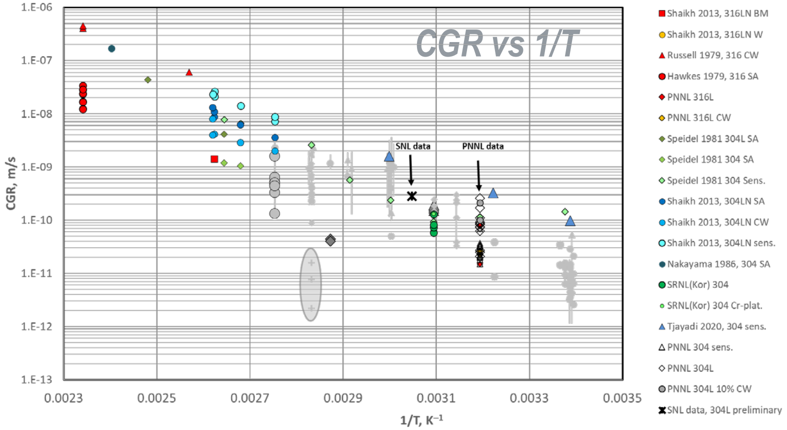
Chemistry– Evaluation of canister relevant brines (influence of Nitrates) to inform CGR studies



SCC Crack Growth Experiments

CGR as a function of brine composition, temperature, material properties.

- *Current immersed results largely consistent with literature data*

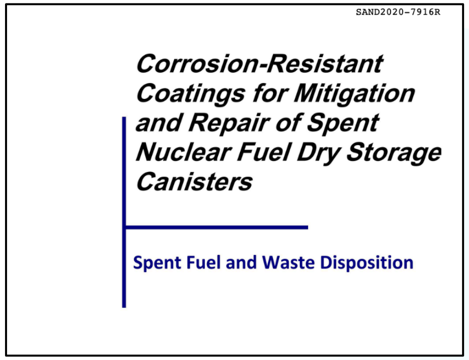


CGR lab at SNL

Canister Coatings to Prevent and Remediate SCC

- Identified coatings for potential SCC repair and mitigation:
  - Described in FY2020 initial scoping report, updated in FY2021
  - Developed MOU with industry partners - *Whitehorse, Flora Coatings, OPM, and LUNA*
  - Initial coating of test coupons underway
- ***Currently in Phase 1:*** performance testing of coatings on pristine surfaces:
  - *Adhesion, Permeability (corrosion barrier), Durability*

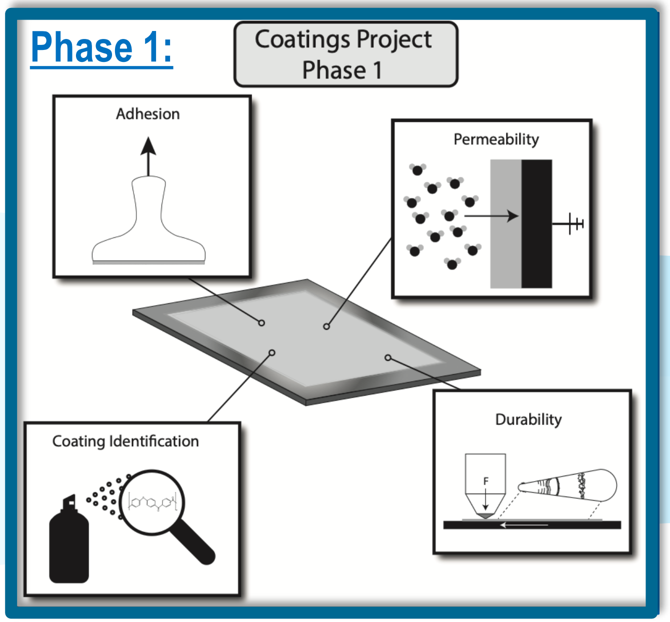
Initial Scoping Report



SAND2020-7916R

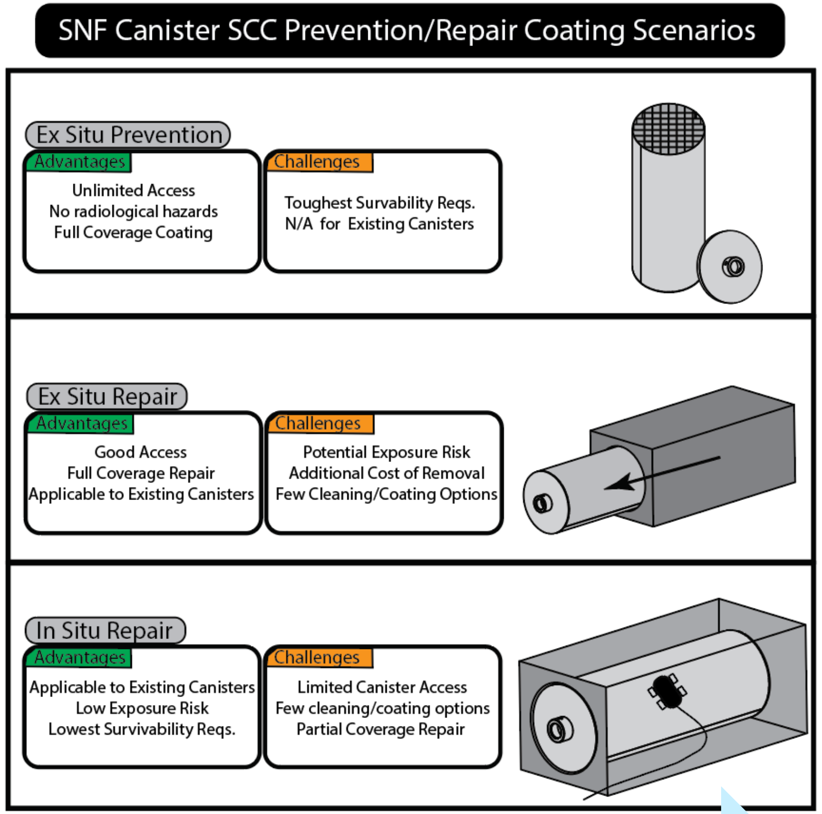
Corrosion-Resistant Coatings for Mitigation and Repair of Spent Nuclear Fuel Dry Storage Canisters

Spent Fuel and Waste Disposition



Phase 1:

Coatings Project Phase 1



SNF Canister SCC Prevention/Repair Coating Scenarios

Scenario	Advantages	Challenges
Ex Situ Prevention	Unlimited Access No radiological hazards Full Coverage Coating	Toughest Survability Reqs. N/A for Existing Canisters
Ex Situ Repair	Good Access Full Coverage Repair Applicable to Existing Canisters	Potential Exposure Risk Additional Cost of Removal Few Cleaning/Coating Options
In Situ Repair	Applicable to Existing Canisters Low Exposure Risk Lowest Survivability Reqs.	Limited Canister Access Few cleaning/coating options Partial Coverage Repair

Phase 2: **Rigorous Performance testing**

Phase 3: **Long Term Corrosion Testing**

Coatings Coordination with Universities and DOE Lab Collaboration

Lead University	***Methods being examined***
Purdue University *(SNL)***	Cold spray ****Collaborative manuscript submitted to Corrosion Science (SNL/Purdue)***
Ohio State University *(PNNL & EPRI)*	Cold spray
	Friction stir welding (FSW)
	Soldering
	Vaporized foil actuator welding (VFAW)
University of Cincinnati *(University of Alabama, INL, HOLTEC)*	Laser-assisted cold-spray (LACS)
	Additive friction stir deposition (AFS-D)
	Laser shock peening
	Ultrasonic nanostructure surface modification
University of Idaho *(PNNL)*	Additive friction stir welding (AFSW)
University of Wisconsin *(PNNL)*	Cold spray
	Friction Surfacing (FS)

Cold Spray (CS) Evaluation (SNL/PNNL)

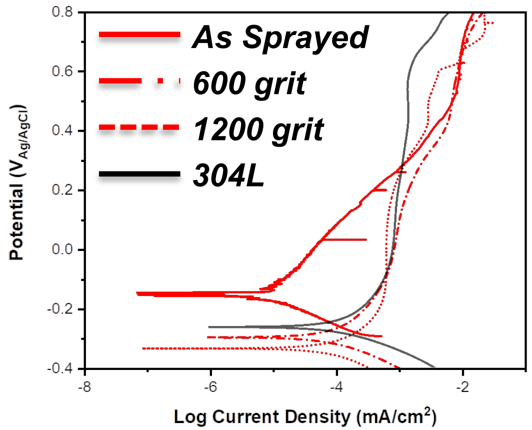
Accelerated Corrosion Testing

- Electrochemical polarization and full immersion pitting test (ASTM G-48)

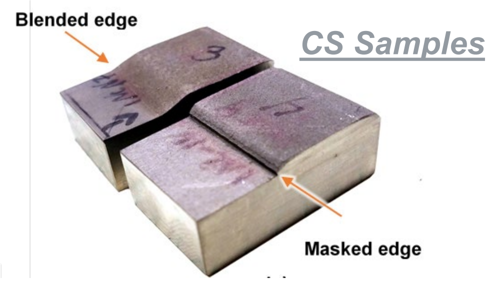
Initial Accelerated Tests Show:

- *Interface is most susceptible region*
  - *Corrosion dependent on material composition & properties (porosity)*
  - *Surface finish can enhance CS corrosion resistance*

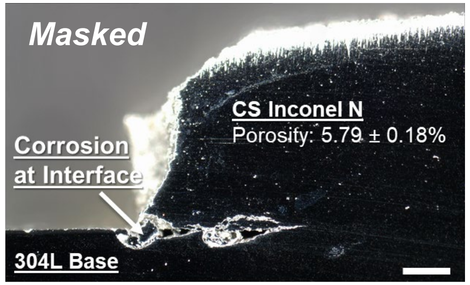
Electrochemical Analysis



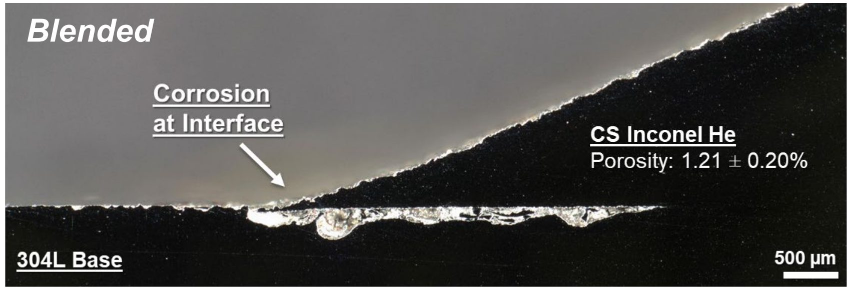
CS Samples



No significant difference in corrosion between masked/blended CS



Full Immersion Testing **Post-Exposure Cross sections**



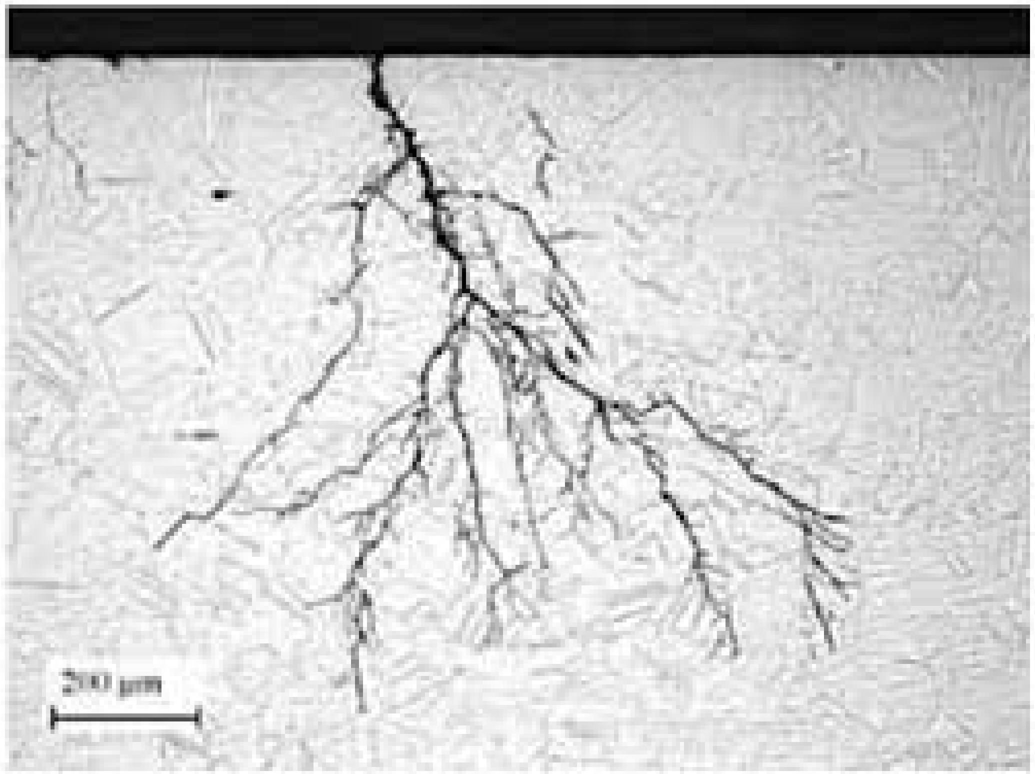
Coatings Coordination with Universities –*2020 Continuing NEUPs**

Lead University	***Methods being examined***
North Carolina State University (*INL*)	Ceramic coatings with ultrasonic spray mist CVD
	Test corrosion, heat, wear, H permeation
University of Nebraska (*Orano*)	Laser Cleaning & Laser Peening for removal of corrosion product and mitigation of pitting and SCC
	Test corrosion
University of Nevada Reno (*LANL*)	Laser Surface Patterning
	FEM of pitting & Test pitting and SCC
University of South Carolina (*EPRI & SRNL*)	Composite patch with inhibitor
	Test/monitor corrosion and SCC
University of Wisconsin Madison (*PNNL & EPRI*)	Shot peening, cold spray peening, ultrasonic nanocrystal surface modification, laser shock peening, & forced pulse water jet peening
	Microstructure, potentiodynamic corrosion tests, crack growth rate
Virginia Tech (*OSU*)	SiOCN(H) coatings
	Evaluate structural changes in coatings in canister environment

Delayed due to COVID-19 Pandemic

Stress Corrosion Cracking - Status

- Some materials show some promise in preventing and remediating SCC
  - The potential inhibitory effects of nitrate in canister surface dusts are being explored
  - Cold spray as a mitigation and repair technology offers promising physical/mechanical properties, but its effects on canister corrosion are poorly understood and require additional investigation
  - Corrosion resistant coatings are also being explored as mitigation and repair options.
- More testing needs to be performed



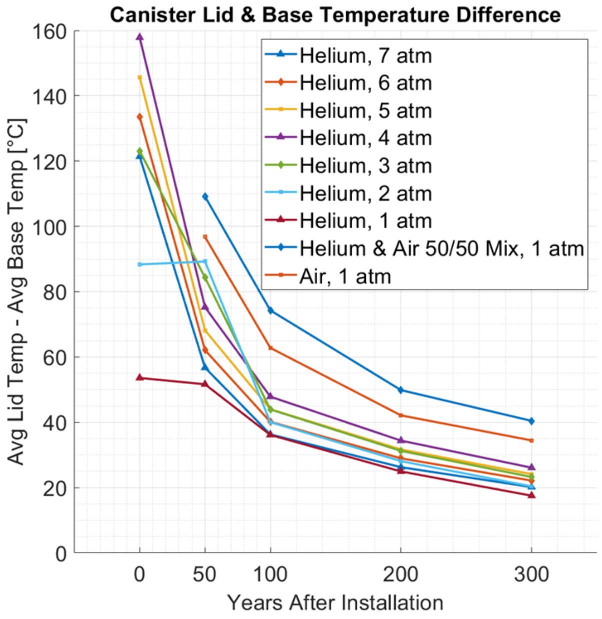
Example of Stress Corrosion Cracking

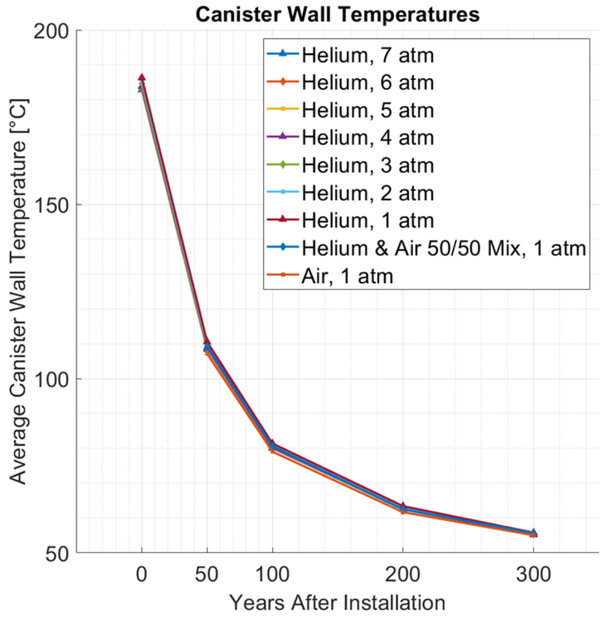
CANISTER / CASK BEHAVIOR

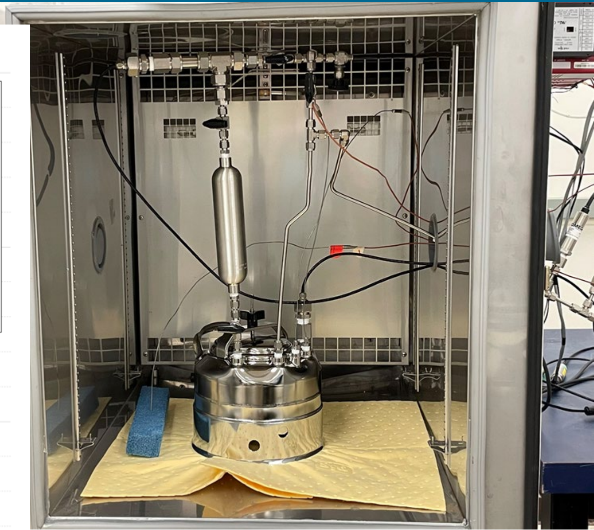
Thermal & Drying

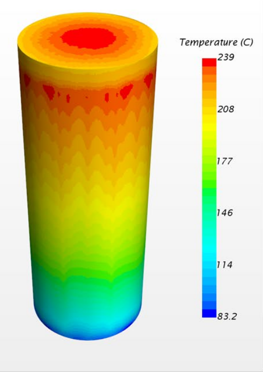
FY21 Thermal & Drying and Water Detection

- Modeled the effects of variable canister He pressure to determine if canister temperatures can be used to detect a leak
- Testing gas sampling and humidity detection using well-controlled atmosphere in equilibrium
- Detection of water in a canister using guided ultrasonic waves

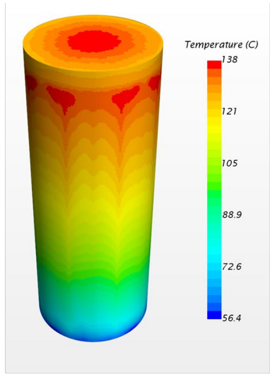




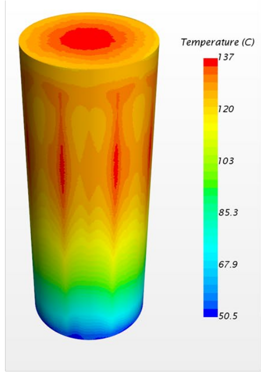




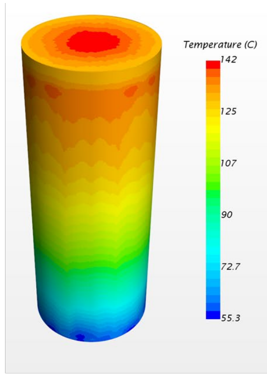
35 kW Heat Load
7 atm He



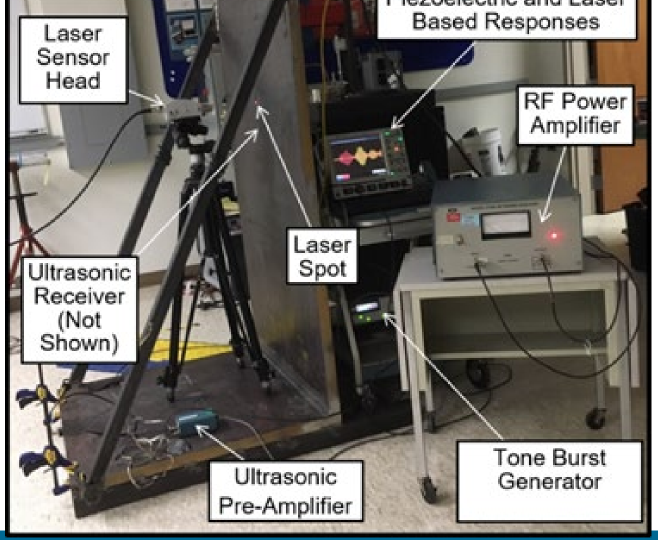
15 kW Heat Load
1 atm He



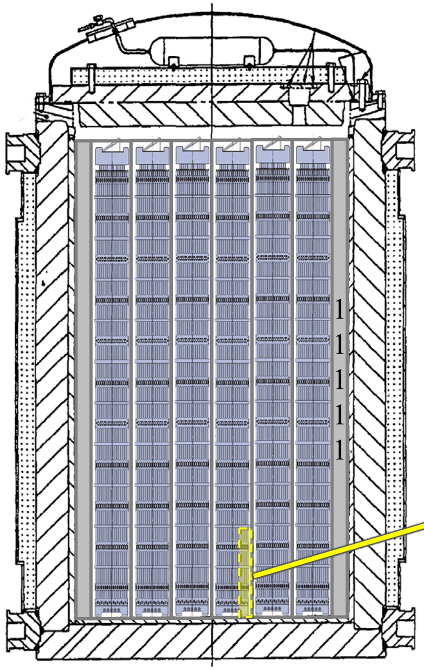
15 kW Heat Load
1 atm He/Air
50/50 Mix



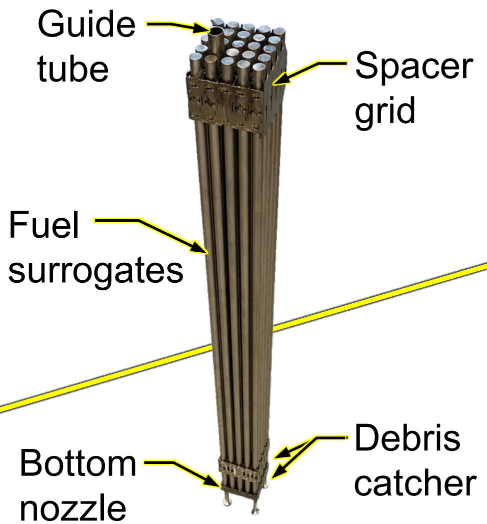
15 kW Heat Load
1 atm Air



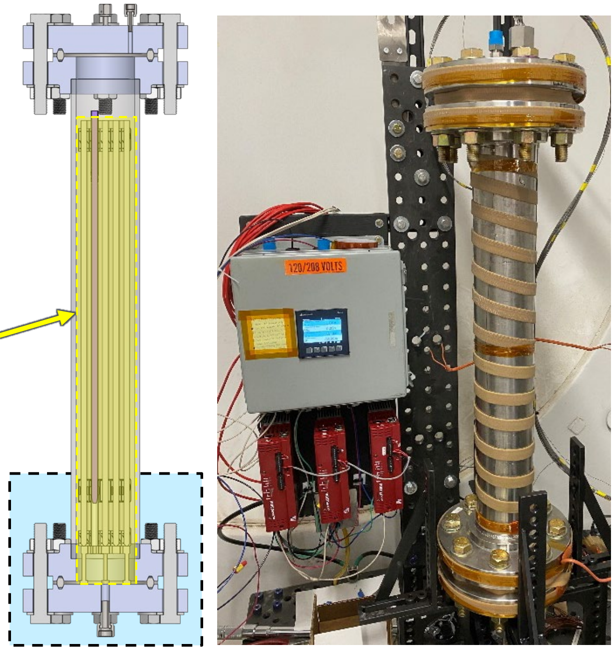
Drying Cycle Simulations



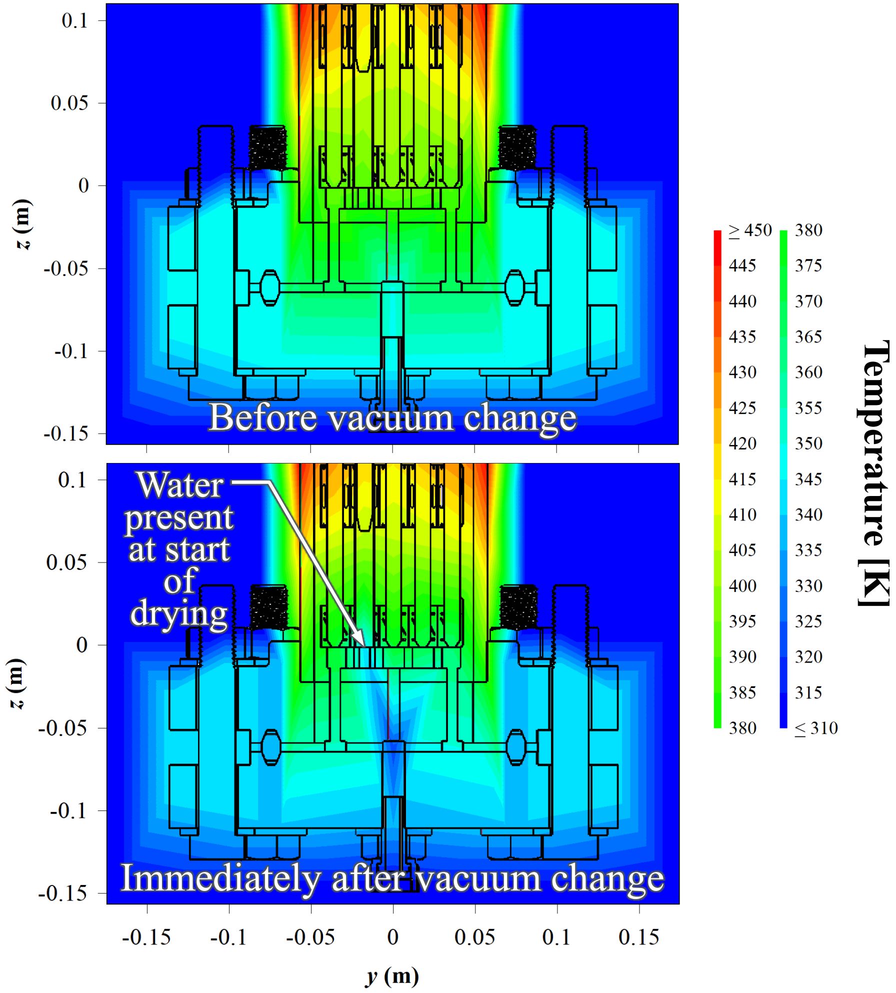
High Burnup Demonstration



5×5 Dashpot Region



Dashpot Drying Apparatus



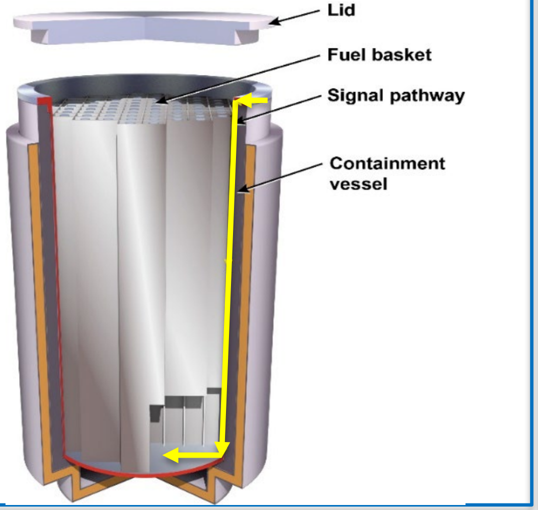
- Small scale drying apparatus
  - One 5×5 section of fuel from dashpot region
  - Heat up and pressure histories from High Burnup Demonstration
  - Capable of detecting water during drying
    - Also measure residual water content with mass spectrometry

Non-Invasive Water Detection in Dry Storage Cask

Ryan M. Meyer, Chen Zhang, Naveen K. Karri, Morris S. Good – PACIFIC NORTHWEST NATIONAL LABORATORY

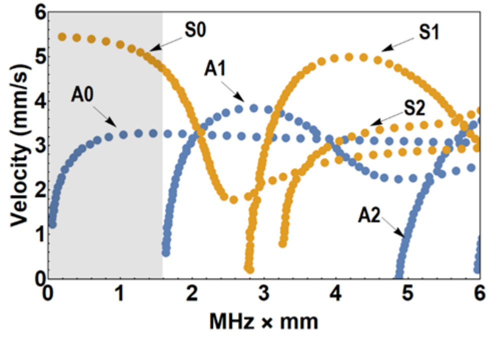
1.0 Concept

Technique to detect water inside of loaded dry storage casks with sensors mounted on accessible, exterior surfaces of cask.



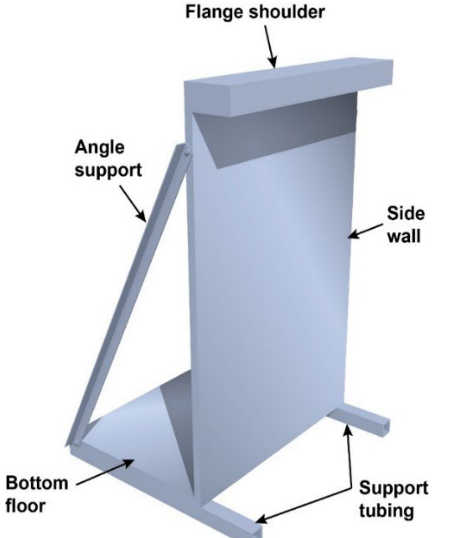
2.0 Approach

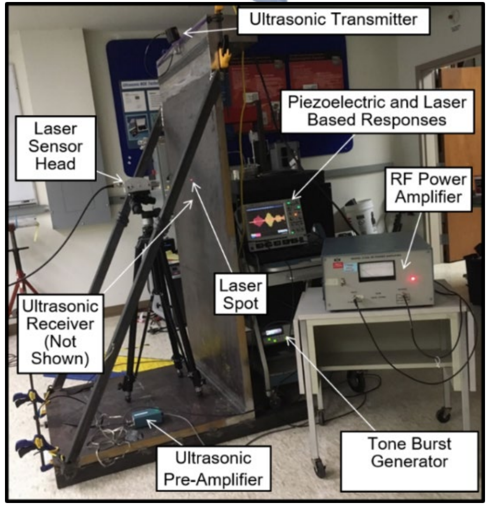
Interrogate for water utilizing sensing with guided ultrasonic wave signals that propagate from external sensors through the walls of the cask.



3.0 Laboratory Testing

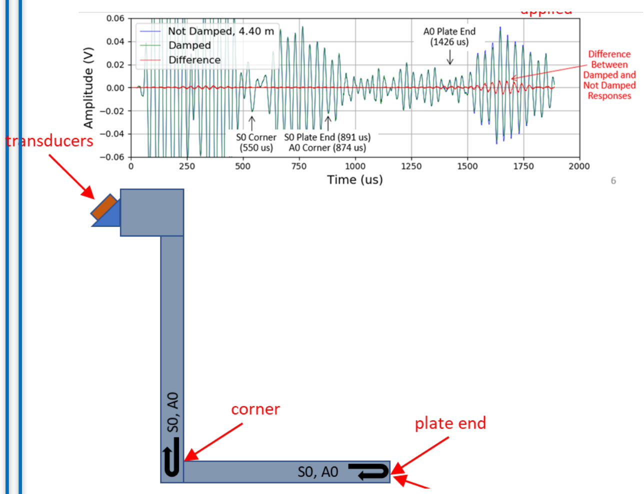
Mockup designed and fabricated to simulate relevant features of signal pathway in cask.

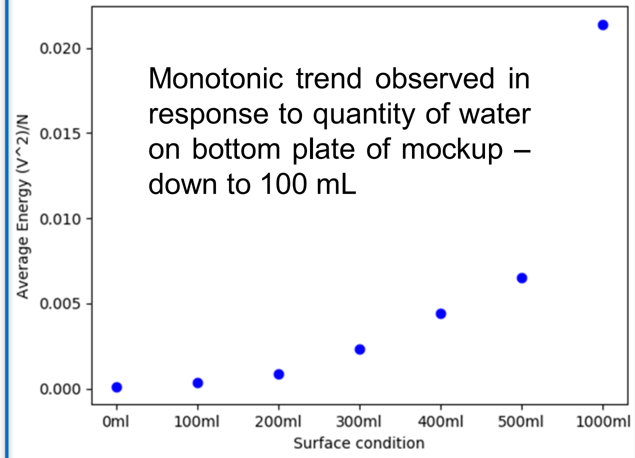




4.0 Laboratory Results

Sensitivity to water tested from 100 mL to 1.0 L of water. Baseline (dry) signal response subtracted from water responses.

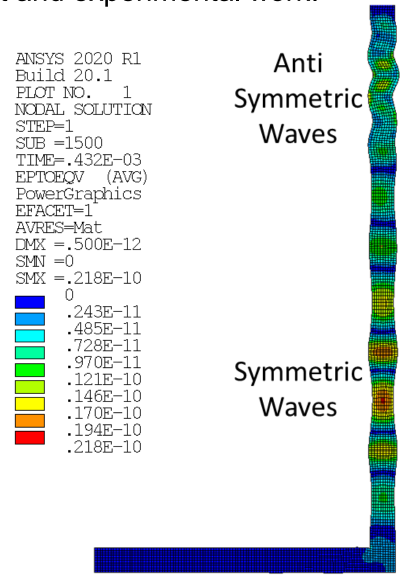




Monotonic trend observed in response to quantity of water on bottom plate of mockup – down to 100 mL

5.0 Numerical Modeling

Finite Element Analysis (FEA) simulation of guided ultrasonic wave mode propagation in mockup components to guide sensor development and experimental work.



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ANSYS 2020 R1
Build 20.1
PLOT NO.   1
NODAL SOLUTION
STEP=1
SUB =1500
TIME=.432E-03
EPTOEQV  (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.500E-12
SMN =0
SMX =.218E-10
      0
      .243E-11
      .485E-11
      .728E-11
      .970E-11
      .121E-10
      .146E-10
      .170E-10
      .194E-10
      .218E-10
```

6.0 Ongoing Efforts

Efforts continue to develop and enhance sensor capability.

- Investigate impact of internal hardware on water detection
- Investigate effect of distribution of water over bottom surface
- Search of “signatures” of presence of water that alleviate need for baseline signal subtraction.

Thermal and Drying - Status

- Residual water (vapor) remaining from drying procedures can provide precursor to fuel cladding corrosion
- However, small quantities of residual water not expected to result in significant fuel cladding corrosion
- Assumptions about potential quantities of residual water have not yet been corroborated with field experience
- Much more work needs to be completed before conclusions can be made.

CANISTER / CASK BEHAVIOR

Full Scale Canister Testing

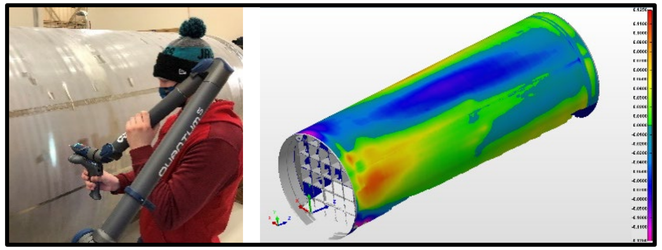
Full-Scale Canister Testing

- DOE-NE supplied 15 canisters
  - 6 TN-32PTH2 and 9 TN-24PT4
  - Delivered to SNL, PNNL, ORNL, and EPRI
- Several different research projects scheduled and proposed
  - Canister deposition sampling
  - Thermal and drying
  - Stress corrosion cracking
  - Seismic
  - Cold sprays
  - Filler (moderator exclusion)

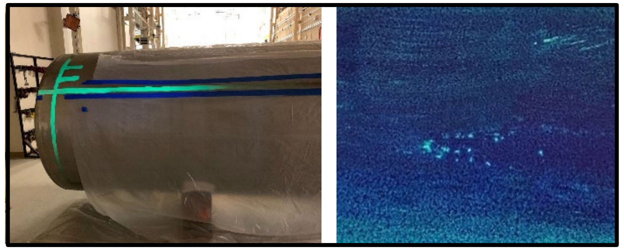
Canister Deposition Field Demonstration (CDFD)

- Purpose: Measure composition and quantity of depositions on the surface of storage canisters
- Place multiple electrically heated canisters in storage configuration
  - Drive realistic thermal and flow patterns
  - Periodically sample canister surface deposits on the order of once per year or every other year
- Current activities
  - Prototype heater testing and model calibration
  - Extensive baseline characterization of canister surfaces

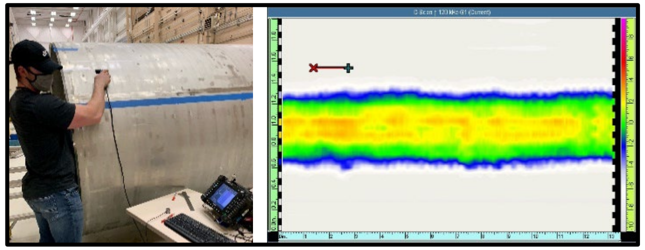
Prototype heater testing



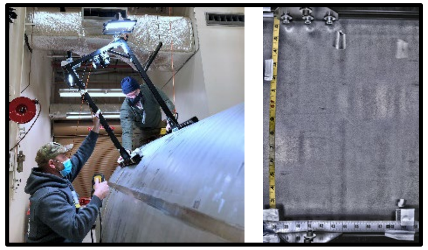
3D surface scans



Dye penetrant inspections



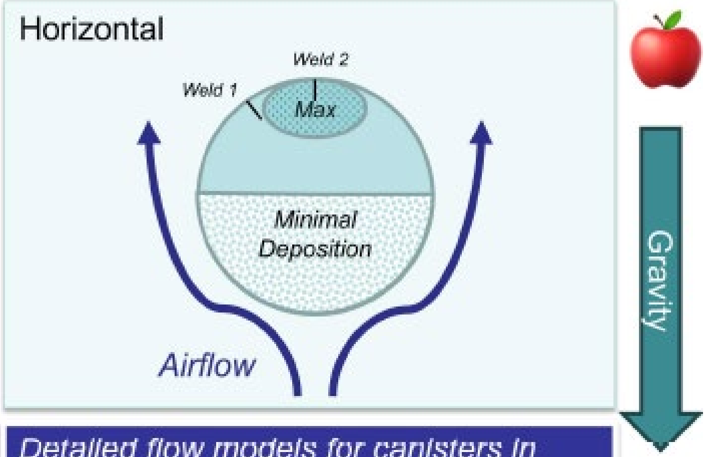
Eddy current array inspections



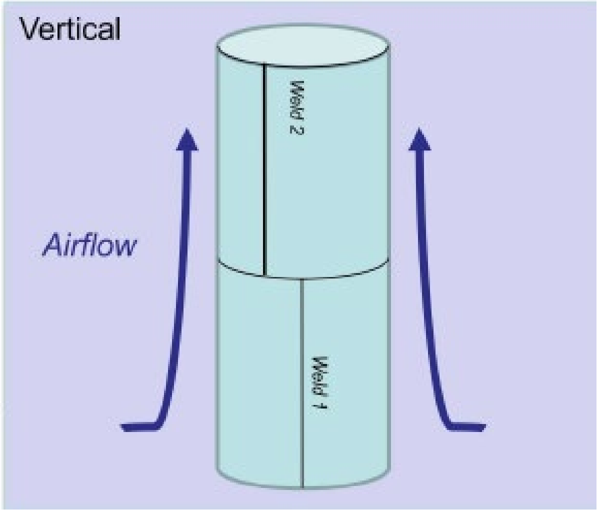
Photomapping

Full Scale Canister Testing - Status

- It is believed that some salts will deposit on a canister but exactly how much is not known
- Full scale testing must be done to know the exact amount of salt deposition

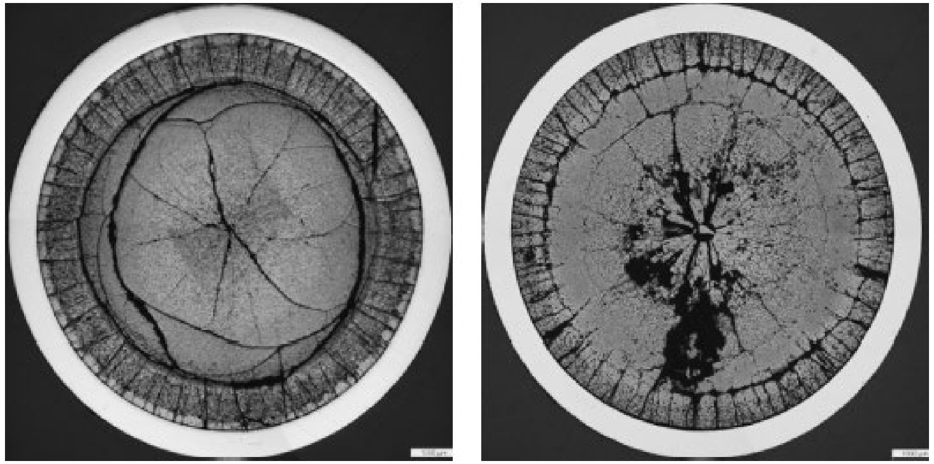


Detailed flow models for canisters in concrete overpack needed!



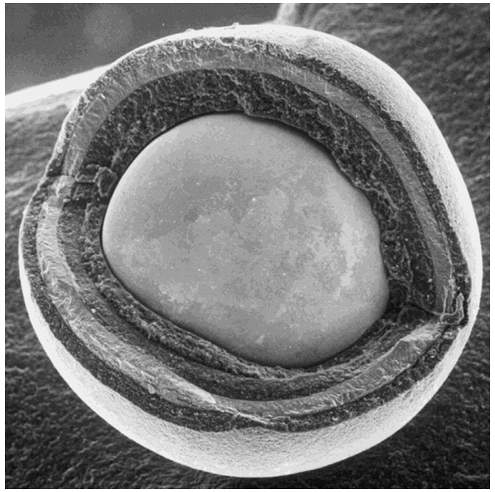
Accident Tolerant Fuel

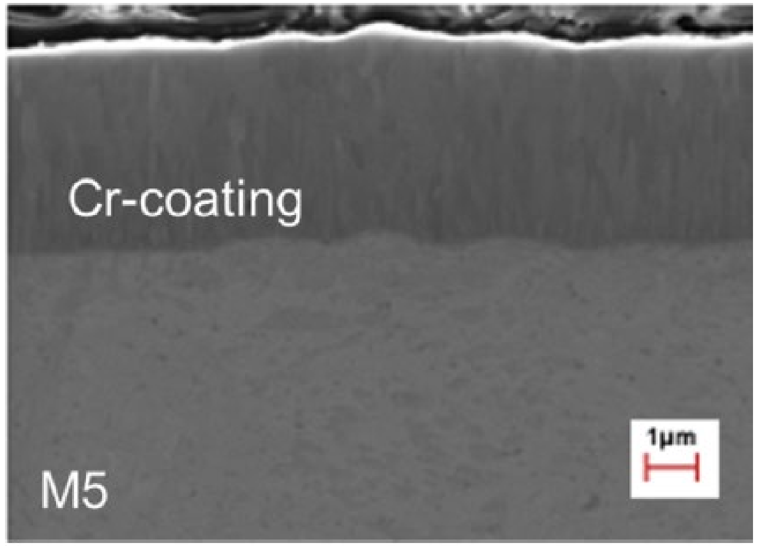
- Complete sibling pin testing 2023 +/-
- ATF focus on LTAs currently in core (high burnup expected ~2025)
  - Cr-doped fuel
  - Cr-coated cladding
- HALEU (effects of higher burnup)
- Advanced Reactor Demonstration Program (both fast reactors)
  - Metal fuel (TerraPower Natrium reactor)
  - TRISO fuel (X-Energy Xe-100 HTGR)
- Hope to test ATF in 2025
- Continue to work with NE-5, NRC, NEI and EPRI



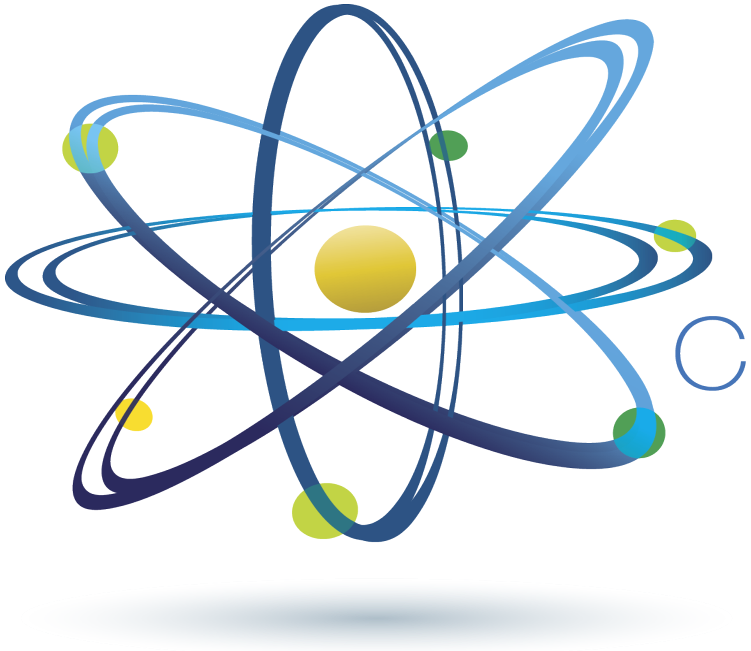
(a) Std Opt2 pellets (b) D1 pellets

Arborelius et al. *Journal of Nuclear Science and Technology* Vol 43, No 9 (2006)





Bischoff et al. *Nuclear Engineering and Technology* 50(2018)



Clean. **Reliable.** **Nuclear.**