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US DOE Scientific-Technical R&D Work to Address Safety Assessments of Spent Nuclear Fuel Storage and Transportation

University of New Mexico, Nuclear Engineering Department

October 31, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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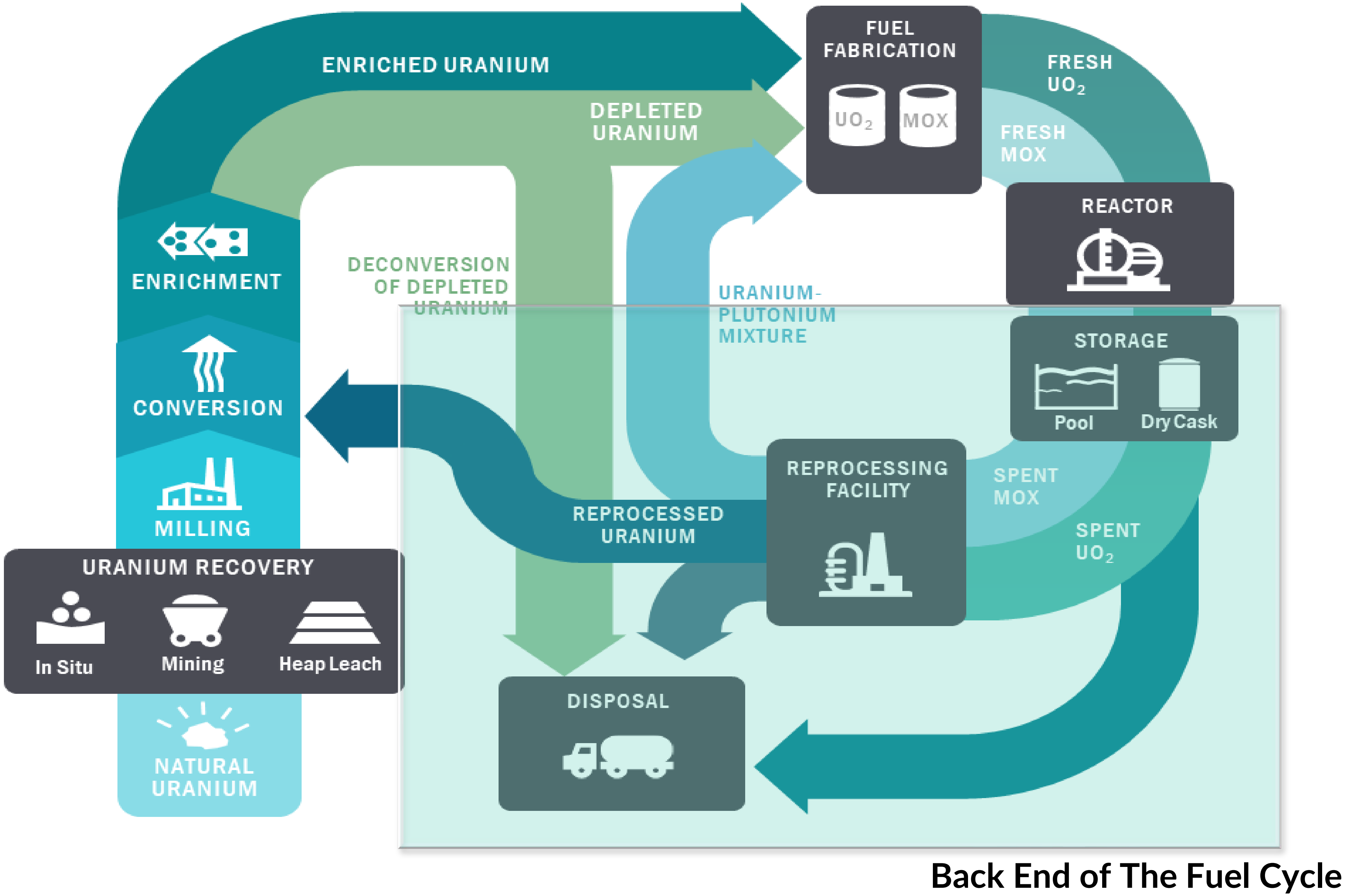
Table of Contents

- Regulatory Framework
  - NWPA
  - Standard Contract
  - Continued Storage Rule
- Focus of US Storage, Transportation and Disposal Research & Development Program
  - Fuel Integrity Testing
  - Transportation (video) & results
  - Storage Container Corrosion and Mitigation
  - Consequence of a Storage Container Crack

Nuclear Energy Fuel Cycle



Regulatory Framework and Public Perceptions

Timeline of the U.S. Nuclear Waste Program

1982
Nuclear Waste Policy Act of 1982:
- EPA sets standards
- NRC grants license
- DOE sites, develops license, and manages repository.

DOE develops “Standard Contracts” with utilities:
- DOE will take fuel and open repository by 1998
- Utilities to provide “bare” fuel from pools to go in TADS.

1984
Waste Confidence Rule: The fuel can be stored safely for 30 years after the plant closes and then it will go into a repository.

1987
Nuclear Waste Policy Amendments Act selects Yucca Mountain as sole site for further characterization

Load first dry storage canister of spent nuclear fuel

1998
DOE fails to take ownership of SNF from Utilities and open repository.

Utilities sue for breach of their “Standard Contracts.”

2002
Yucca Mountain Site Recommendation
Site is designated by DOE and President G.W. Bush as suitable for repository development and licensing

June 3, 2008
Yucca Mountain Repository License Application submitted to the NRC

2010
Obama Administration decides Yucca Mountain is not workable; Project suspended

Spent nuclear fuel continues to be generated at ~2,200 MTHM/yr.

August 26, 2014
US NRC “Continued Storage Rule”
Generic EIS of “Small” Impact may be used for waste storage.
Repackage every 100 years

2018 to Present Day
SNF continues to accumulate in dry storage at commercial reactor sites (>2000 Metric Tons HM per year)

1982 | 1986 | 1990 | 1994 | 1998 | 2002 | 2006 | 2010 | 2014 | 2018

US NRC Waste Confidence Rule (1984)

Purpose: To generically assess whether the NRC could have reasonable assurance that radioactive wastes "can be safely disposed of, to determine when such disposal or offsite storage will be available, and to determine whether radioactive wastes can be safely stored onsite past the expiration of existing facility licenses until offsite disposal or storage is available"

This Decision provided an EA and Finding of No Significant Impact (FONSI) to ... rule

The Commission Made 5 Findings:

Revised numerous times and then vacated by US Court of Appeals in 2010

1. A mined geologic repository is technically fe...

2. One or more repositori... ...able by the years 2007—2009

3. Radio... ...nd spent fuel will be managed in a safe manner until sufficient repository capacity is

4. Spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 30 years beyond the expiration of that reactor's operating license at that reactor's spent fuel storage basin or at either onsite or offsite ISFSIs; and

5. The Commission finds reasonable assurance that safe independent onsite or offsite spent fuel storage will be made available if such storage capacity is needed.

US NRC Continued Storage Rule (2014)

Generic Environmental Assessment can be used which stated small* environmental impact over 3 time periods after the end of the reactor's license.

60 years "Short"	100-years "Long"	Indefinite
Routine maintenance of pools and dry storage	Routine maintenance of dry storage One-time replacement of ISFSI and spent fuel canisters and casks Construction and operation of a dry transfer system at each ISFSI	Same as "long" but the replacement activities would occur every 100 years.

Assumptions:

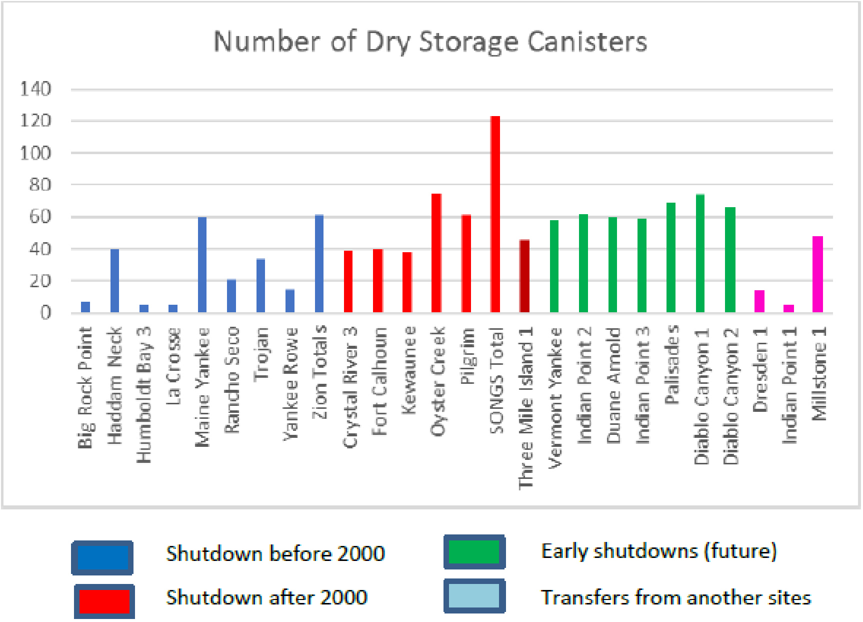
1. Continued Institutional Controls
2. The NRC would continue to regulate spent fuel storage to protect public health and safety and security.

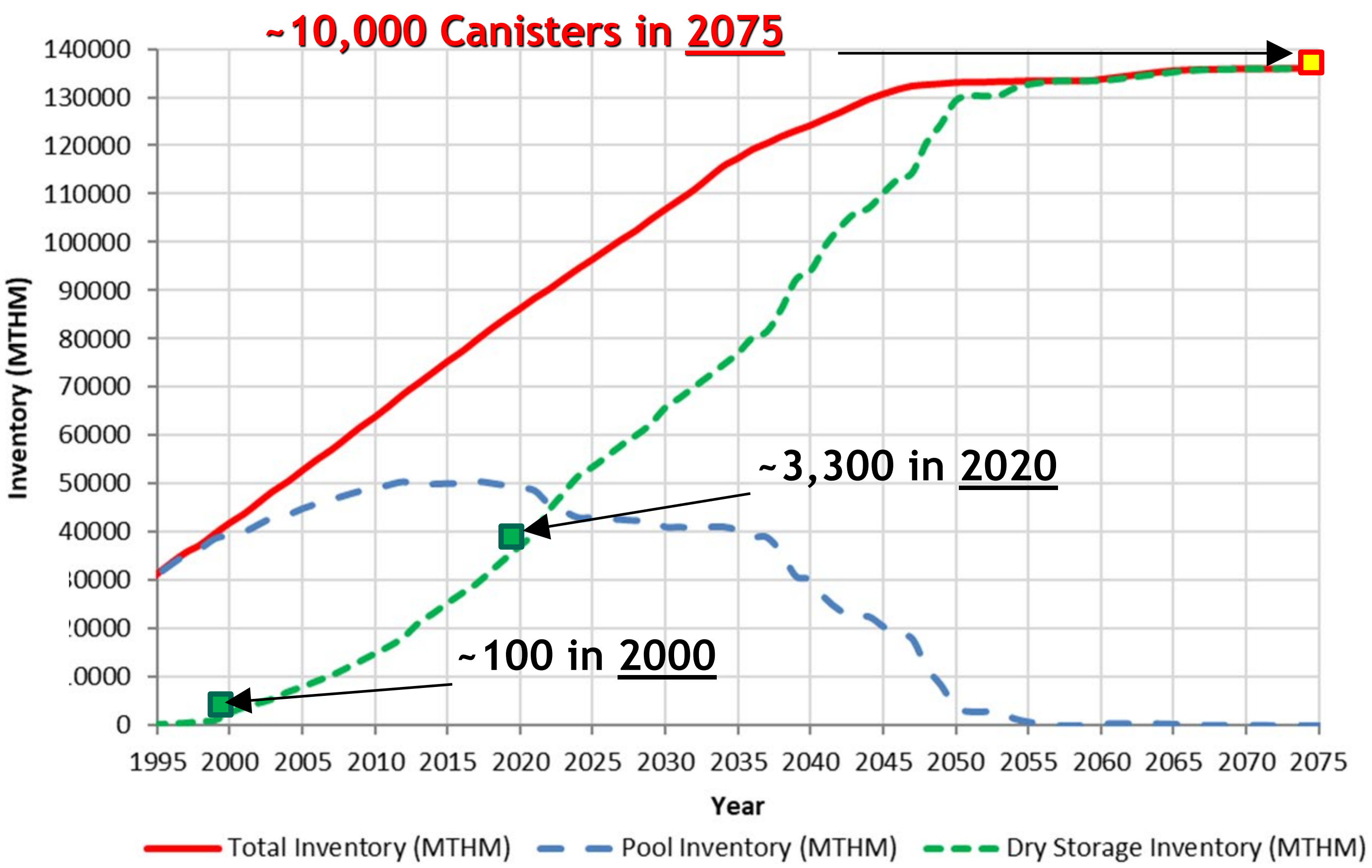
* "Commission has concluded that radiological impacts that do not exceed permissible levels in the Commission's regulations are considered small."

Federal; Register. Vol; 79. No 182. 9/19/2014

2009-Present: Current State – US Commercial Inventory

- Approx. **85,000 MTHM** (metric tons heavy metal) **of commercial SNF in storage** in the US as of Dec. 2020 (red line)
- Approx. **38,000 MTHM in dry storage at reactor sites**, in approximately 3,300 cask/canister systems (green dashed line)
  - Balance in pools, mainly at reactors (blue line)
  - Approx. **2200 MTHM of SNF generated nationwide each year**





Projection assumes full license renewals and no new reactor construction or disposal (updated from Bonano et al., 2018*)

Kalinina et al, Seismic Shake Test Plan, SAND2021-11207 R

Reprocessing: Why don't we reprocess our waste?

"The processes used to separate spent nuclear reactor fuel into nuclear materials that may be recycled for use in new fuel and material that would be discarded as waste. The fuel would be used in breeder reactors, which turned out to be too expensive, especially when the cost of reprocessing was added. Then the discovery of huge deposits of high-grade uranium in Australia and Canada has flooded the market with cheap uranium."

US Policy:

Banned by President Carter in 1982 for proliferation and cost reasons. Ban lifted by President Reagan, but not funded. In 1999, the DOE started to build a MOX fuel fabrication facility, but construction stopped in 2011 after costs soared nearly $5B.

Economics:

Reprocessing cost twice that of deep geologic disposal plus then you will still need deep geologic disposal, Japan 2011 and US National Academy of Sciences 1996.

The US is generating ~2,200 MTHM of SNF a year, directly disposing of the existing SNF inventory would still provide sufficient feedstock to support future advanced reactors. *Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*, ORNL/TM-2012/308, FCRD-FCT-2012-000232

Safeguards:

"U.S. Government policy turned against reprocessing after India, in 1974, used the first plutonium recovered by its U.S.-assisted reprocessing program to make a nuclear explosion."

Managing Spent Fuel in the United States: The Illogic of Reprocessing. Frank von Hippel. International Panel on Fissile Materials, 2007

Table 2. Spent-fuel disposal costs in four scenarios for the French Fuel Cycle[61]
(Billions of 2006 $, 58,000 tons of spent fuel)

	Percentage of Spent LEU Fuel Reprocessed			
	100% (Derived scenario)	67%	27% (Reprocessing ends in 2010)	No Reprocessing
Back end costs	84	74	61	41
Front end cost savings from plutonium recycle	-10	-8	-2	0
Net costs	74	66	59	41

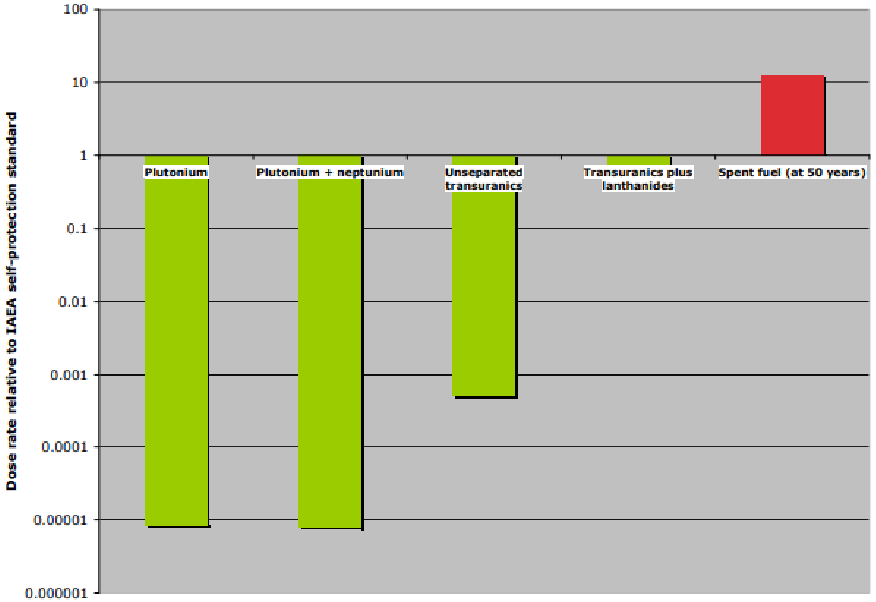
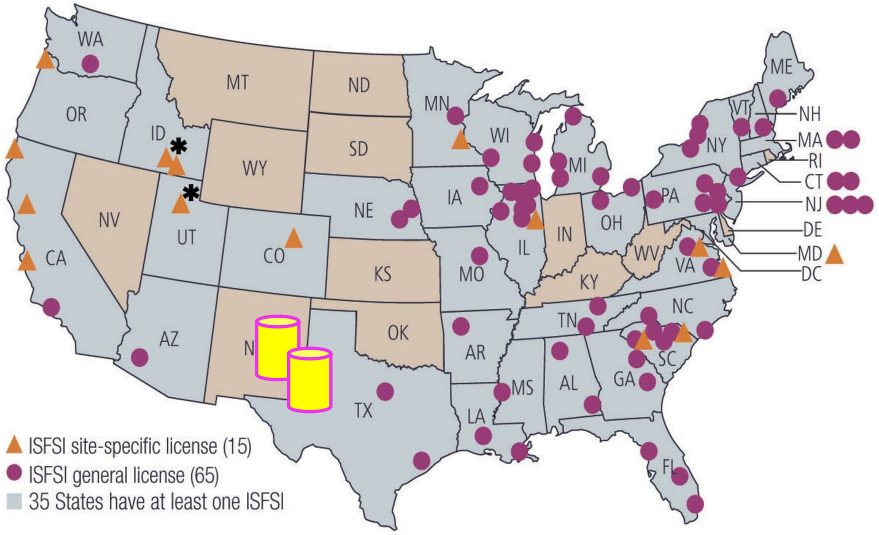


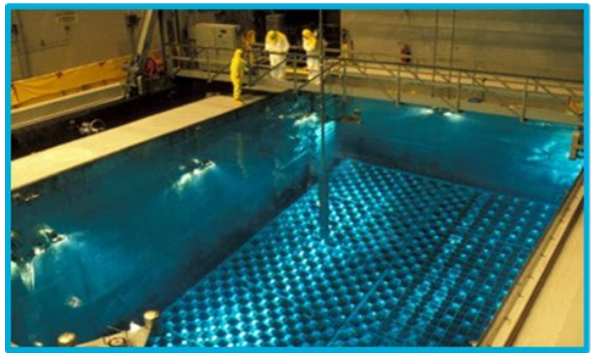
Figure 7. Factors by which dose rates from 1-kg spheres of transuranic metal produced by various versions of UREX+ fall short of the IAEA threshold for self protection (1 Sievert or 100 rems per hour at one meter). For example, the dose rate from unseparated transuranics is about 0.001 or one thousandth of the self-protection standard. [69]

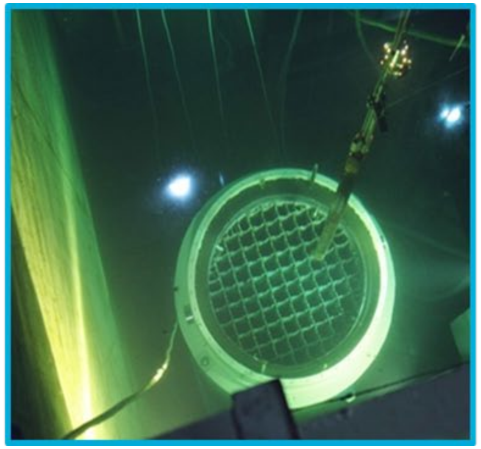
Commercial SNF is in Temporary Storage at 75 Reactor Sites in 33 States

- US pools have reached capacity limits and utilities have implemented **dry storage**
- Some facilities have shutdown and all that remains is **"stranded" fuel** at an independent spent fuel storage installation (ISFSI)
- Private sector applications to the NRC for consolidated interim storage:
  - Interim Storage Partners in Andrews, TX: granted 9/2021.
  - Holtec in Eddy/Lea Counties, NM: in review

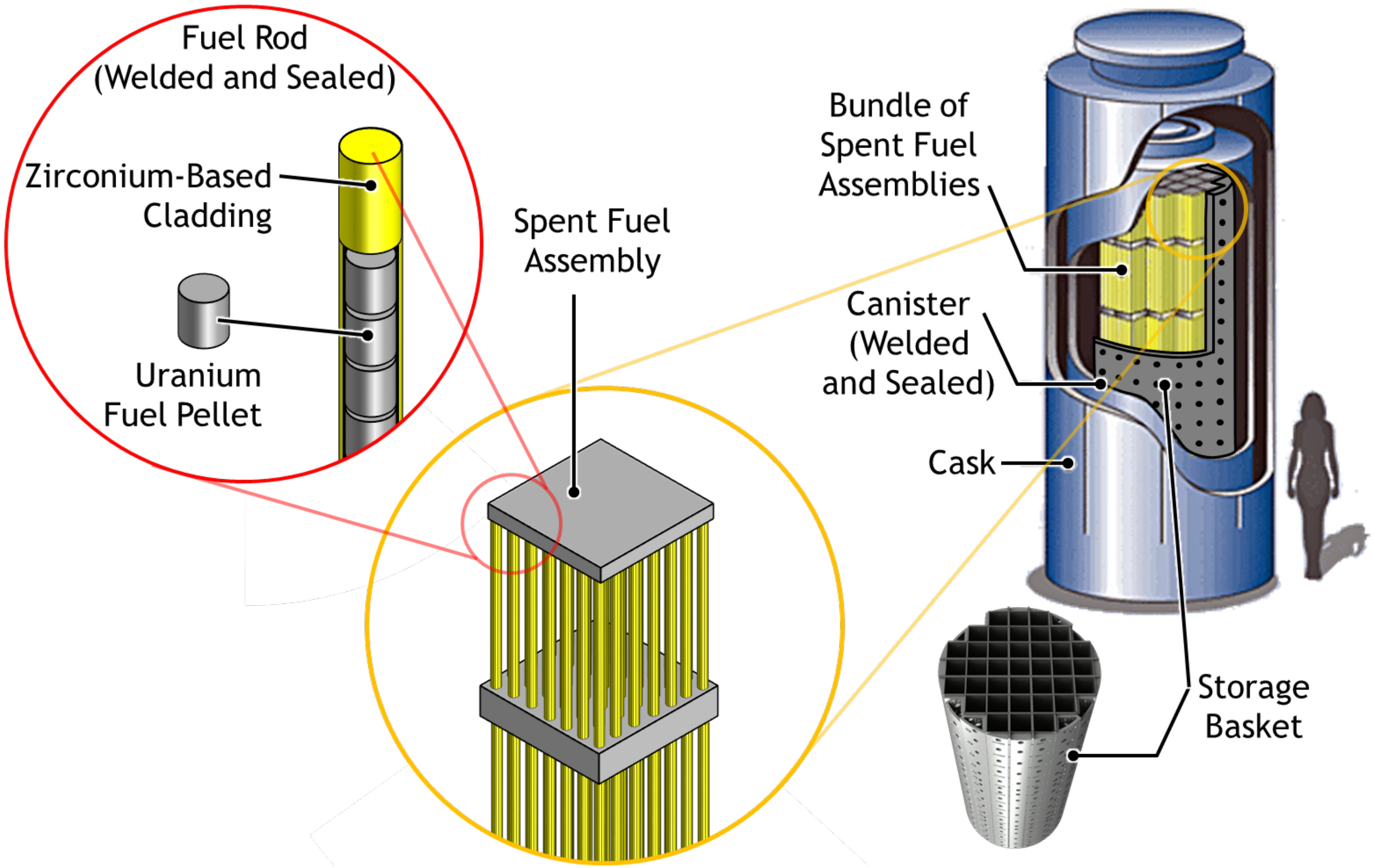
Licensed and Operating Independent Spent Fuel Storage Installations by State







What Are Spent Fuel and Dry Cask Storage Systems (DCSS)?

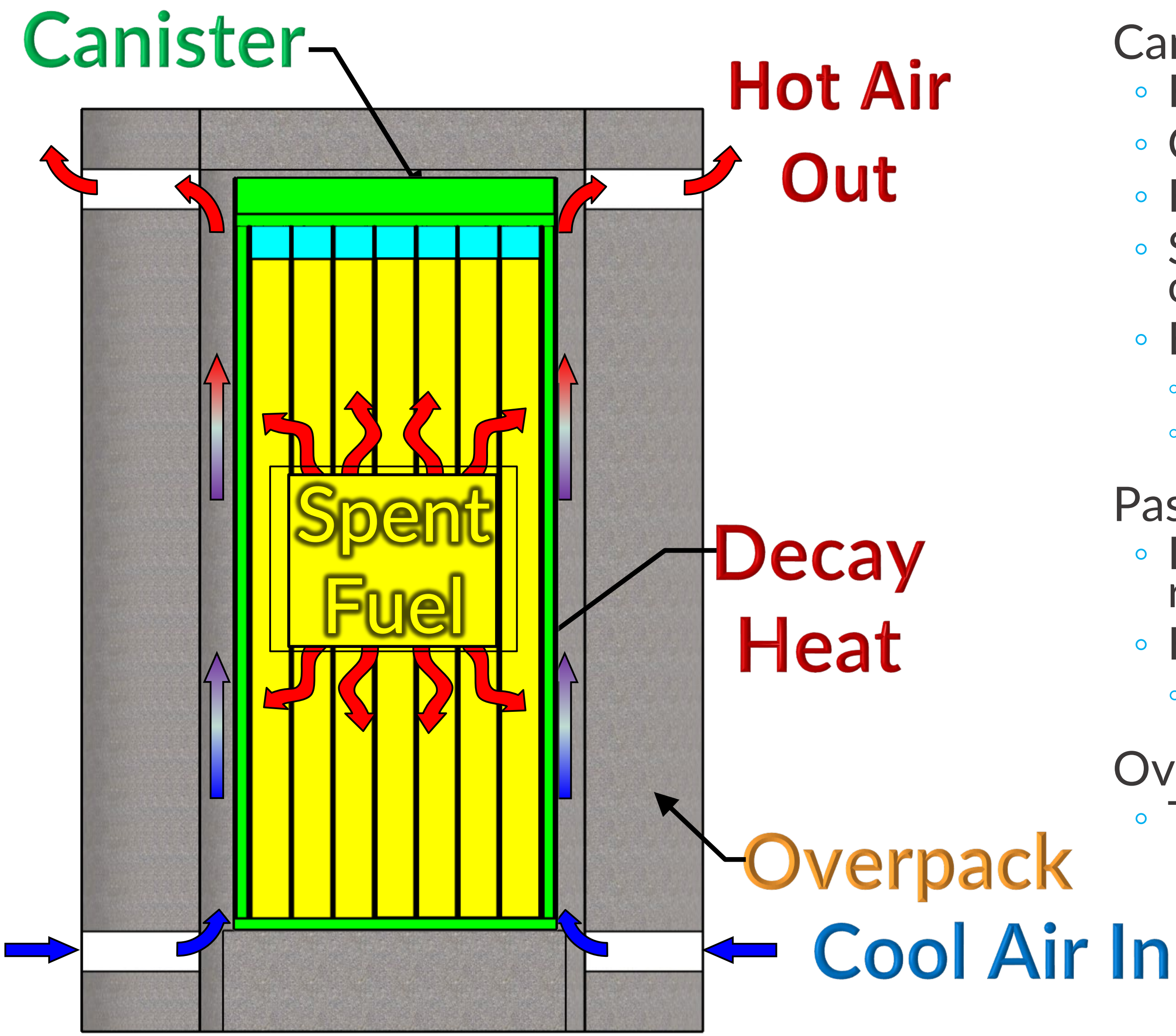


Aboveground

Belowground

Horizontal

How Storage Casks Work



Canister holds spent fuel assemblies
- Fuel rods individually sealed (welded)
- Canister also sealed (welded or bolted)
- Fuel gives off heat from radioactive decay
- Stainless steel cylinder with regularly spaced compartments
- Backfilled with inert helium
  - No chemical interaction
  - Good thermal properties (Think double pane windows in reverse)

Passively cooled storage
- Decay heat conducted, convected, and thermally radiated to canister wall
- Heat externally removed by natural air flow
  - Air not in contact with spent fuel

Overpack provides shielding from radioactivity
- Typically made from reinforced concrete

Focus of US Storage, Transportation and Disposal Research & Development Program

Used Fuel Disposition R&D Campaign Mission

The *DOE Office of Used Nuclear Fuel Disposition Research and Development and nine national laboratories participate in the DOE Office of Nuclear Energy's "Used Fuel Disposition Campaign"*

Campaign Mission: to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles

Los Alamos National Laboratory
Pacific Northwest National Laboratory
Argonne National Laboratory
Sandia National Laboratories
Berkeley Lab
SRNL Savannah River National Laboratory
INL Idaho National Laboratory
ornl Oak Ridge National Laboratory
Science in the National Interest
Lawrence Livermore National Laboratory

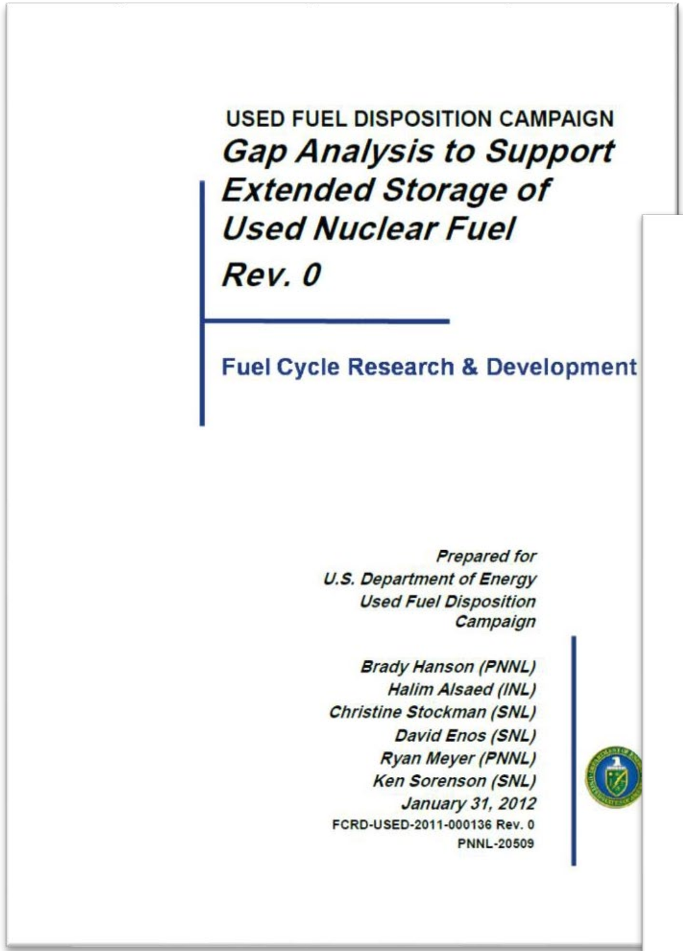
Goal: Understanding fuel integrity during extended storage and subsequent transportation.

With a focus on high burnup fuel (>45 GWd/MTU)

Gap Analyses

After the suspension of the Yucca Mountain Project, the DOE needed to determine what the potential concerns were if commercial fuel remained stored at the nation's nuclear power reactors for decades or centuries, instead of going into a deep geologic repository, as was planned for Yucca Mountain

- The DOE funded the national labs to determine what R&D was needed to develop the technical basis for the extended storage and subsequent transportation of spent nuclear fuel. This started by completing a Gap Analysis in 2012. That Gap Analysis has been updated multiple times.



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

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January 31, 2012
FCRD-USED-2011-000136 Rev. 0
PNNL-20509

Spent Fuel and Waste Science and Technology Storage and Transportation 5-Year R&D Plan

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology

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August 28, 2020
M2SF-20SN010201062
SAND2020-9310 R

DOE Spent Nuclear Fuel Storage and Transportation R&D Plan Overview

GAPS

Demo/Sibling Pin Testing	• Continue collecting temperature data from the Research Project Cask and plan for its transport • Develop a gap analysis for ATF and higher burnup fuels	• Continue and complete Phase I sibling pin testing. • Develop Phase 2 test Plan and Assessment of Gross Rupture. • Obtain Data on BWR, IFBA, and ATF cladding/fuels • Clean up hotcells and dispose of waste.	• Prepare facility and move canister
Thermal Profiles	• Complete Round Robins • Perform Sensitivity and Uncertainty Analyses • Conduct small & large scale vertical and horizontal testing	• Continue testing/analyses on canistered and bare fuel systems in horizontal and vertical orientations, emplacement in transportation cask, leaking canisters, plugged vents, wind effects, and time to boil.	Close Gap
Stress Profiles	• Design, Fabricate, and Test 8-Axle Railcar • Complete 30cm drop test analysis • Determine pinch loads and seismic loads adding simulated irradiated materials	• Determine the magnitude of pinch loads via drop tests in the horizontal and Vertical Orientations adding simulated irradiated materials.	• Build cumulative effects models • Collaborate with the Republic of Korea on their MMTT program
Welded Canister- Atmospheric Corrosion	• Continue corrosion initiation and crack growth rate tests • Continue brine stability testing and collect additional dust samples • Refine, improve, and validate deposition models	• Obtain residual stress measurements on different canisters • Perform small scale and larger-scale testing to provide data for deposition modeling	• Conduct a full-scale canister deposition demonstration at various heat loads to provide data on deposition and brine stability • Examine multiple repair and mitigation techniques to extend the lifetime of a canister
Drying	• Design and perform lab-scale tests with well-defined conditions to improve sampling and analysis techniques • Collect and analyze in-service gas samples	• Design and perform larger-scale tests using heater assemblies to quantify residual water as a function of drying parameters	• Design and perform a full-scale test using heater assemblies • Perform a consequence analysis Close Gap
Canister Failure Consequence	• Grow through wall stress corrosion cracks for testing • Incorporate particle size distribution of SNF released in different scenarios • Test and model flow through more realistic microchannels and aerosols. • Analyze particulates captured in filters used during the drying process of failed fuel.	• Test viability of canister repair and mitigation techniques under realistic pressure and canister conditions. • Measure aerosol release and depletion in realistic DSC environments	Close Gap

EPRI/DOE High Burnup Demonstration Project

Also called the "Demo Project" and the "Demo Cask"

- The High Burnup Demonstration Project is being performed at North Anna Nuclear Power Plant to understand how High Burnup fuel ages during long-term storage.

  - In 2017, a cask was loaded with
    - 32 assemblies of high burnup fuel
    - 63 thermocouples placed inside the canister
      - collecting temperature data at least daily and downloaded quarterly.
  - Also in 2017
    - 25 similar fuel rods (sibling pins) were pulled from the North Anna storage pool and are being characterized/tested to document initial conditions and mechanical integrity at PNNL, ORNL, and ANL.

Loaded TN-32 for the High Burnup Demo at North Anna NPP. The solar panel is powering the 63 thermocouples inside the canister. Photo Credit: North Anna NPP

25 similar fuel rods (also called “sibling pins”) were pulled from the North Anna Spent Fuel Pool in 2017 that had very similar manufacturing and burnup histories to the fuel in the Demo Cask.

- Extensive testing is ongoing at PNNL, ORNL, and ANL to document the mechanical integrity of the fuel.
- Some of the pins are tested as-irradiated, some are heated to mimic the environment the pins experienced in the Demo cask during drying. Some are then re-heated to mimic the maximum temperature they would have during potential transport.
  - This provides data on the mechanical effects of drying and shows a worst case during transportation

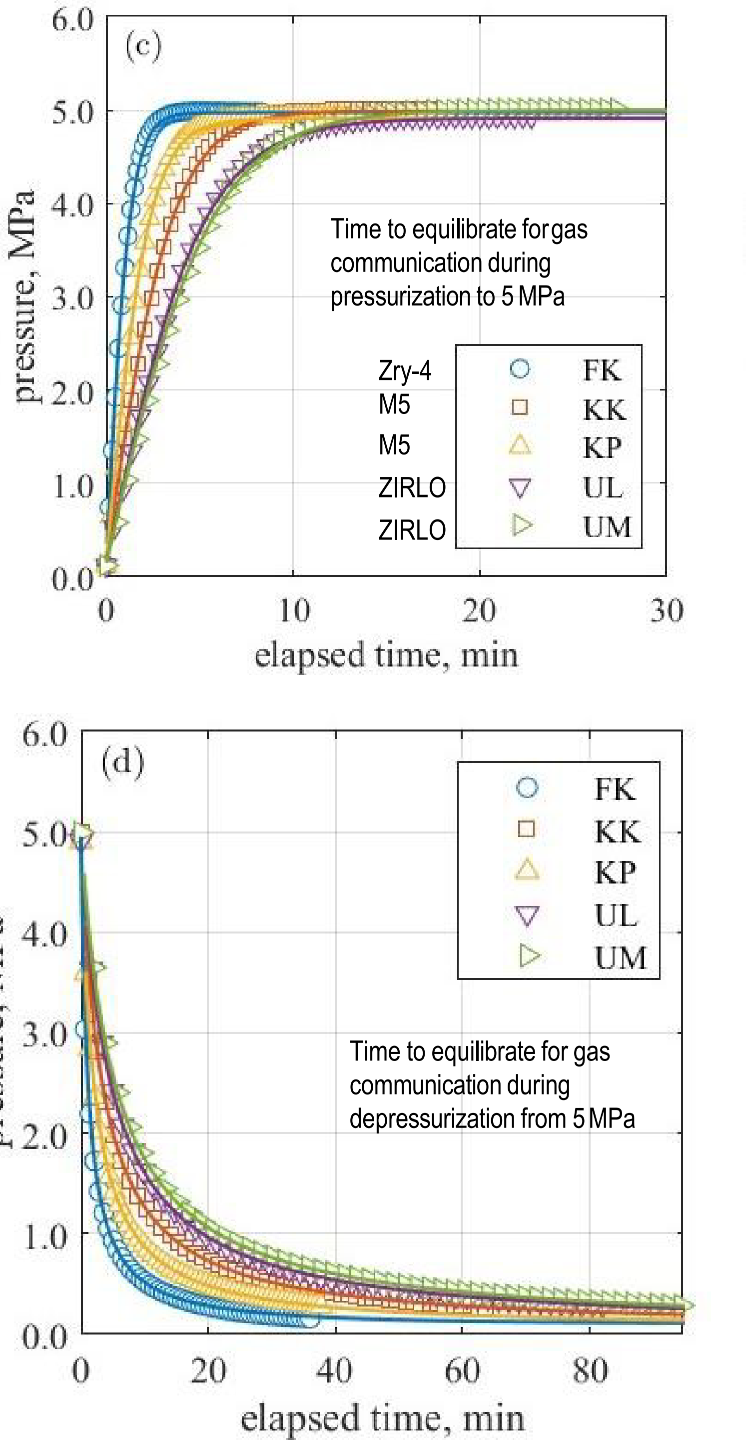
Note: This is all PWR fuel.

Gas Communication within a Spent Fuel Pin

- Rod puncture for end-of-life (EOL) rod internal pressures (RIP) and volumes and fission gas release
- ORNL tested full rods and PNNL tested ¼ length rods.
- Each segment of the 5 rods under Phase 1 (either as-received or radial hydride treatment to 400° C) had gas communication performed at EOL RIP (typically <4 MPa) and at 5 MPa
    - Excellent gas communication for all rods/segments in the ORNL and PNNL tests
- Rod internal pressure should be uniform axially during drying and initial storage

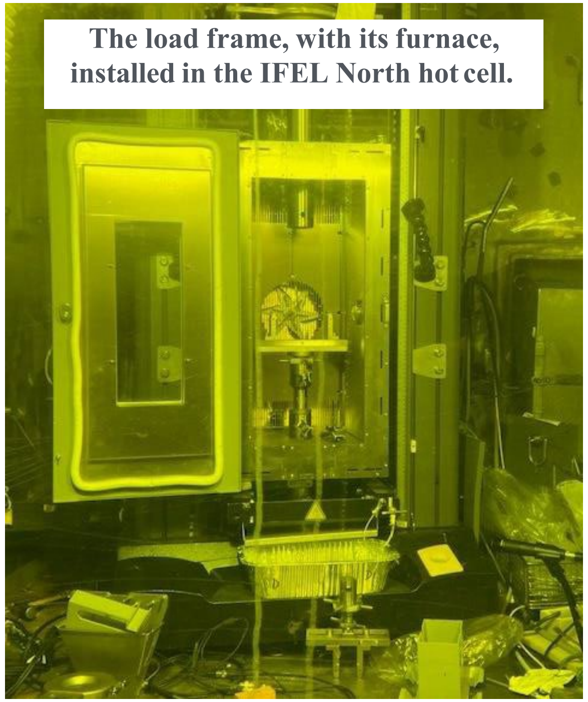
Conclusion: Internal pressures within a spent nuclear fuel rod are most likely the same from top to bottom. Therefore, there should not be extensive areas of higher rod internal pressure.

PNNL Gas Communication Results

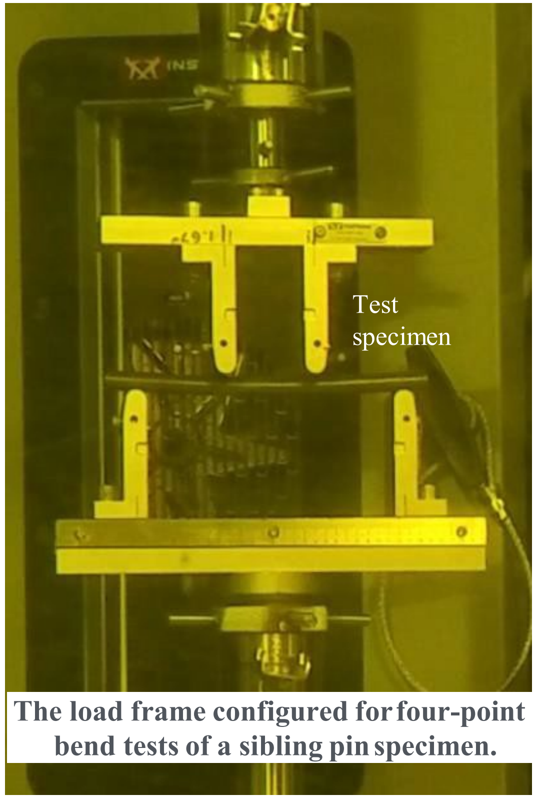


Stored Nuclear Fuel Mechanical Testing

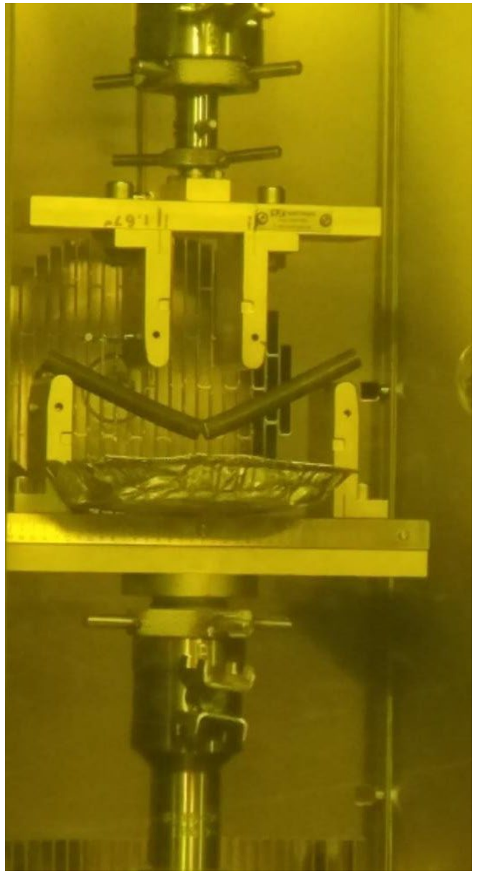
Mechanical testing in hot cells is generating mechanical data at Pacific Northwest National Labs, Oak Ridge National Labs, and Argonne National Labs. The photos of work below are from the hot cells at Oak Ridge National Labs.

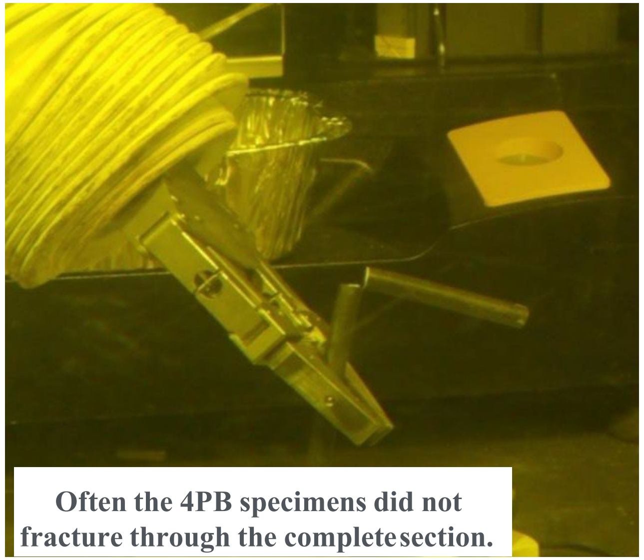


The load frame, with its furnace, installed in the IFEL North hot cell.



The load frame configured for four-point bend tests of a sibling pin specimen.



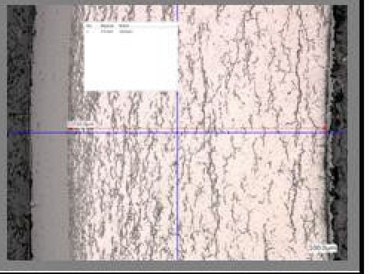
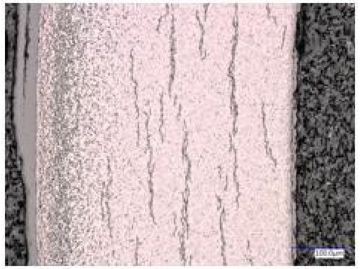


Often the 4PB specimens did not fracture through the complete section.

ORNL Metallography Samples Reveal Baseline and Heat-Treated Cladding Hydrides

- For the M5-clad rod, the heat-treatment resulted in hydride reorientation and many radial hydrides are visible, particularly at the inner diameter of the cladding
- ZIRLO-clad sister rods have short radial hydrides both before and after heat treatment
- Both the Zirc-4- and LT Zirc-4-clad rods have high hydride density and while the heat-treatment did result in reorientation, the resulting radial hydrides are very short

Conclusion: The radial hydrides that formed in the three claddings were very short and are not expected to contribute to cladding breakage.

Cladding	Baseline	Heat-treated
M5		
ZIRLO		
Zirc-4	N/A	
LT Zirc-4		N/A

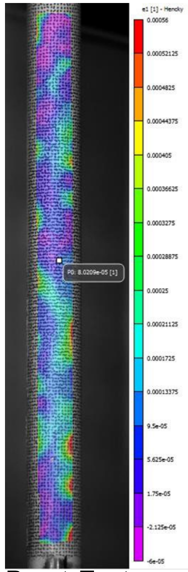
Selected METs illustrating primary hydride density and orientations for baseline and heat-treated sister rods. Photo: ORNL.

PNNL Sibling Pin Testing with Defueled Rods

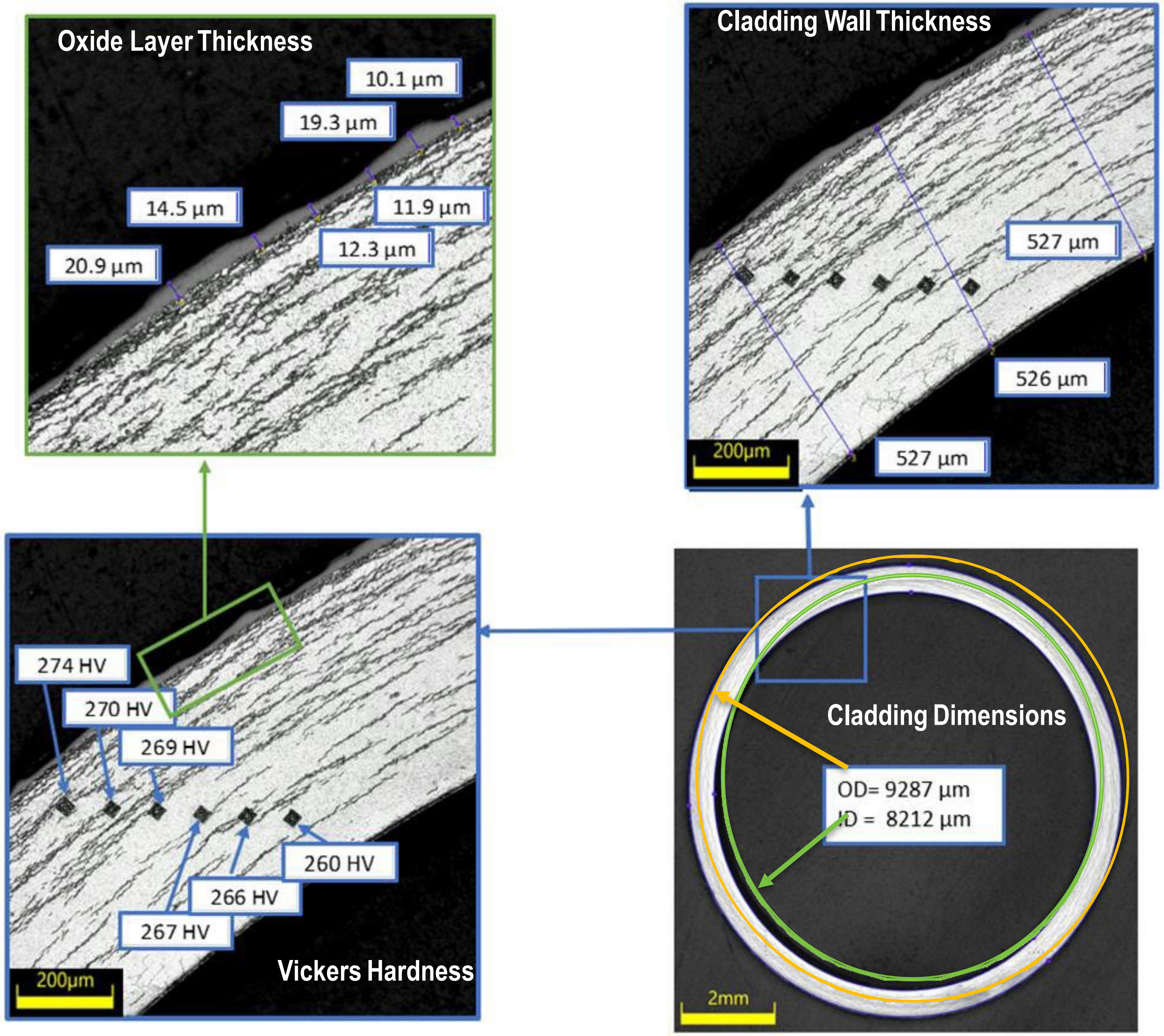
- 5 rods sectioned
  - 6 inch mechanical property specimens
  - 0.5 inch metallography samples
- Metallography samples every ~6 inches
  - OM
  - Microhardness
  - LECO total hydrogen analysis

Axial tube tensile test

4 point bend test



Burst Test Stress Analysis



Metallography from ZIRLO sibling pin 6U3L8 (sample UL-1-2; 3049 mm – 3061 mm) Photos from PNNL

Conclusions from Sibling Pin Test

- Initial tests indicate that the fuel will not generate radial hydrides during prototypic drying conditions.
- This indicates that the fuel will remain ductile until it reaches room temperature.

Big Question: Can the fuel remain intact through extended storage and subsequent transportation to a final repository?

- What are the external loads that spent nuclear fuel could experience during its lifetime?
- How does this compare to the mechanical integrity after extended storage?
  - Storage is very benign with few external loads
  - Transportation is the time fuel will experience the most external loads.

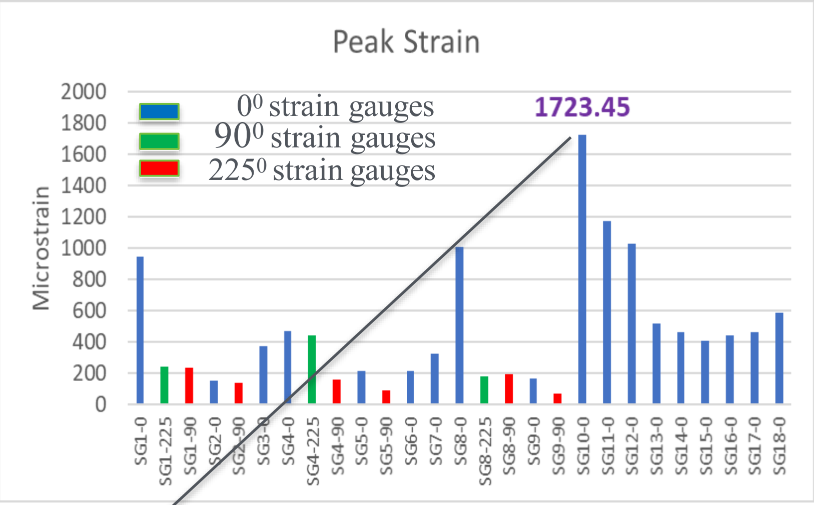
The following tests were performed to quantify these loads and quantify the safety margin

External Loads to the Fuel

VIDEO

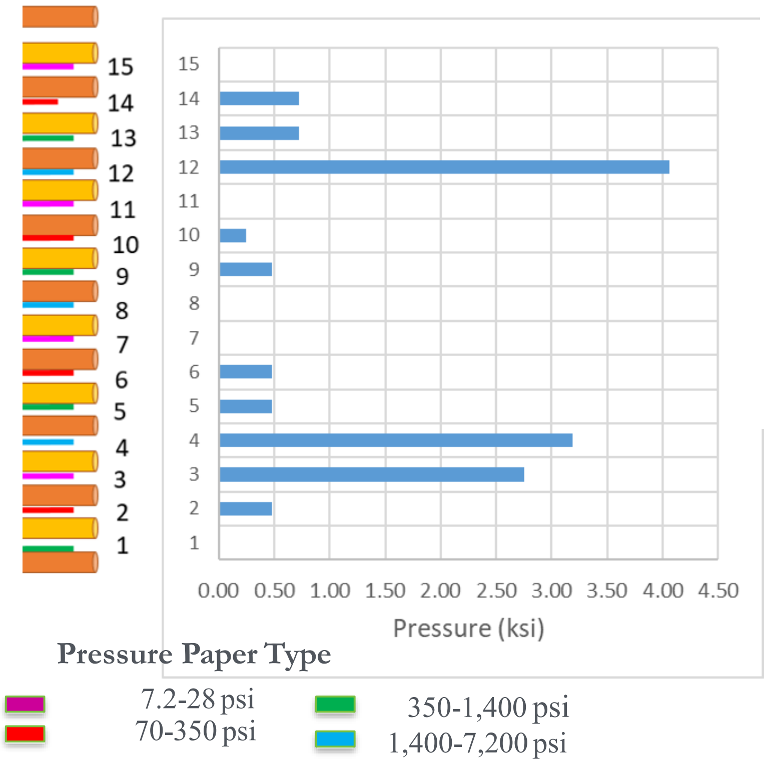
https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be

30-cm Drop Test

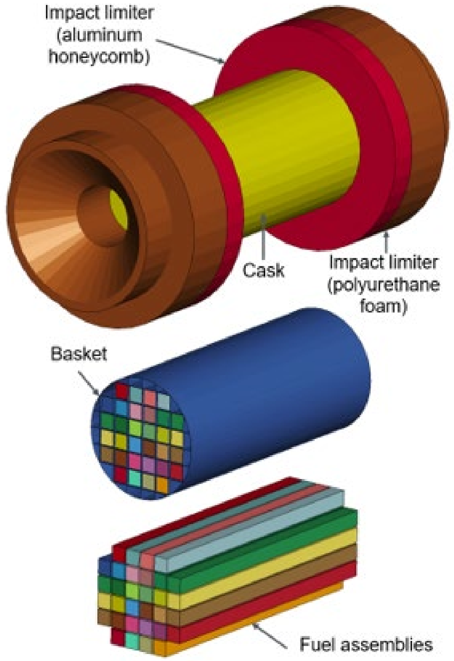


Photos and graphs from SNL

Rod-to-Rod Contact Pressure

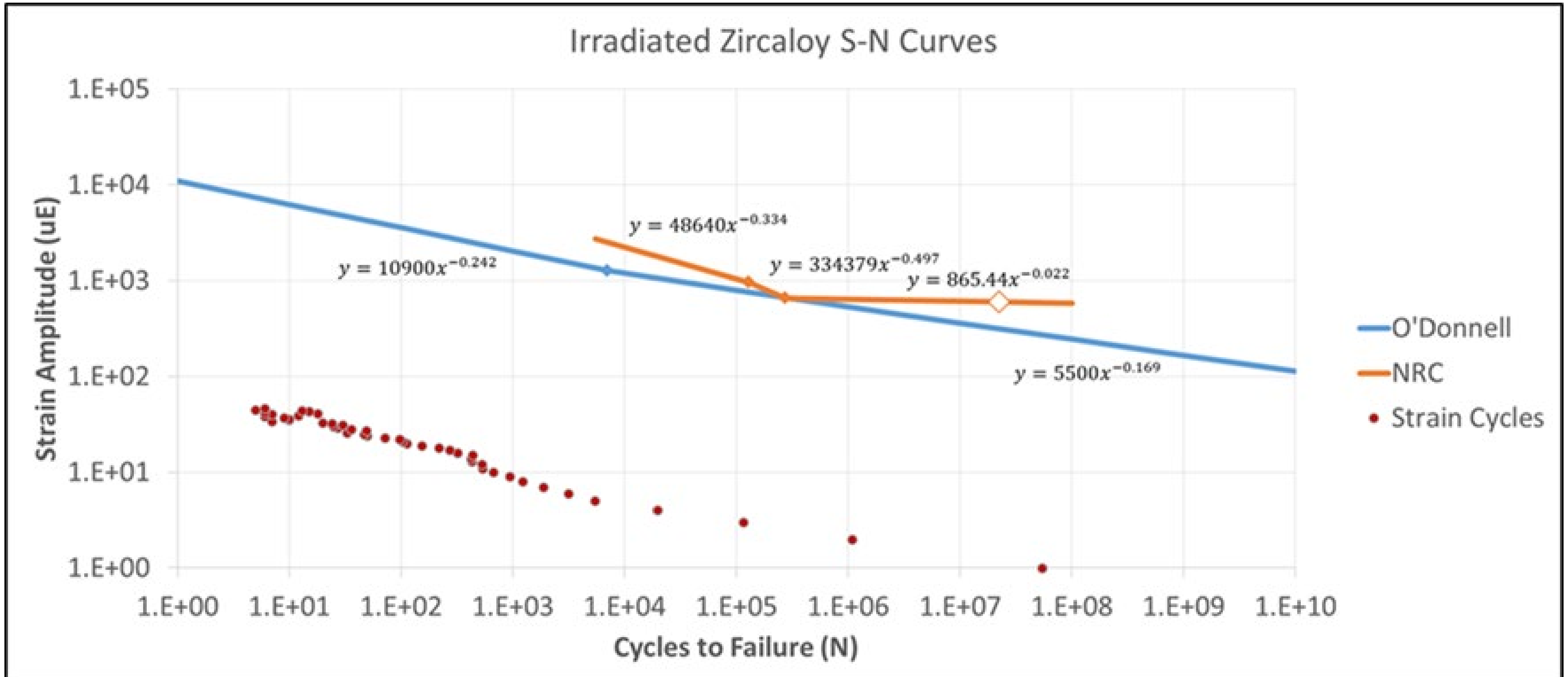


Klymyshyn et al, Mechanical Loads on SNF in the General 30-cm Package Drop Scenario, PNNL 2021



Conclusion: The fuel rods will maintain their integrity after being dropped 30 cm more than once

Transportation Loads Compared to Cladding Fatigue Damage



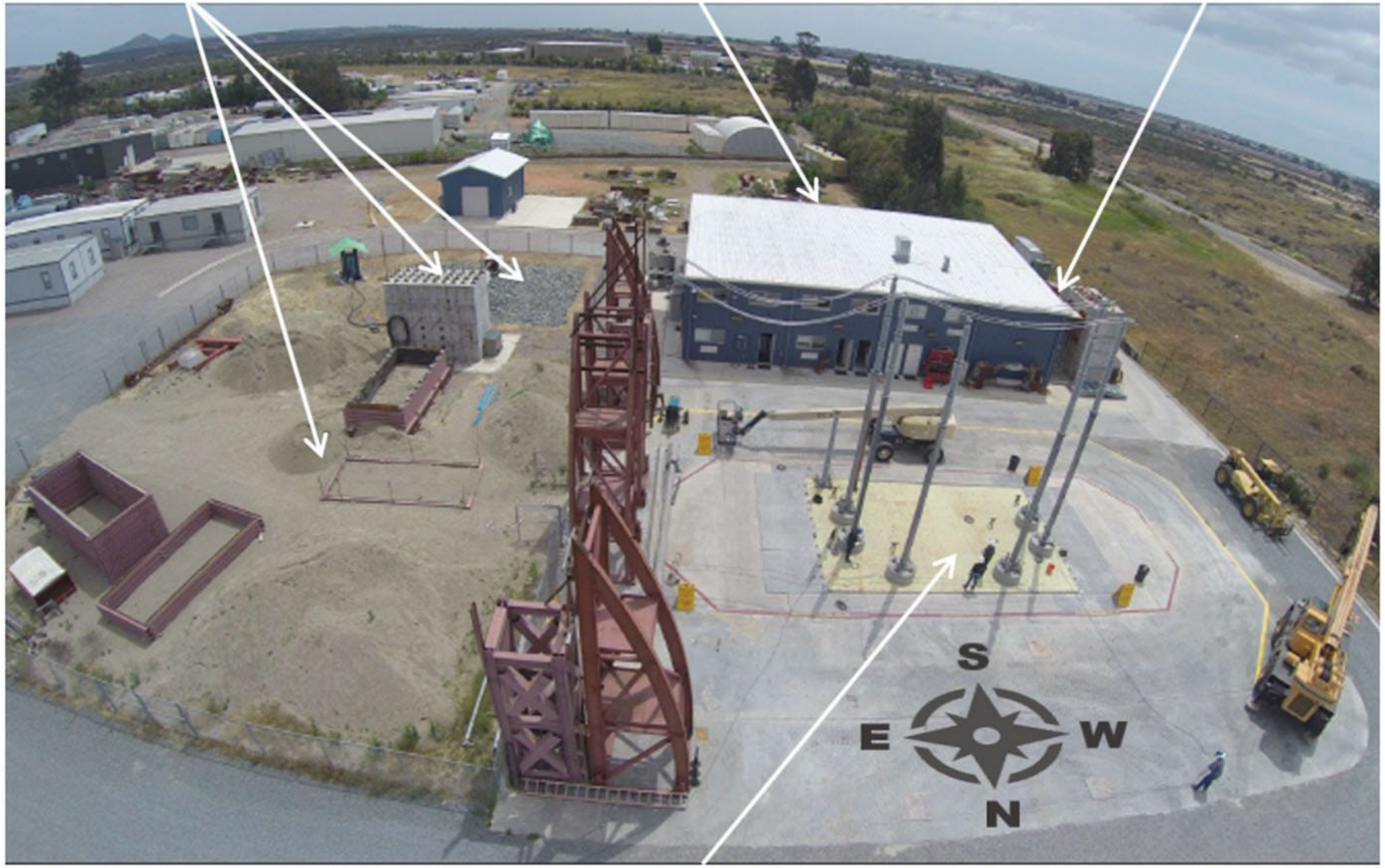
- O'Donnell: S-N curve used to define accumulated damage in this work. O'Donnell WJ and BF Langer. 1964. "Fatigue design basis for zircaloy components." *Nuclear Science and Engineering* (20):1–12
- NRC: S-N curve based on CIRFT data. Defined in NUREG-2224, Dry Storage and Transportation of High Burnup Spent Nuclear Fuel. Draft for Comment, 2018.
- Strain Cycles: Actual strain cycle counts from the MMTT test data. (SG28-0)

Conclusion: The external loads measured on the surrogate fuel during transportation and handling (red dots) are much lower than the fatigue damage S-N curves derived from hot cell data for spent fuel cladding. The fuel has a large margin of safety for damage during transportation.

Klymyshyn et al, Modeling Shock and Vibration on Used Nuclear Fuel During Normal Condition of Transportation,
Pressure Vessels & Piping Conference PVP2019 July 14-19, 2019, San Antonio, TX, US

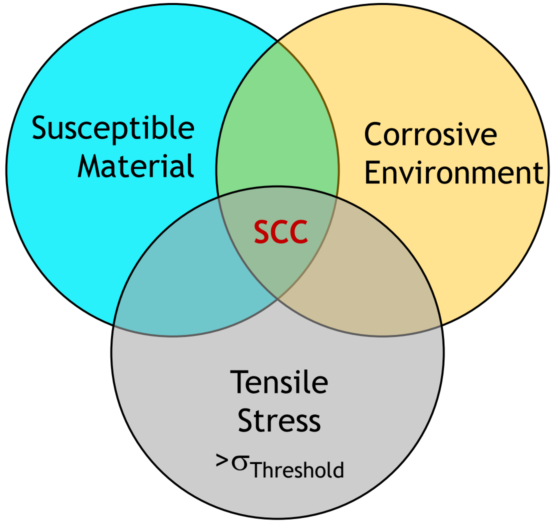
Conclusion: With the data that are currently available, it is believed that the cladding will remain intact and its integrity will not be challenged during extended storage and normal conditions of transportation

Next: Dry Storage Seismic Testing



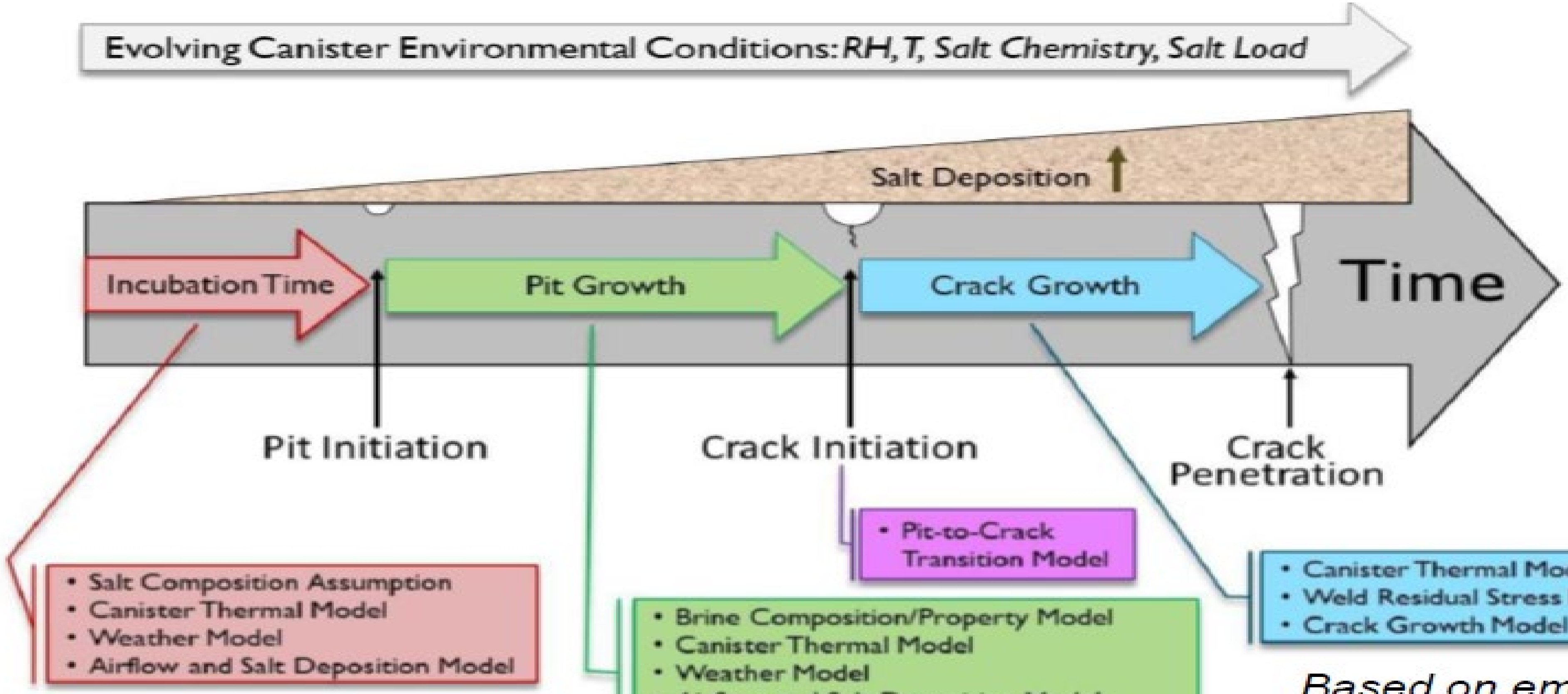
Can the Canisters Leak or Crack Over Time?

- Most of the canisters that comprise the 3000+ spent fuel canisters currently storing fuel around the country are:
  - ✓ Made of a material that is susceptible to corrosion (304 or 316SS)
  - ✓ Have documented through-wall tensile stress at the welds and heat affected zones
  - ☐ Are in areas with environments where the passive cooling design can deposit dusts and brine onto the surface of the stainless-steel canister.



1. We are working to understand the composition of the dusts/brines that are deposited on the surface of the canister and how that dust/brine evolves over time to influence corrosion risk
2. We are working to identify mitigation and repair technologies if corrosion is found.

Understanding the Progression of Corrosion



Based on environment model ($RH < RH_L$)

Controlled by environment and salt load (constraints on maximum pit size), and stress field (depth of conversion to SCC crack)

Based on empirical measurements of SCC crack growth rates and calculated time-of-wetness

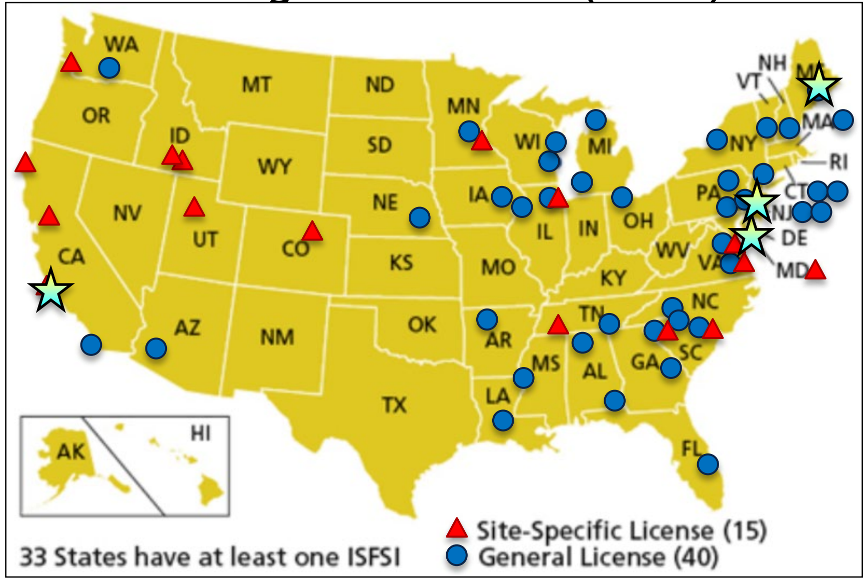
Corrosion Video

https://www.youtube.com/watch?v=dQr3iBT8XOo

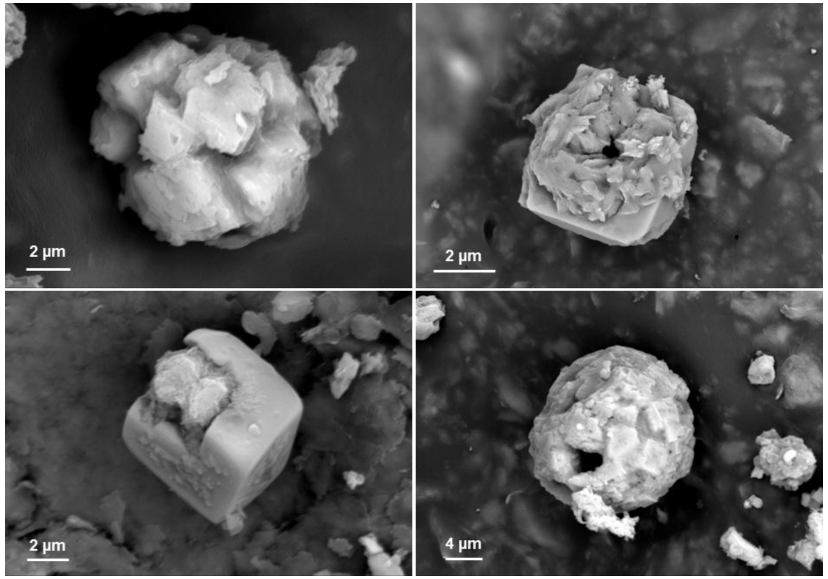
Sea-Salt Aerosols

- **Many ISFSIs are at coastal sites. Anticipated deposition of chloride-rich sea-salts.**
- **EPRI-led sampling program confirmed that sea-salt aerosols are deposited on canisters at least at some sites.**
- **At near-marine sites, salt aggregates formed by evaporation of sea-spray can be deposited on canister surfaces, and will deliquesce to form chloride-rich brines as the canisters cool.**

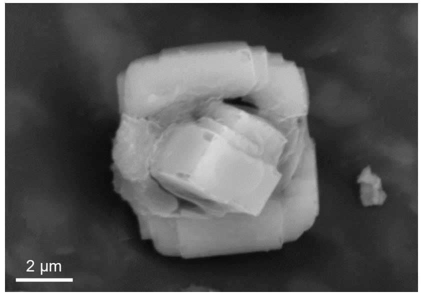
Locations of U.S. Spent Nuclear Fuel Independent Storage Installations (ISFSIs)

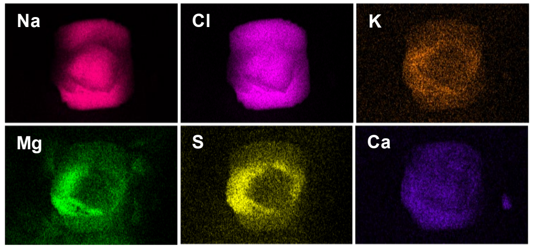


ISFSI locations sampled.



Sea-salt aerosols recovered from the surface of SNF dry storage canisters at Diablo Canyon ISFSI





Salt aggregates: dominantly NaCl with interstitial $MgSO_4$ and trace K, Ca phases. Consistent with seawater ion composition.

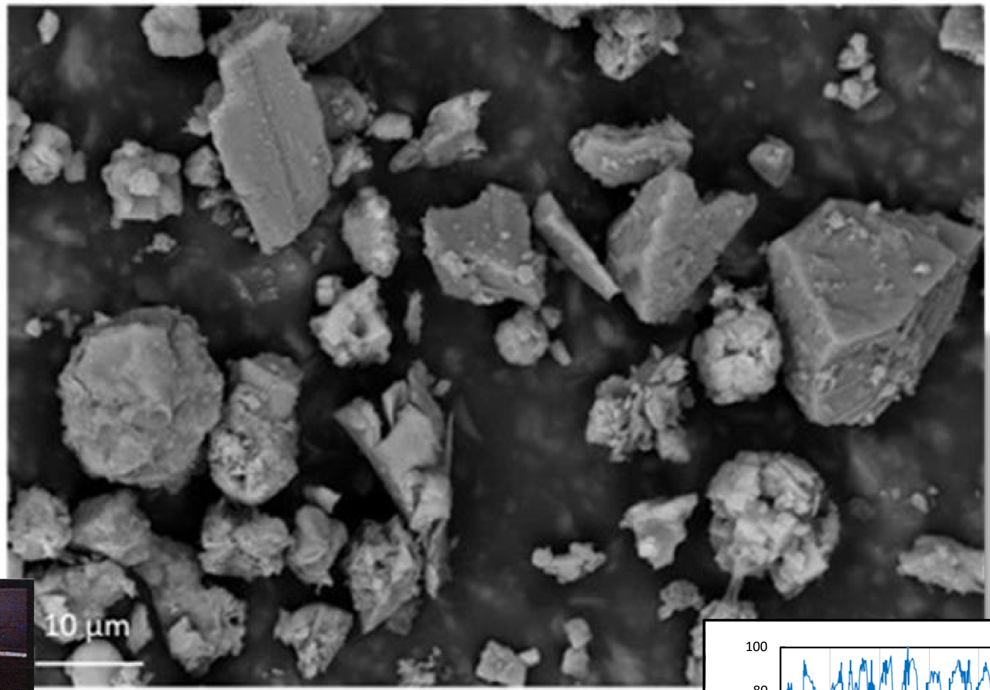
At coastal sites, canister SCC due to deliquescence of chloride-rich salts is a potential failure mechanism.

Stress Corrosion Cracking (SCC): What deposits on the Canisters?

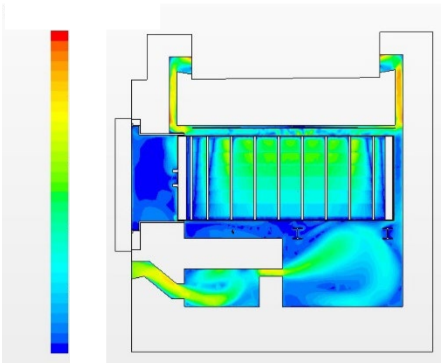
Canister surface environment controls corrosion susceptibility, pit growth, and SCC initiation and growth.

Environment: Site sampling and geochemical modeling provides critical data on canister surface brines.

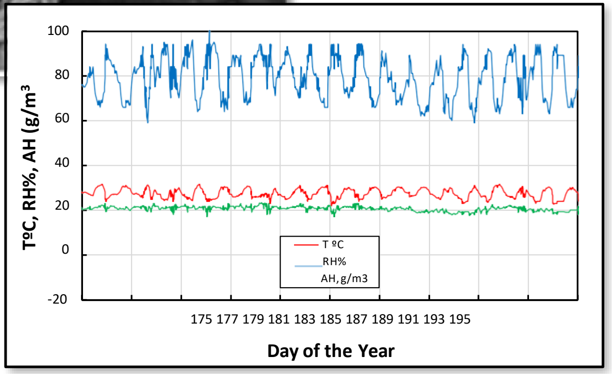
- *First data from inland independent spent fuel storage installation (ISFSI) sites collected.*
- *Realistic environments for corrosion testing defined.*



Dust and salts from canister surface, Diablo Canyon ISFSI



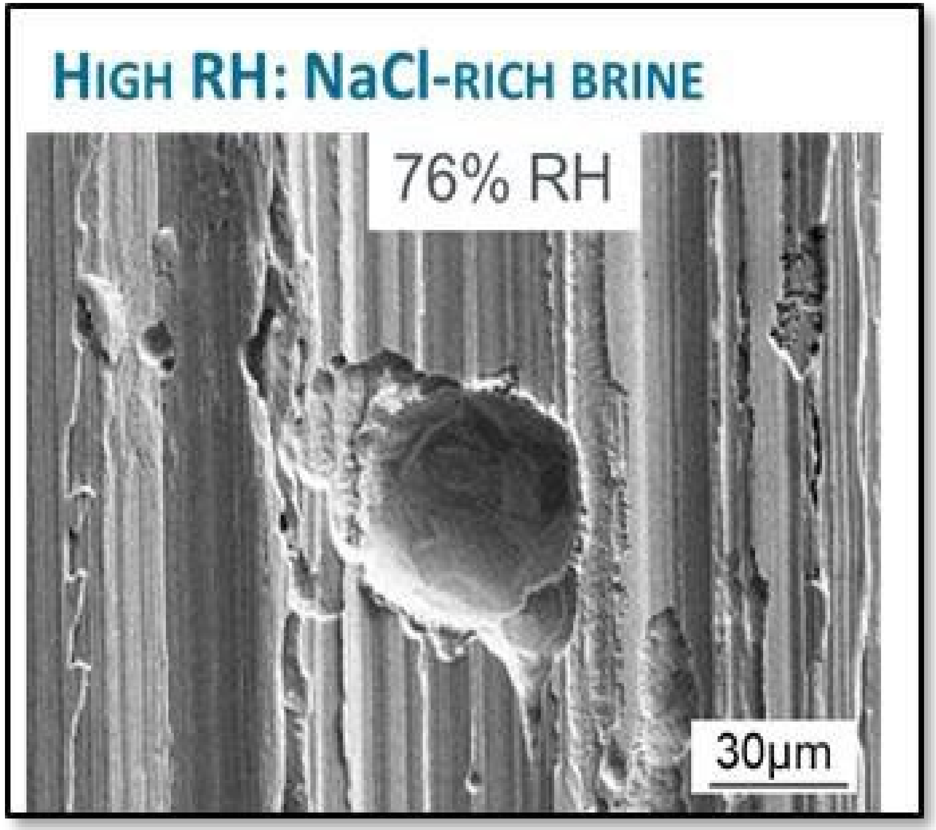
Diurnal cycles in Temp and humidity, Turkey Point ISFSI

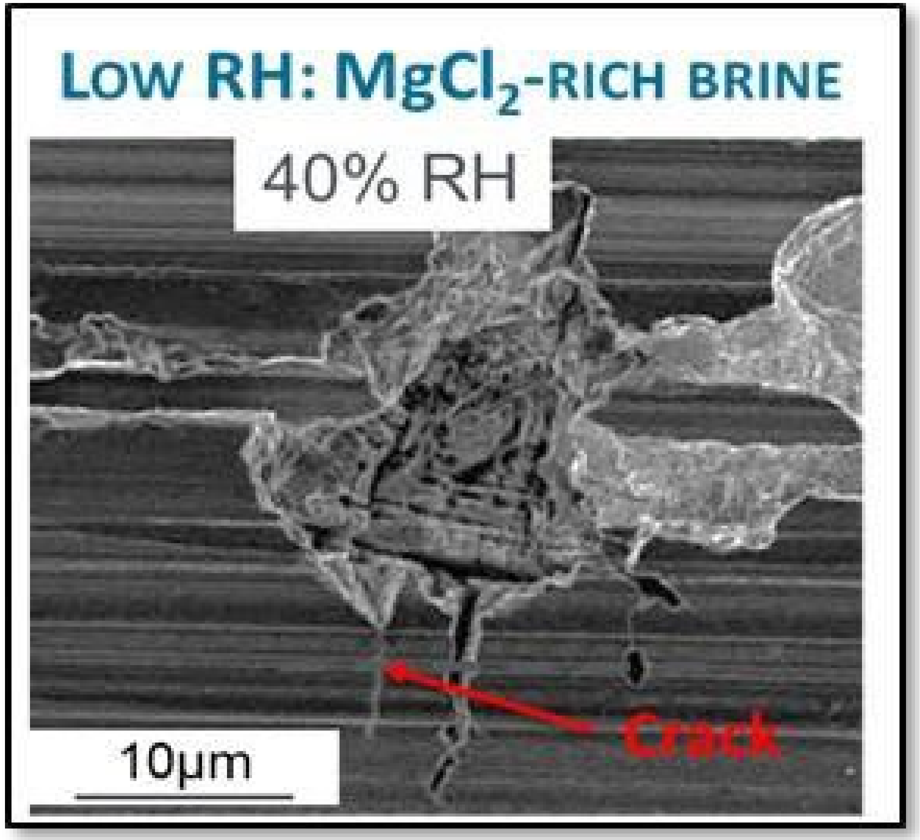


Photos and graphs from SNL

Corrosion Experiments: Determine environmental controls on pitting and SCC initiation.

- *Important effects of low-relative humidity (RH) $MgCl_2$ brines demonstrated.*
- *Testing to evaluate diurnal cycles, NO_3^-/Cl^-, dust, in FY21*



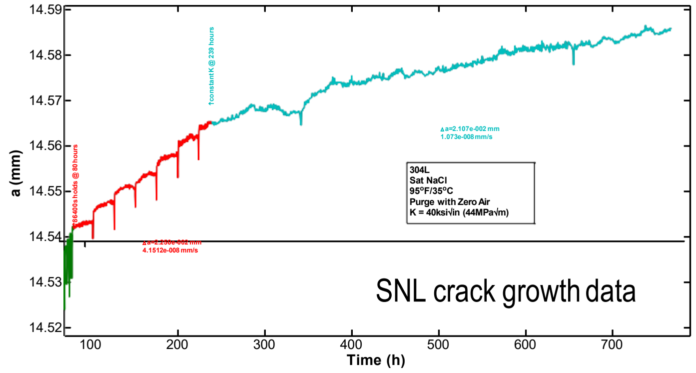


Photos and graphs from SNL

SCC Crack Growth Rate (CGR) Experiments

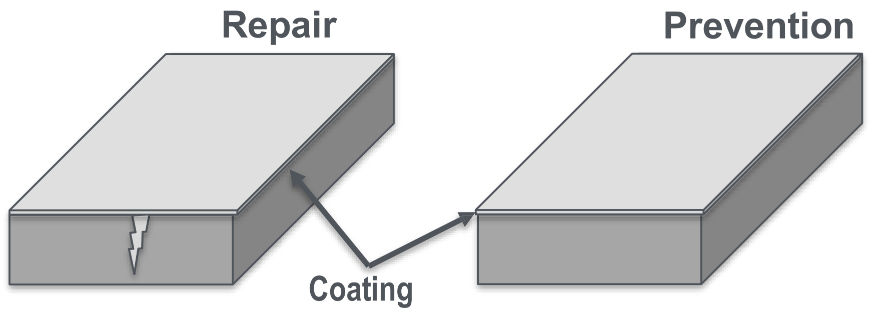
CGR as a function of brine composition, temperature, material properties.

- *Current immersed testing results largely consistent with literature data*
- *Atmospheric testing to start this FY.*



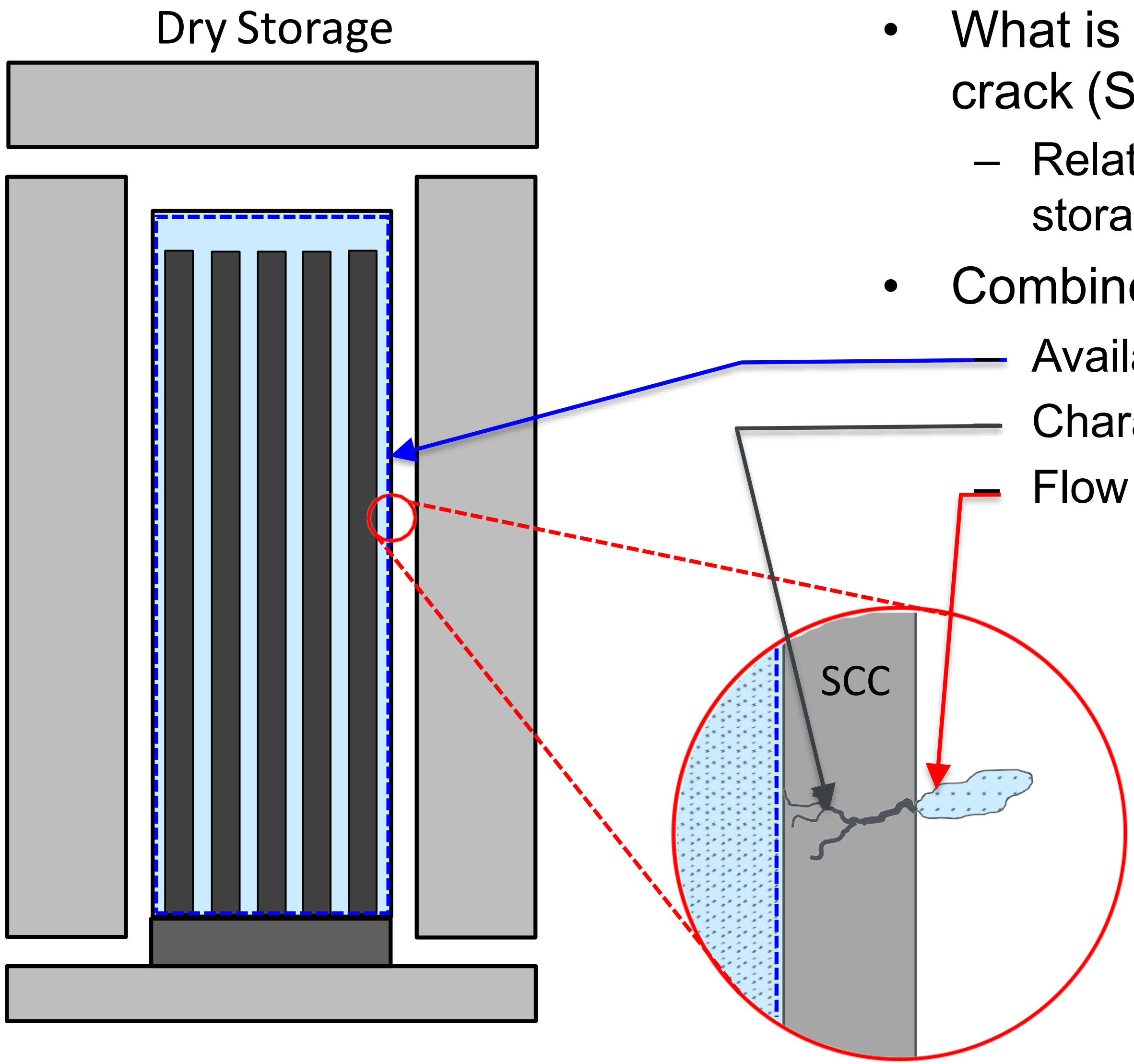
Canister Coatings to Prevent and Remediate SCC

- Difficult to identify cracks quickly and effectively.
- Coatings could be an effective option as:
  - Mitigation/Repair of cracks once they are identified
  - Application as a preventative measure



SNL Coatings Report (2020): *Down-selection of coatings for follow-on testing*

	Attribute	Implementation		
Coating Name	**Properties/Degradation**	**In situ repair**	**Ex situ repair**	**Ex situ prevention**
Air Dry Epoxy	Susceptible to radiolytic degradation; not stable above 130°C	Minimal surface preparation; Requires T< 130° C	Minimal surface preparation; Requires T< 130° C	Susceptible to radiolytic degradation; Requires T< 130° C
Polyethylene	Chemically and mechanically stable; radiolytically sensitive; unknown thermally; multiple layers application can increase time to degradation	Can be easily applied as short term patch due potential radiolytically degradation	Can be easily applied as short term patch due potential radiolytically degradation	Poor radiolytic stability
Rubber	Robust but susceptible to permeation but can be improved with multiple layers; stable to high temperatures	Can be painted or sprayed on	Can be painted or sprayed on	Can be painted or sprayed on
Sol-gel	Chemically, thermally, radiolytically and mechanically stable; adhesion and application depends on additives and surface finish, prone to brittle failure	Can be applied by spray or brush methods	Prone to scratching and brittle failure, but can be improved with additives	Prone to scratching and brittle failure, but can be improved with additives
Phosphate Conversion	Chemically, thermally, radiolytically and mechanically stable; great adhesion; Complex application and reapplication process	Complex application and reapplication process	Complex application and reapplication process	Effective coating if applied during prior to SNF fuel loading
Cold spray *(*ongoing effort with PNNL)*	Robust and great adhesion; surface modification effects on corrosion must be demonstrated	Can be applied locally with robotic crawler	Can easily be applied locally	Can be easily applied



- What is the potential impact of a through-wall stress corrosion crack (SCC)?
  - Relatively low availability of mobile radionuclides under normal storage and transportation conditions
- Combined analysis needed from following topics
  - Available source term inside canister
  - Characteristics of SCC
  - Flow and particle transport through prototypic SCCs

Pacific Northwest NATIONAL LABORATORY

- GOTHIC modeling of canister and SCC flows

Sandia National Laboratories

- MELCOR modeling of canister
- Aerosol transmission testing

OAK RIDGE National Laboratory

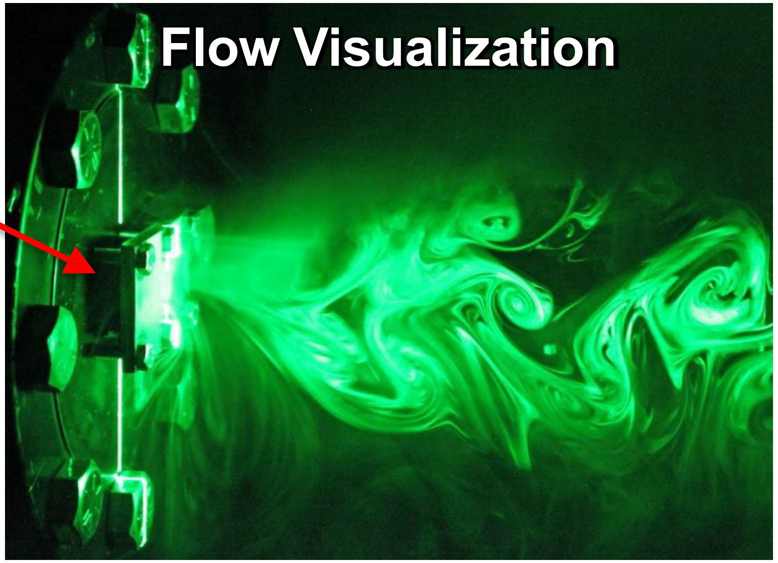
- 1st principles modeling of SCC flow

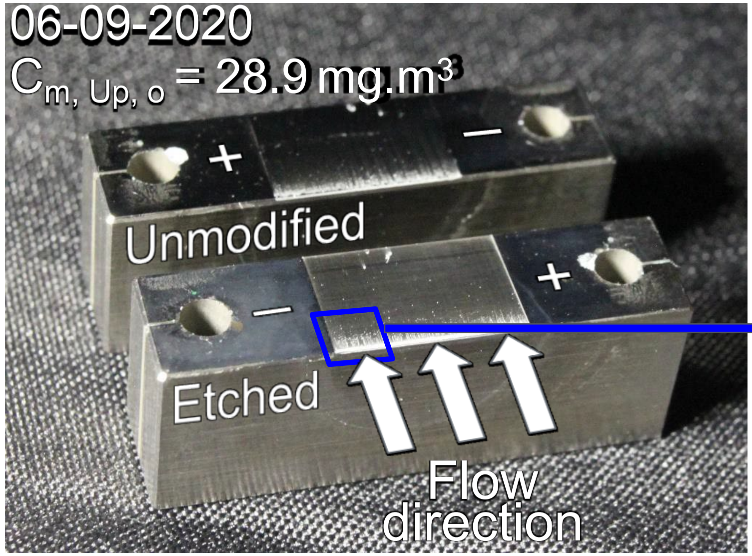
Transmission of Aerosols Through Cracks

Photos and graphs from SNL

- Tests with slot orifice to represent SCC
  - Simplified microchannel
    - 29 μm x 12.7 mm x 8.86 mm)
  - *Average aerosol mass transmission fraction = 0.41*

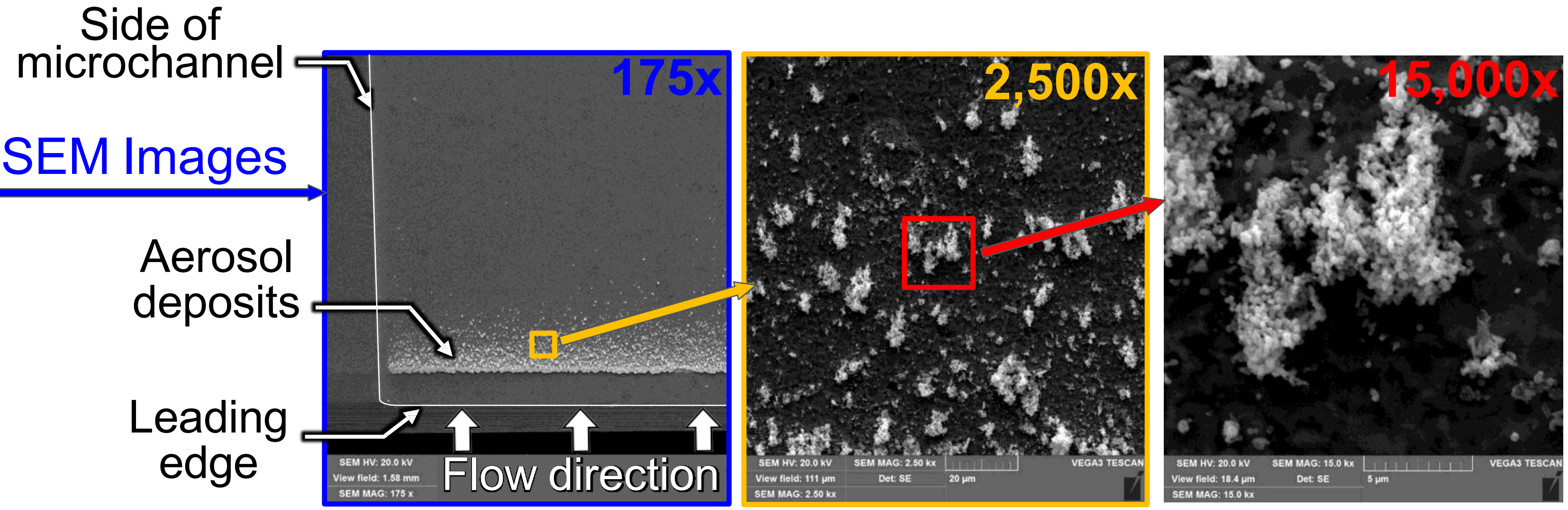
Assembled Microchannel





Disassembled Microchannel
(Post-Test)

SEM Images

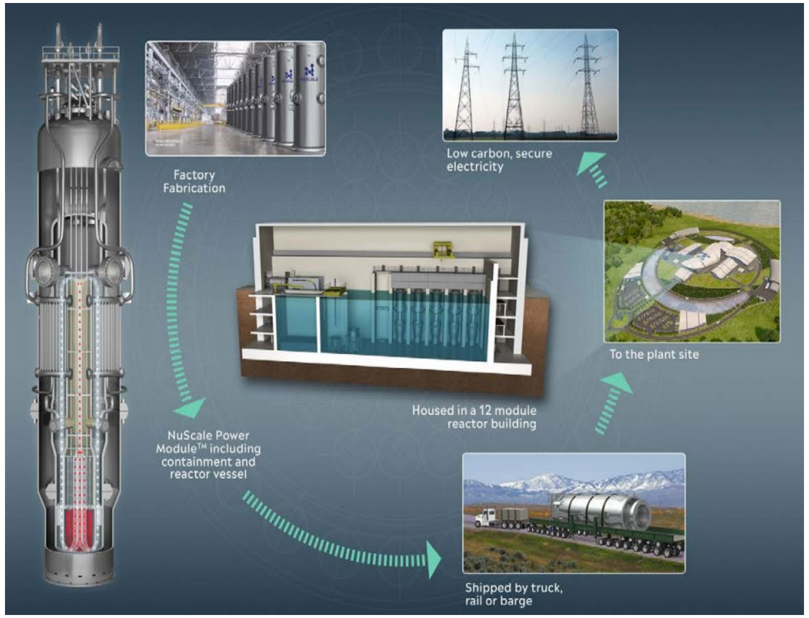


New Reactor Designs and Accident Tolerant Fuel

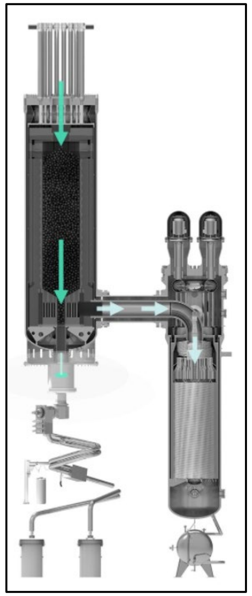
New Reactor Designs

There are around 20 paper designs in pre-licensing stages with the US NRC.

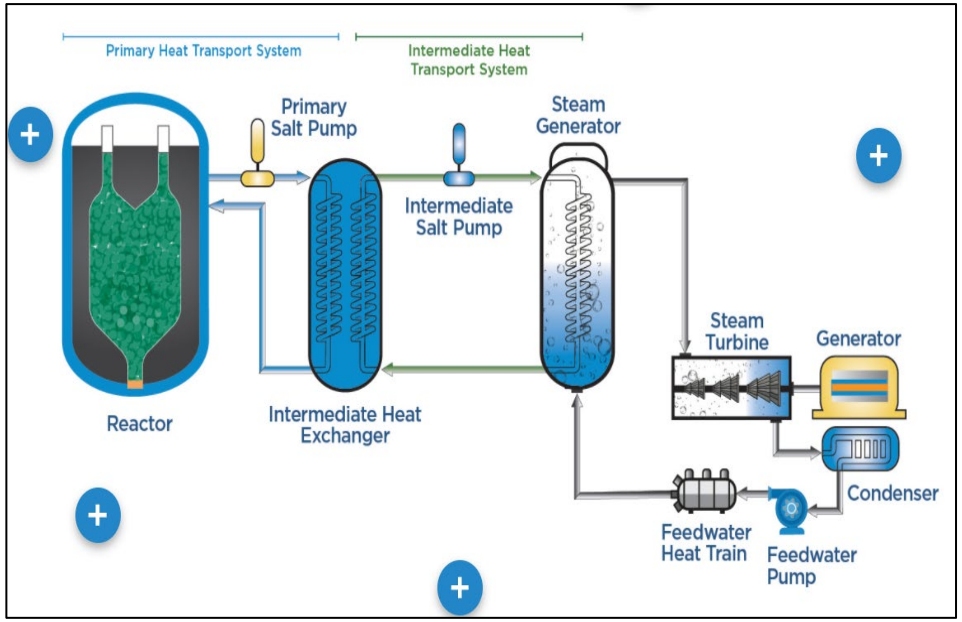
Waste and safeguards issues are not being addressed yet.



NuScale: received NRC design certification in January 2017. The original design is modular with each module producing 160 MWth, 50 MWe—the 12-pack plant will produce 600 MWe.



X-Energy: TRISO-X fuel. Xe-100 is an 80 MWe reactor, designed as a module with up to 4 modules per site.

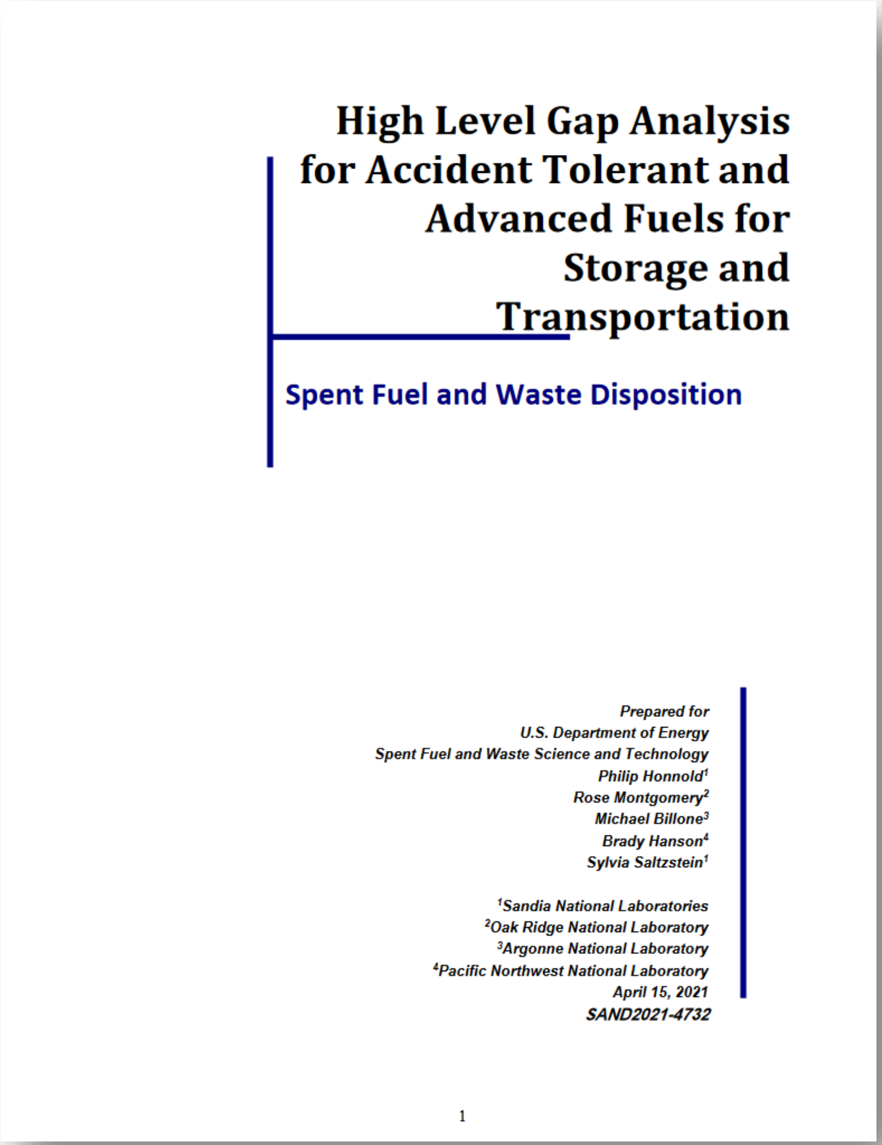


Kairos Power: The KP-FHR is a fluoride salt-cooled high temperature reactor, 140 MWe, uses TRISO fuel pebbles with a low-pressure molten salt (fluoride salt) coolant

Investigating Back-End Implications of Accident Tolerant Fuels

Based on the current knowledge of ATF cladding and fuel designs, attention should focus on damaged spent fuel particulate size and quantity; cladding coating robustness and potential corrosion and hydride potential in areas of damaged cladding coatings; the impact of unknown molten metals in some fuel rod designs; and increased container weight, temperatures, and radiation levels.

https://www.osti.gov/biblio/1813674-high-level-gap-analysis-accident-tolerant-advanced-fuels-storage-transportation



High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology
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April 15, 2021
SAND2021-4732

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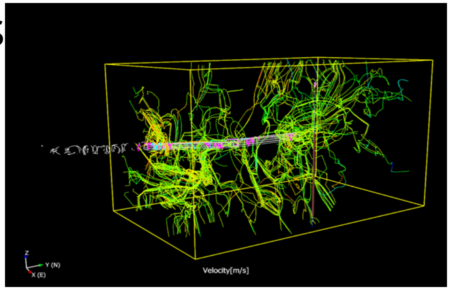
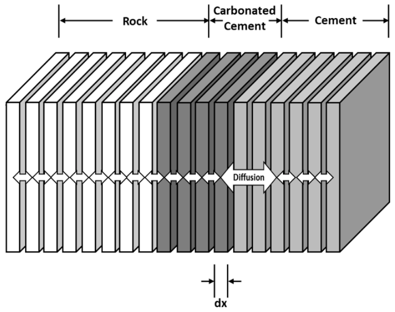
Disposal Research and Analysis

NUCLEAR WASTE DISPOSAL RESEARCH & ANALYSIS

PROJECTS

Projects primarily support R&D developments and enhancements needed for Geologic Disposal Safety Assessment





Crystalline Host Rock R&D (NE-8)

- Fractured media and fluid flow/transport

Argillite Host Rock R&D (NE-8)

- Temperature effects on clay, bentonite, and barrier system

Engineered Barrier System R&D (NE-8)

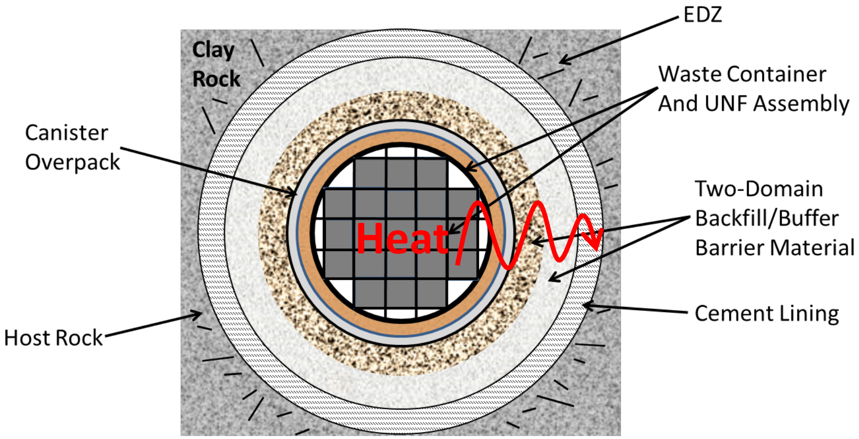
- Seal integrity, material interfaces, coupled processes

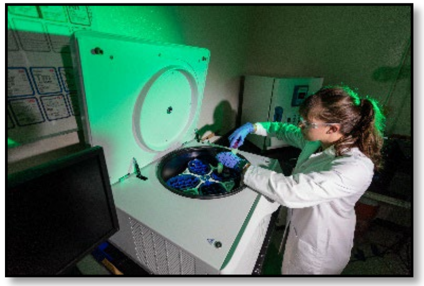
Lab Facilities – 823 Basement B45/52, B59

- State of the art facilities

International Partnerships

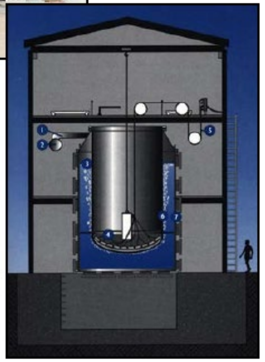
- NUMO, JAEA, NEA, NTAG, NTI, DECOVALEX, RANGERS





ADVANCED NUCLEAR FUEL CYCLE TECHNOLOGY

Surtsey



CYBL

Testing and Analysis of Dry Storage Canisters (NE-8)

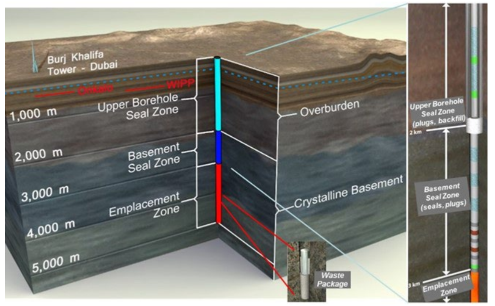
- Canister Deposition Field Demonstration (CDFD) – controlled dust deposition at an ISFSI
- Horizontal Dry Cask Simulator (HDCS) – thermal behavior of prototypic canister and cask
- Advanced Drying Cycle System (ADCS) – potential for residual moisture after drying
- Aerosol Crack Flow Testing – potential releases through stress corrosion cracks
- Thermal-Hydraulic Modeling – estimation of temperature profiles; test planning

Direct Disposal of Dual-Purpose Canisters (NE-8)

- Engineering Feasibility, Thermal Management , Post-Closure Criticality Control
- Criticality Consequence Modeling – steady state and transient events using PFLOTRAN
- Fillers – injectable cementitious slurries for moderator exclusion

Deep Borehole Disposal of Nuclear Waste (NA-20, CE)

- NNSA-IAEC (Israel Atomic Energy Commission) intermediate-depth borehole developm
- Borehole demonstration collaboration with ANSTO and CSIRO (Australia)
- Support for IAEA Cooperative Research Project (CRP) on borehole disposal



APPLIED SYSTEMS ANALYSIS & RESEARCH

PROJECTS

Geologic Disposal Safety Assessment (GDSA) : https://pa.sandia.gov/

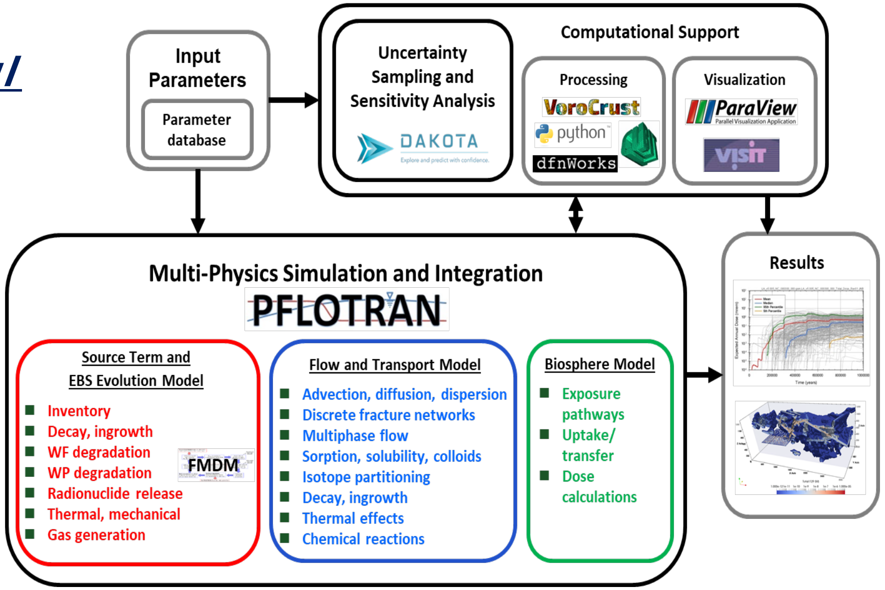
- GDSA Framework
- Repository Systems Analysis (RSA)
- PFLOTRAN Development
- Uncertainty Quantification and Sensitivity Analysis (UQ/SA)

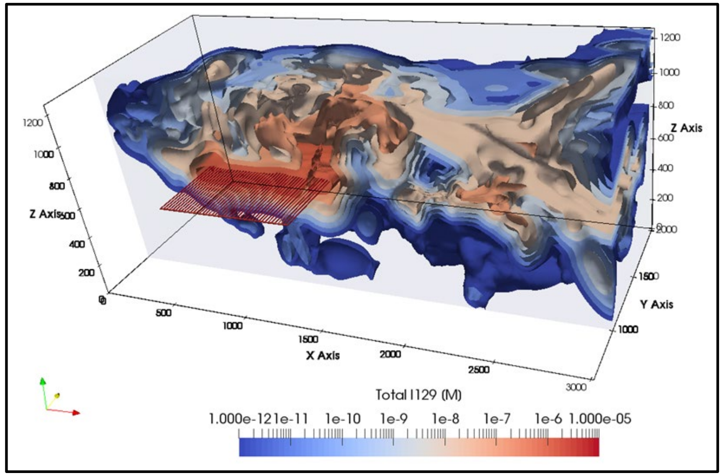
Salt

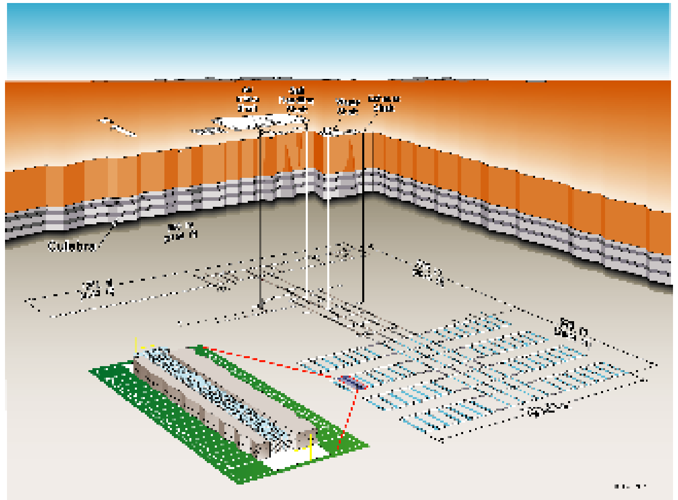
- Brine Availability Test in Salt (BATS)
- International Collaborations

Waste Isolation Pilot Plant (WIPP): https://www.sandia.gov/salt/

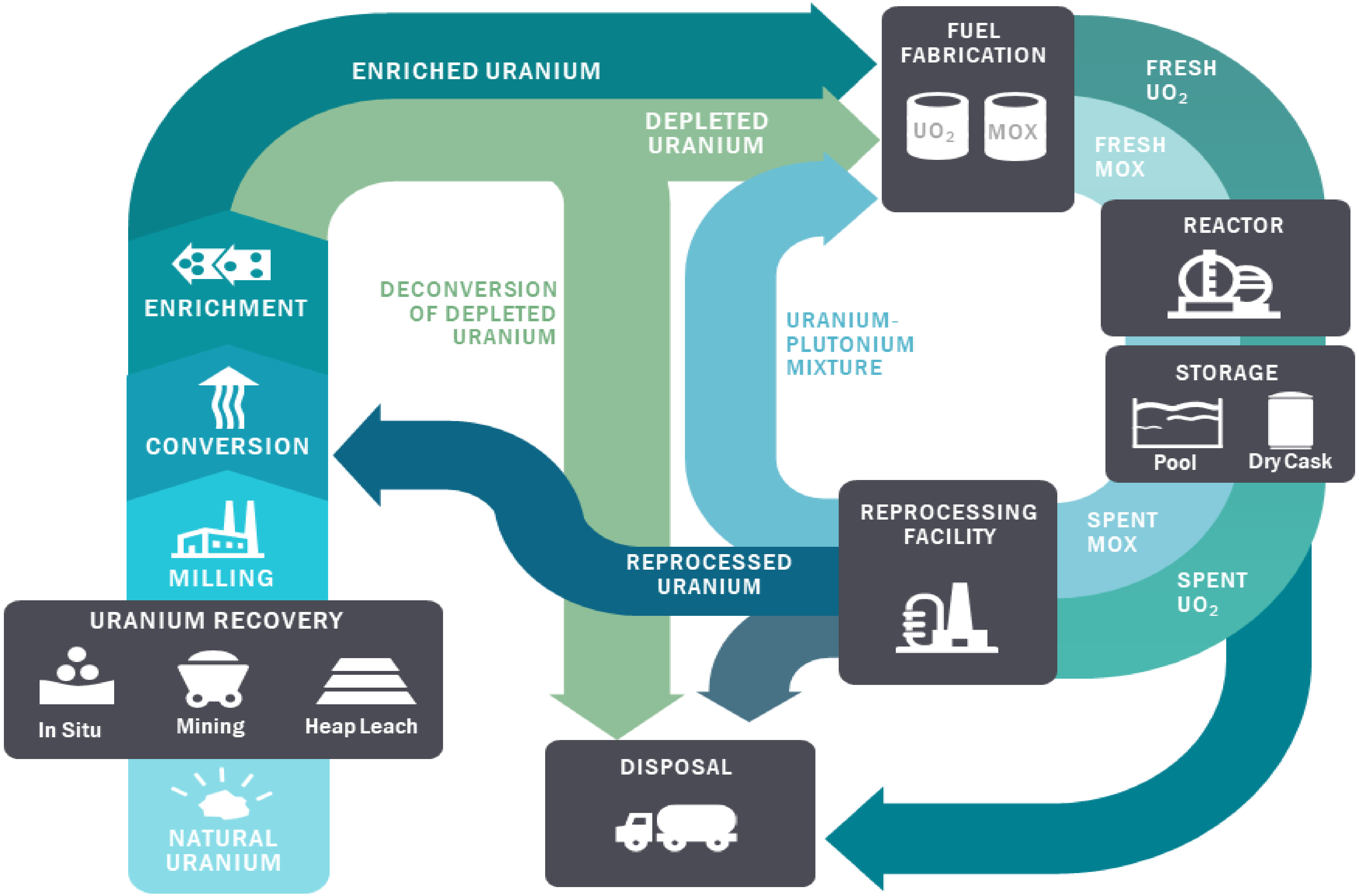
- PFLOTRAN Development







Can We Keep the Cycle Going?



Thank you! Questions?