SAND2021-10253C

Sandia National Laboratories

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

SAND XXXX

Sylvia Saltzstein

Senior Manager, Nuclear Fuel Cycle

sjsaltz@sandia.gov

Sandia National Laboratories

Albuquerque, NM

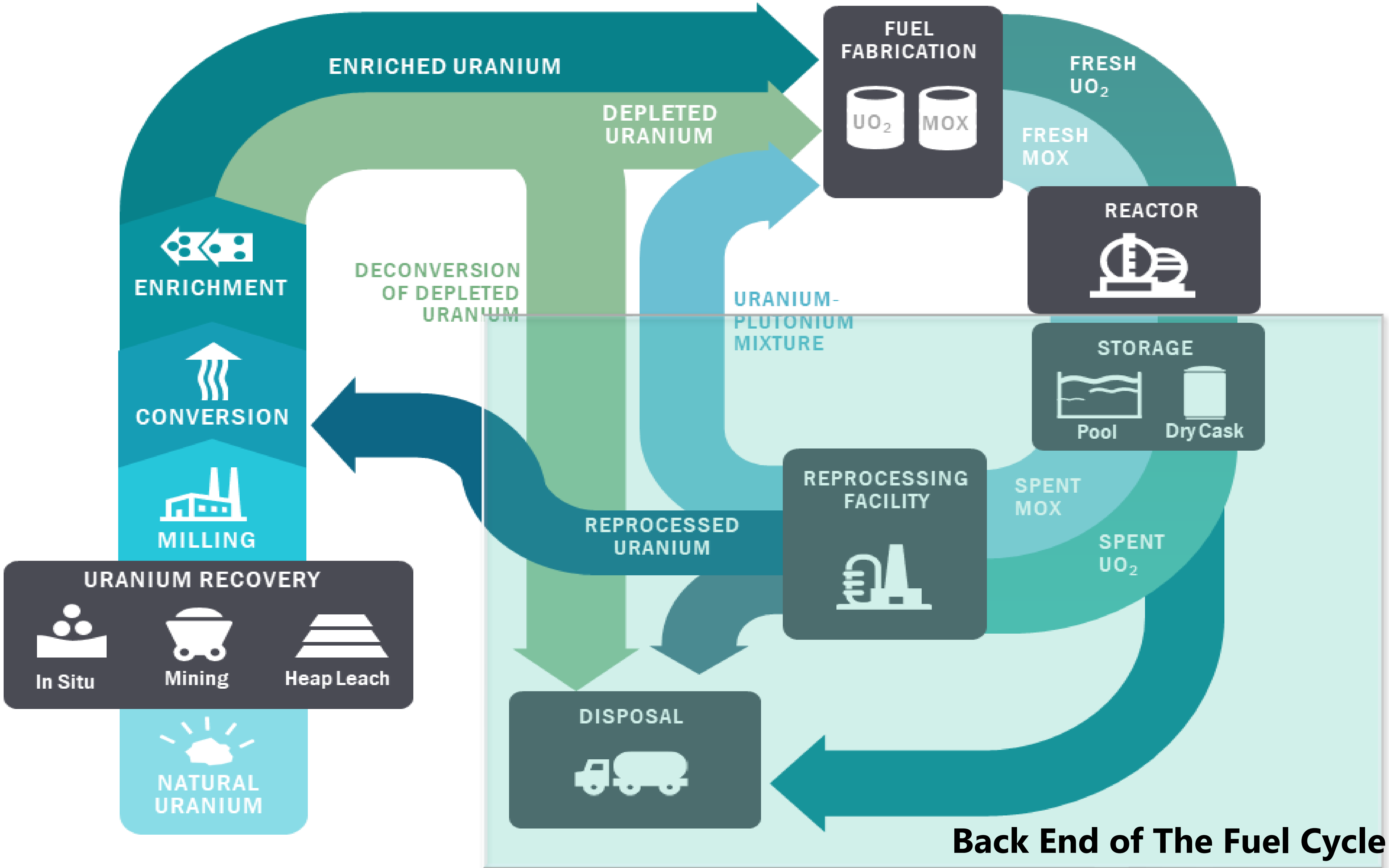
Institute of Nuclear Materials Management & European Safeguards Research and Development Association Joint Meeting

August 23 to September 1, 2021

Virtual

Table of Contents

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 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. Funds cannot be spent on other sites.

A Monitored Retrievable Storage Facility is considered.

Load first dry storage canister of spent nuclear fuel

Note: This is still the law.

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

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

Utilities sue for breach of the "Standard Contract."

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 per year)

Private sector applications to the NRC for consolidated interim storage (Waste Control Specialists [now Interim Storage Partners] in Andrews, TX and Holtec in Eddy/Lea Counties, NM)

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 … ule

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.

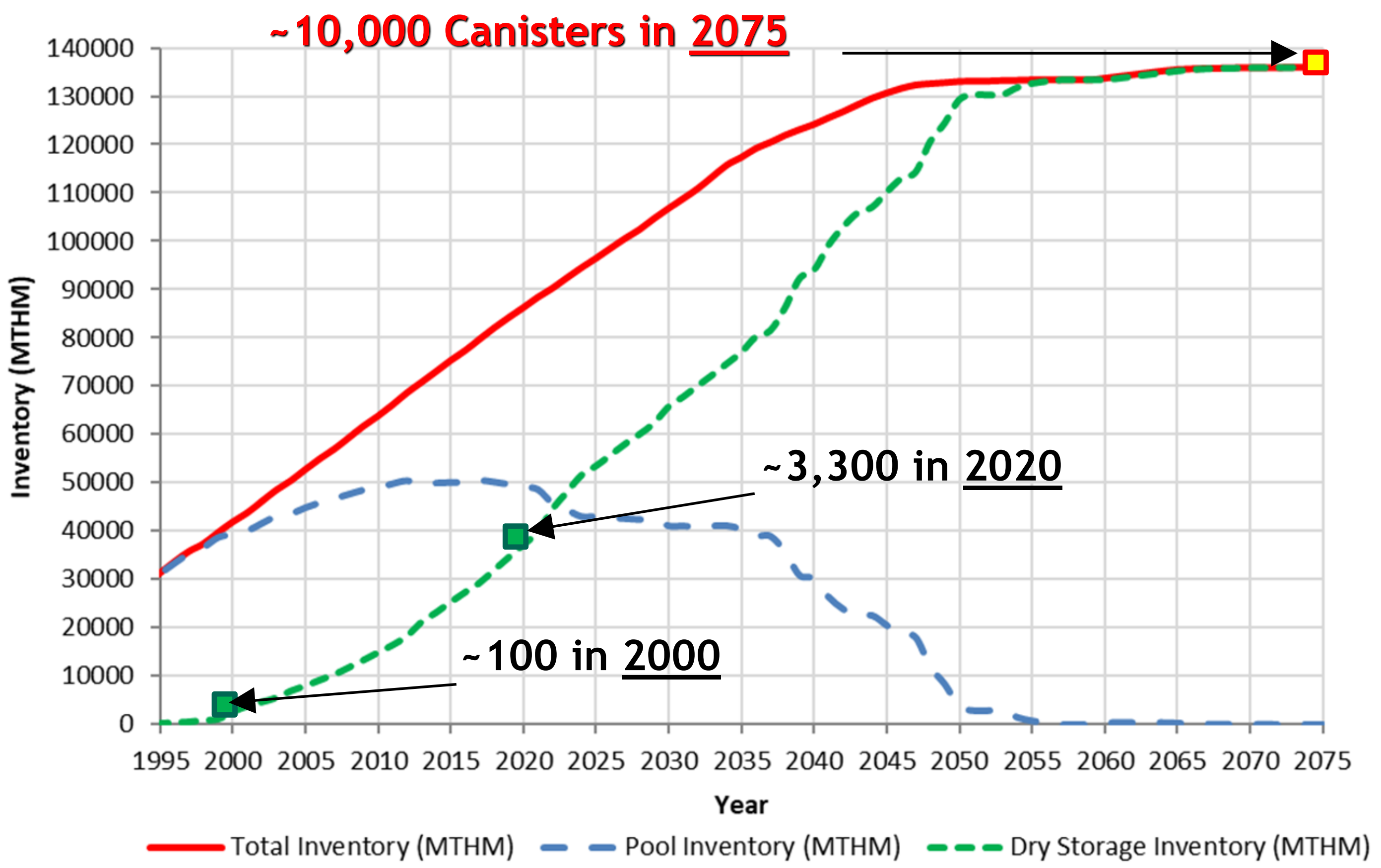
* "Commission has concluded that radiological impacts that do not exceed permissible levels in the Commission's regulations are considered small."

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

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)

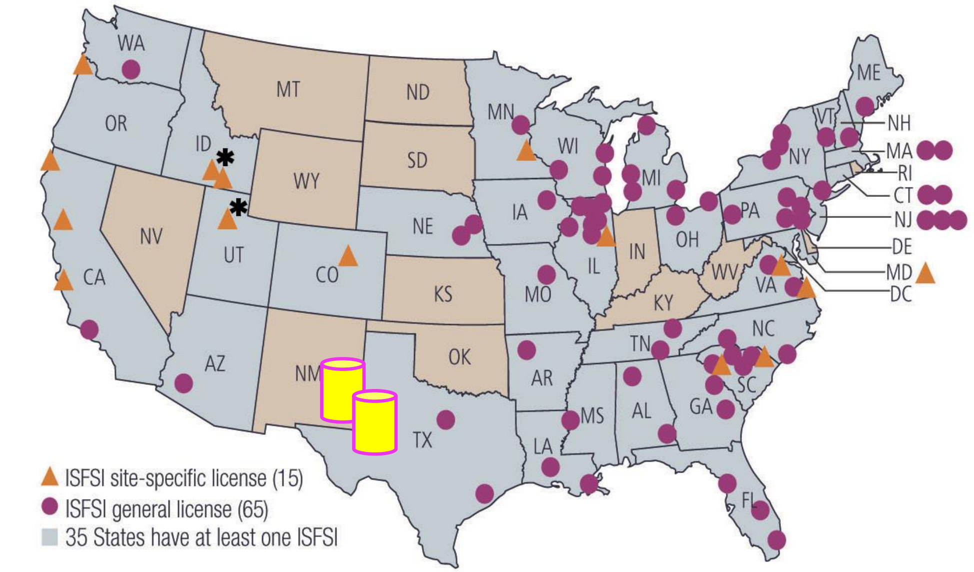
- Approx. **38,000 MTHM in dry storage at reactor sites**, in approximately 3,300 cask/canister systems (green dashed line)
  - Balance in pools, mainly at reactors (blue line)
  - Approx. **2200 MTHM of SNF generated nationwide each year**



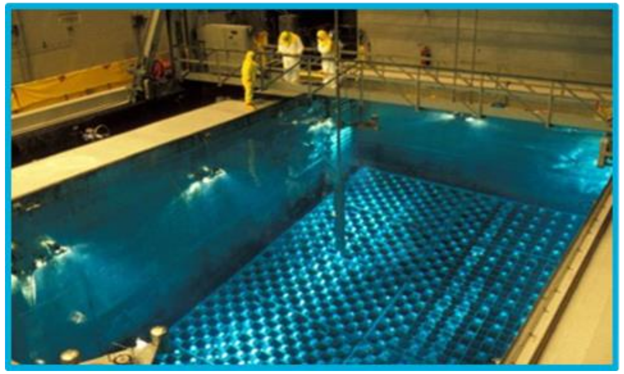
Projection assumes full license renewals and no new reactor construction or disposal (updated from Bonano et al., 2018*)

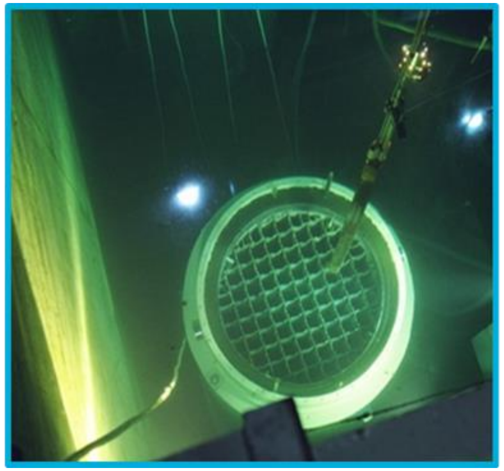
Commercial SNF is in Temporary Storage at 75 Reactor Sites in 35 States

- 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)
- Two private sites have submitted license applications to the NRC for consolidated storage for the nation's dry storage containers. One is in West Texas and one is in SE New Mexico.

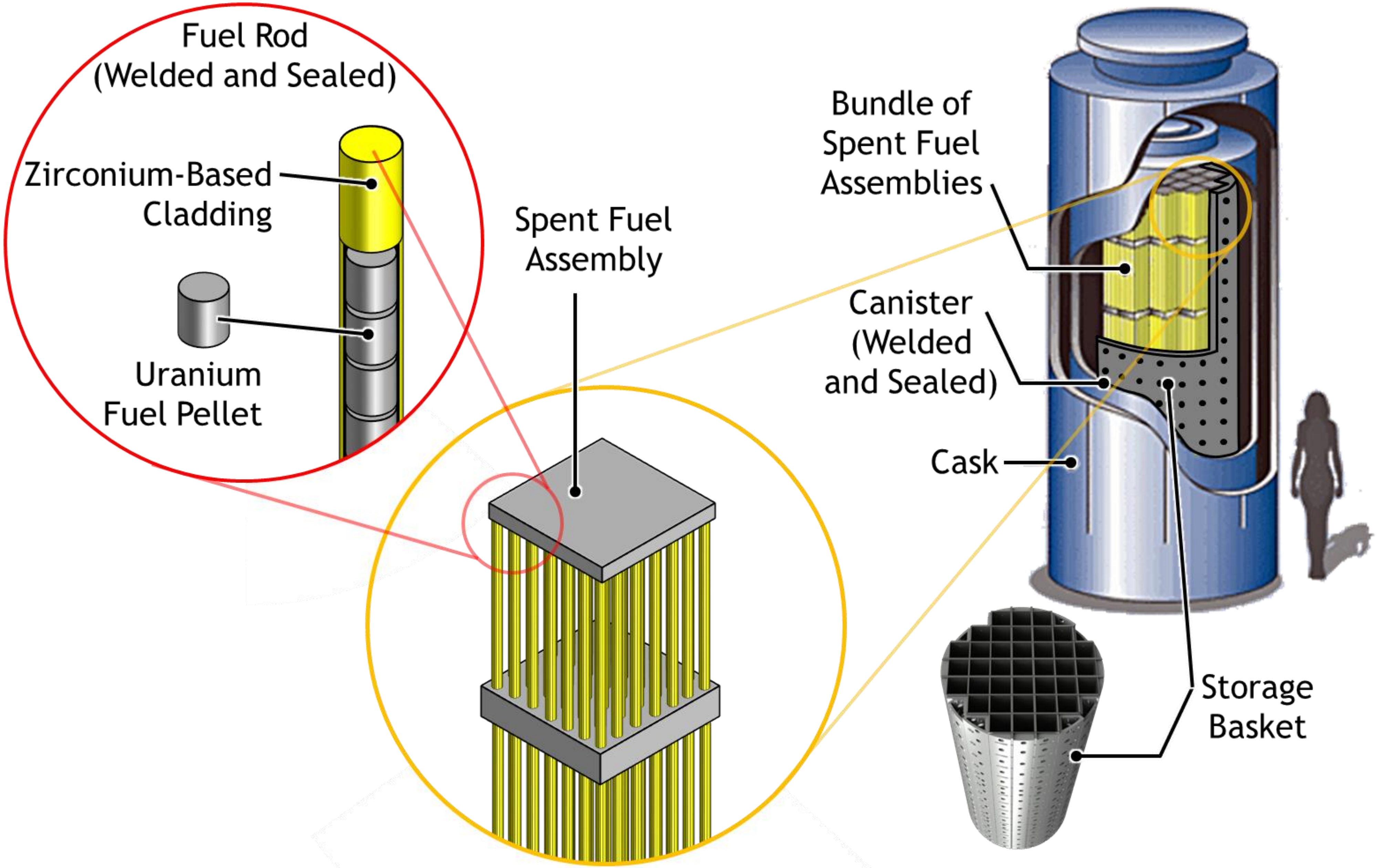


Left photo: Fuel in a spent fuel pool
Middle photo: Fuel assembly being placed in a storage cask in a spent fuel pool.
Right Photo: Spent Nuclear Fuel Dry Cask Storage

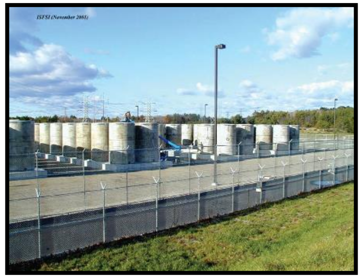




What Are Spent Fuel and Dry Cask Storage Systems (DCSS)?



Vertical

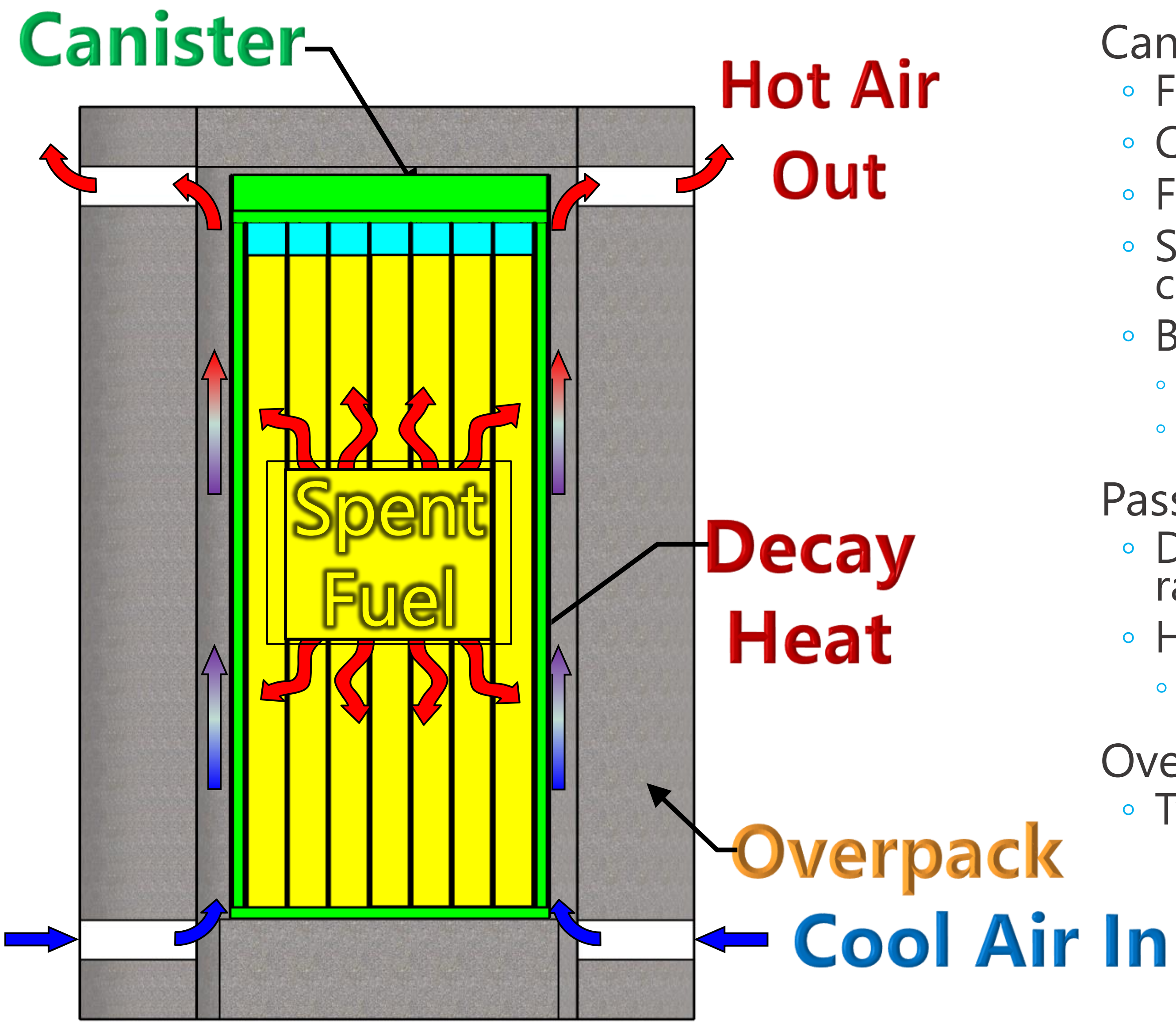


Above ground

Below ground

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

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

GAPS

Gap			
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"

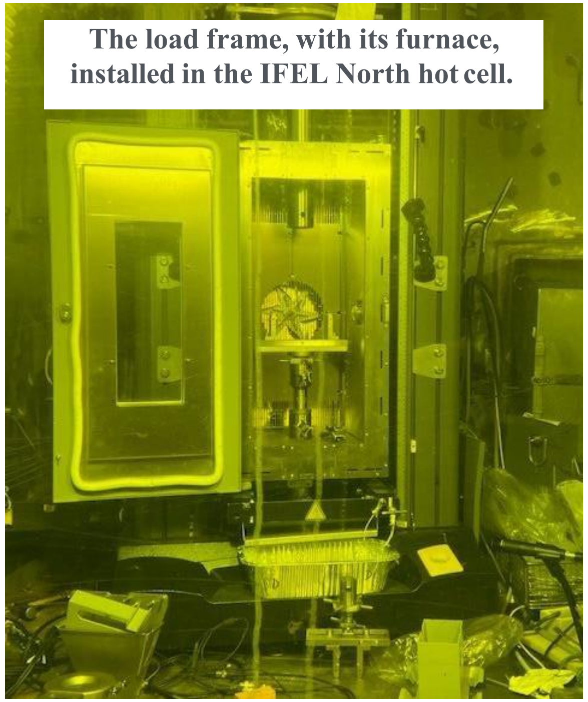
- The High Burnup Demonstration Project is being performed at North Anna Nuclear Power Plant to understand how High Burnup fuel ages during long-term storage.

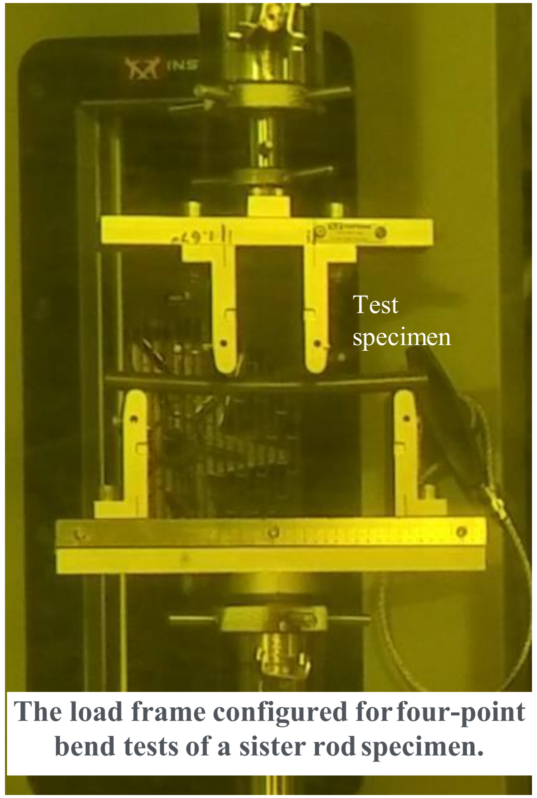
  - In 2017, a cask was loaded with
    - 32 assemblies of high burnup fuel
    - 63 thermocouples placed inside the canister
      - collecting temperature data at least daily and downloaded quarterly.
  - Also in 2017
    - 25 similar fuel rods (sibling pins) were pulled from the North Anna storage pool 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

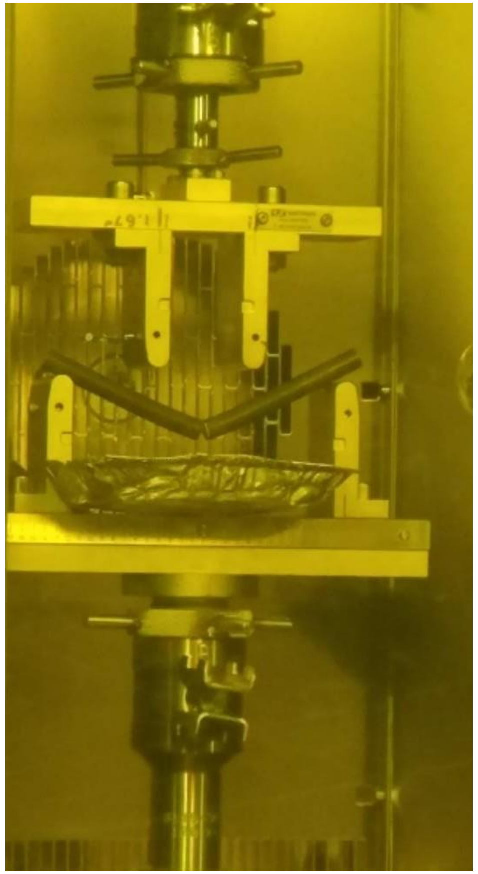
Stored Nuclear Fuel Mechanical Testing

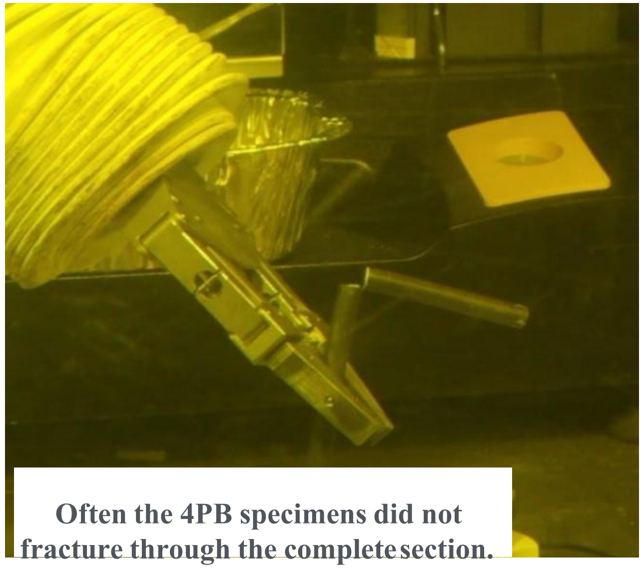
Mechanical testing in hot cells is generating mechanical data at Pacific Northwest National Labs, Oak Ridge National Labs, and Argonne National Labs. The photos of work below are from the hot cells at Oak Ridge National Labs.


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



The load frame configured for four-point bend tests of a sister rod specimen.



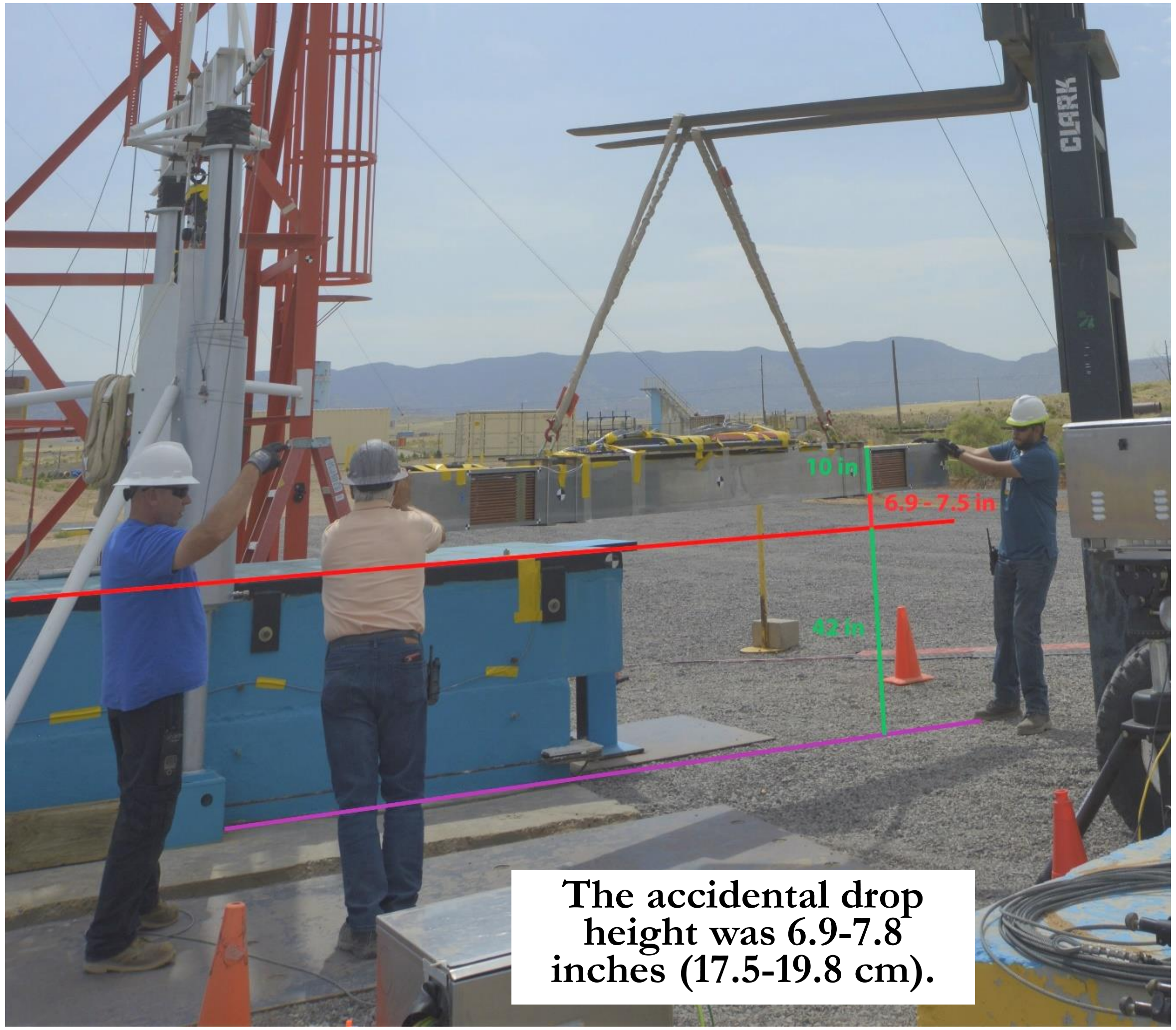

Often the 4PB specimens did not fracture through the complete section.

Quantification of External Loads on the Fuel

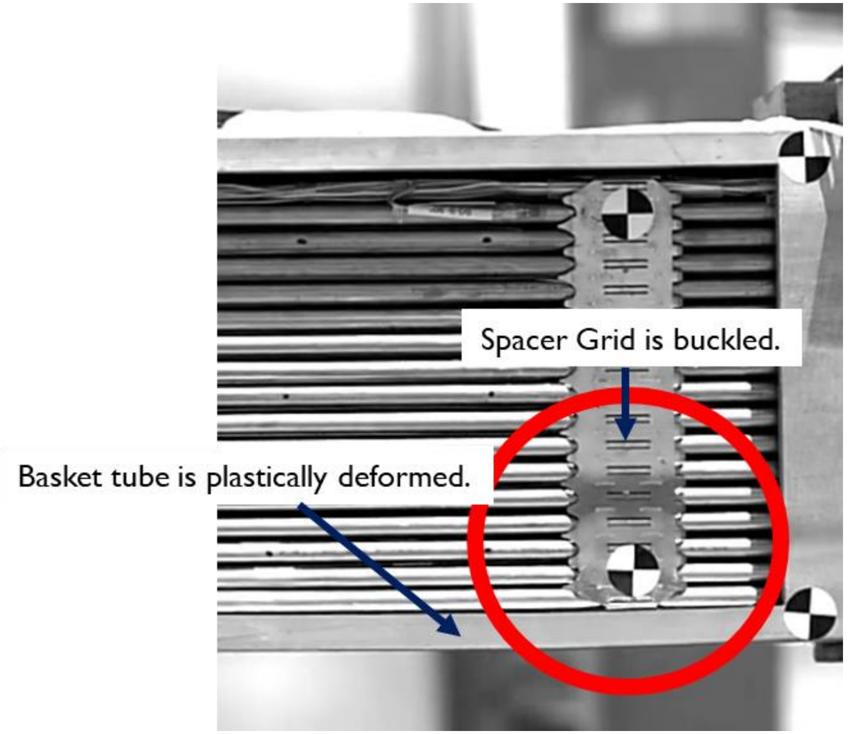
VIDEO

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

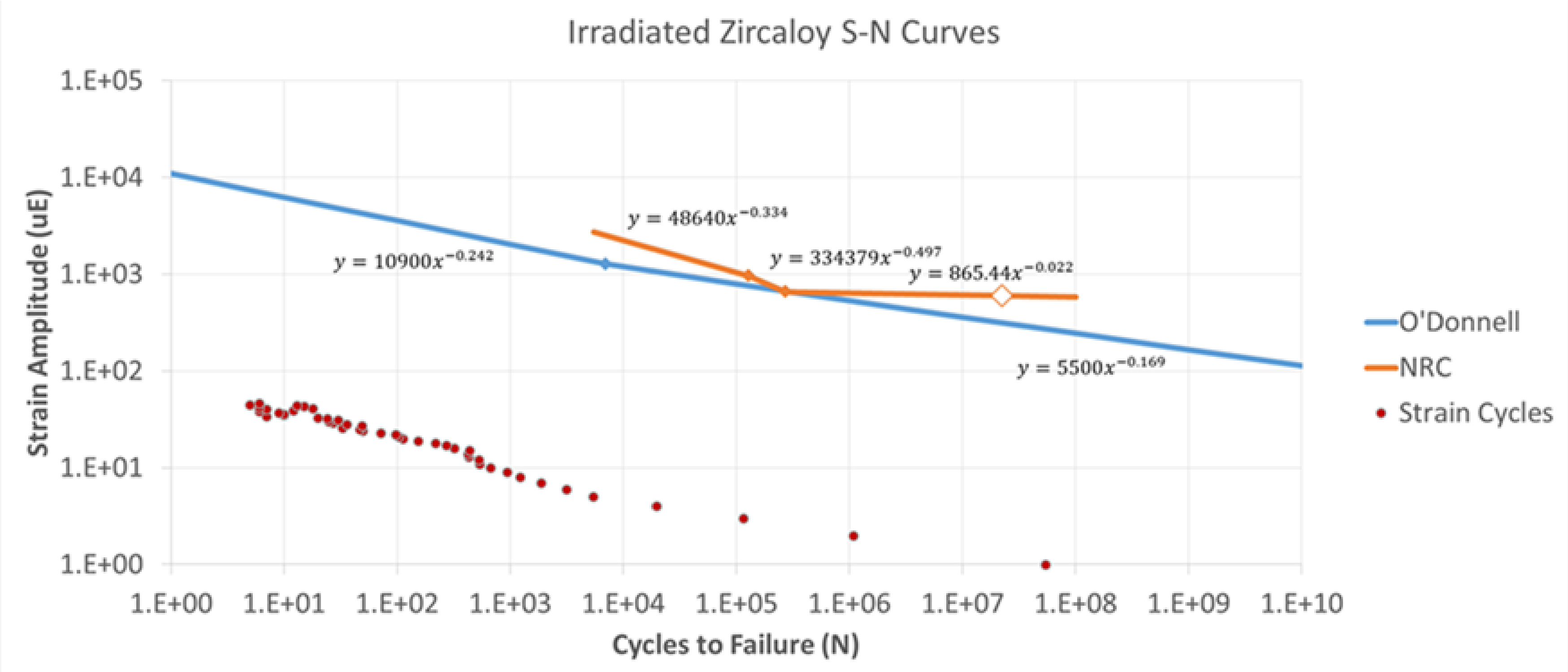
Pre-Accident Photo Used in Estimating Accidental Drop Height



Damage Observed After the Accidental Drop



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)

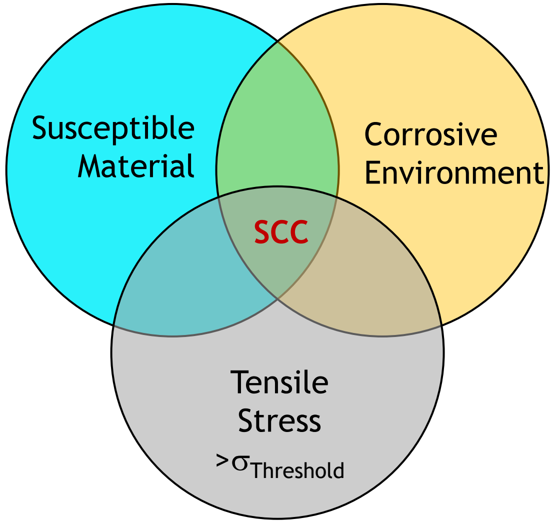
Conclusion: The external loads measured on the surrogate fuel during transportation and handling (red dots) are much lower than the fatigue damage S-N curves derived from hot cell data for spent fuel cladding. The fuel has a large margin of safety for damage during transportation.

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

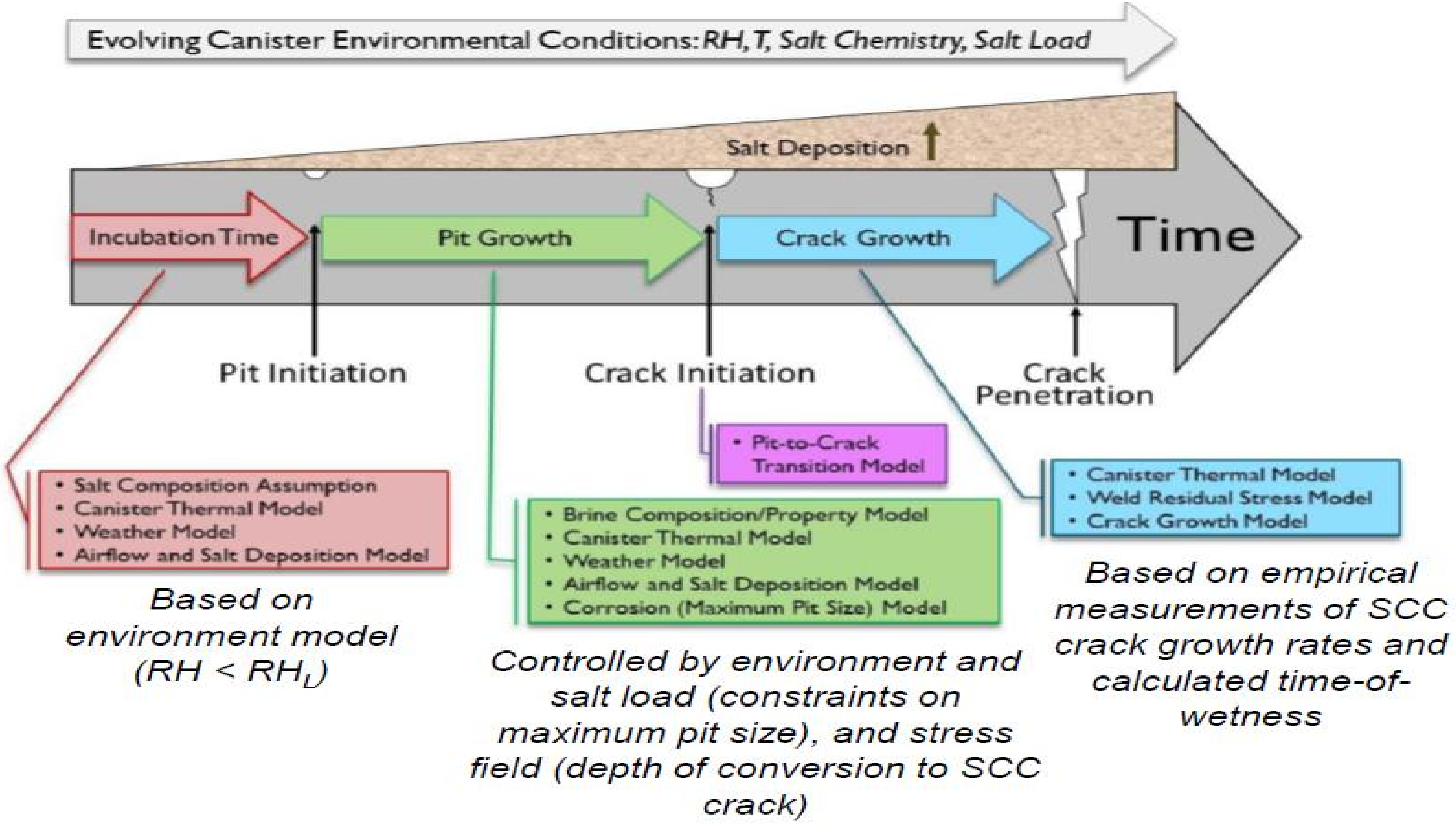
Can the Canisters Leak or Crack Over Time?

Can Canisters Corrode During Extended Storage?

- 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.



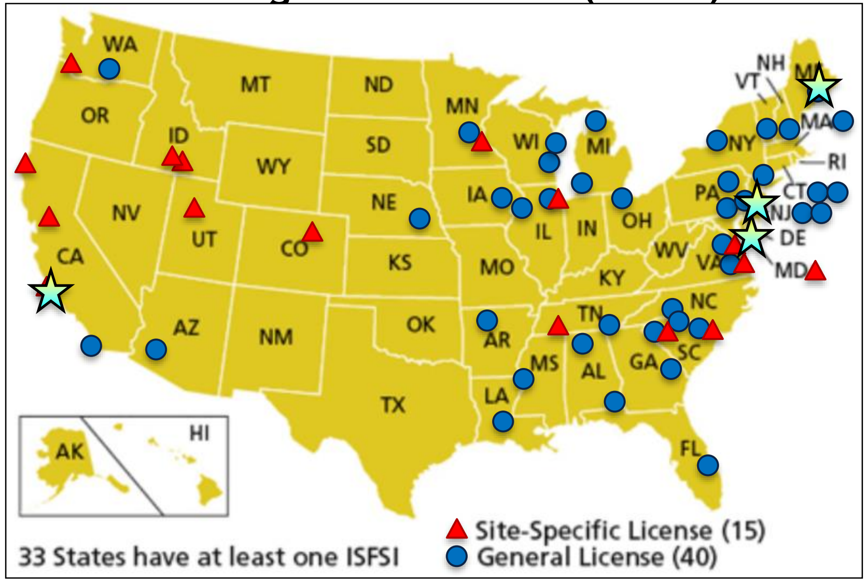
1. We are working to understand the composition of the dusts/brines that are deposited on the surface of the canister and how that dust/brine evolves over time to influence corrosion risk
2. We are working to identify mitigation and repair technologies if corrosion is found.


Evolving Canister Environmental Conditions: RH, T, Salt Chemistry, Salt Load
Salt Deposition
Incubation Time
Pit Growth
Crack Growth
Time
Pit Initiation
Crack Initiation
Crack Penetration
• Pit-to-Crack Transition Model
• Salt Composition Assumption
• Canister Thermal Model
• Weather Model
• Airflow and Salt Deposition Model
• Brine Composition/Property Model
• Canister Thermal Model
• Weather Model
• Airflow and Salt Deposition Model
• Corrosion (Maximum Pit Size) Model
• Canister Thermal Model
• Weld Residual Stress Model
• Crack Growth Model
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

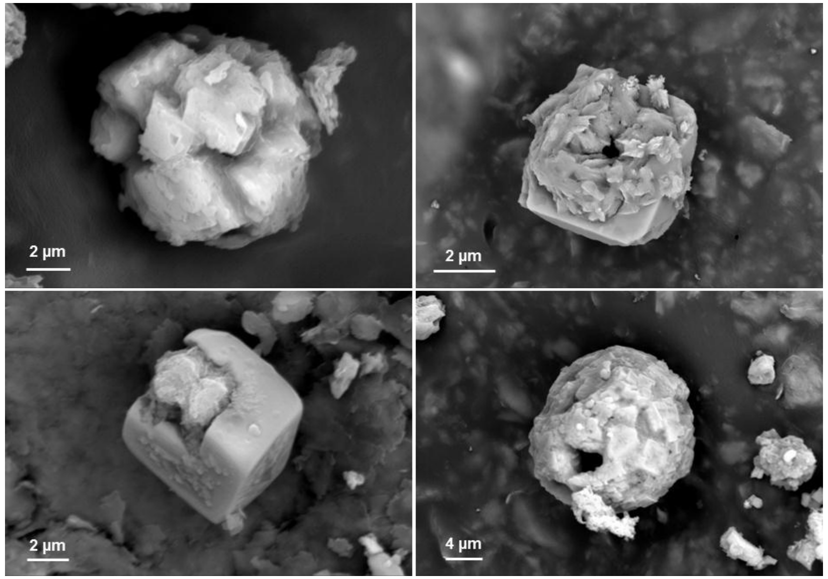
Sea-Salt Aerosols

- **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.**

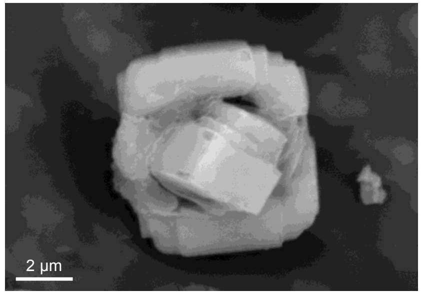
Locations of U.S. Spent Nuclear Fuel Independent Storage Installations (ISFSIs)

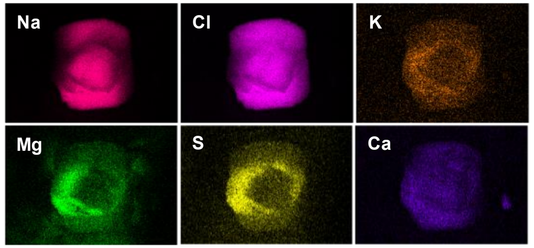


☆ ISFSI locations sampled.



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



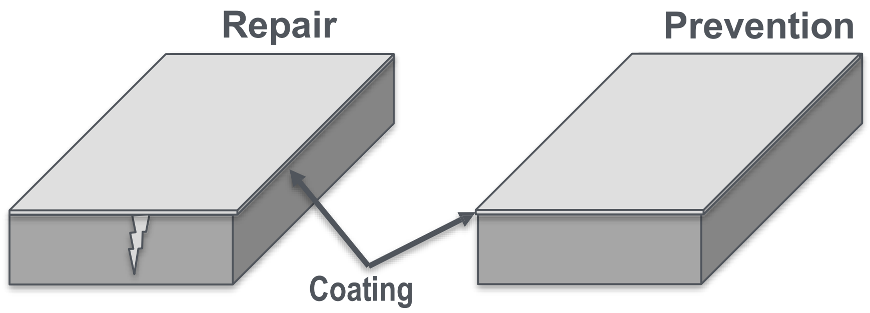


Salt aggregates: dominantly NaCl with interstitial $MgSO_4$ and trace K, Ca phases. Consistent with seawater ion composition.

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

Canister Coatings to Prevent and Remediate SCC

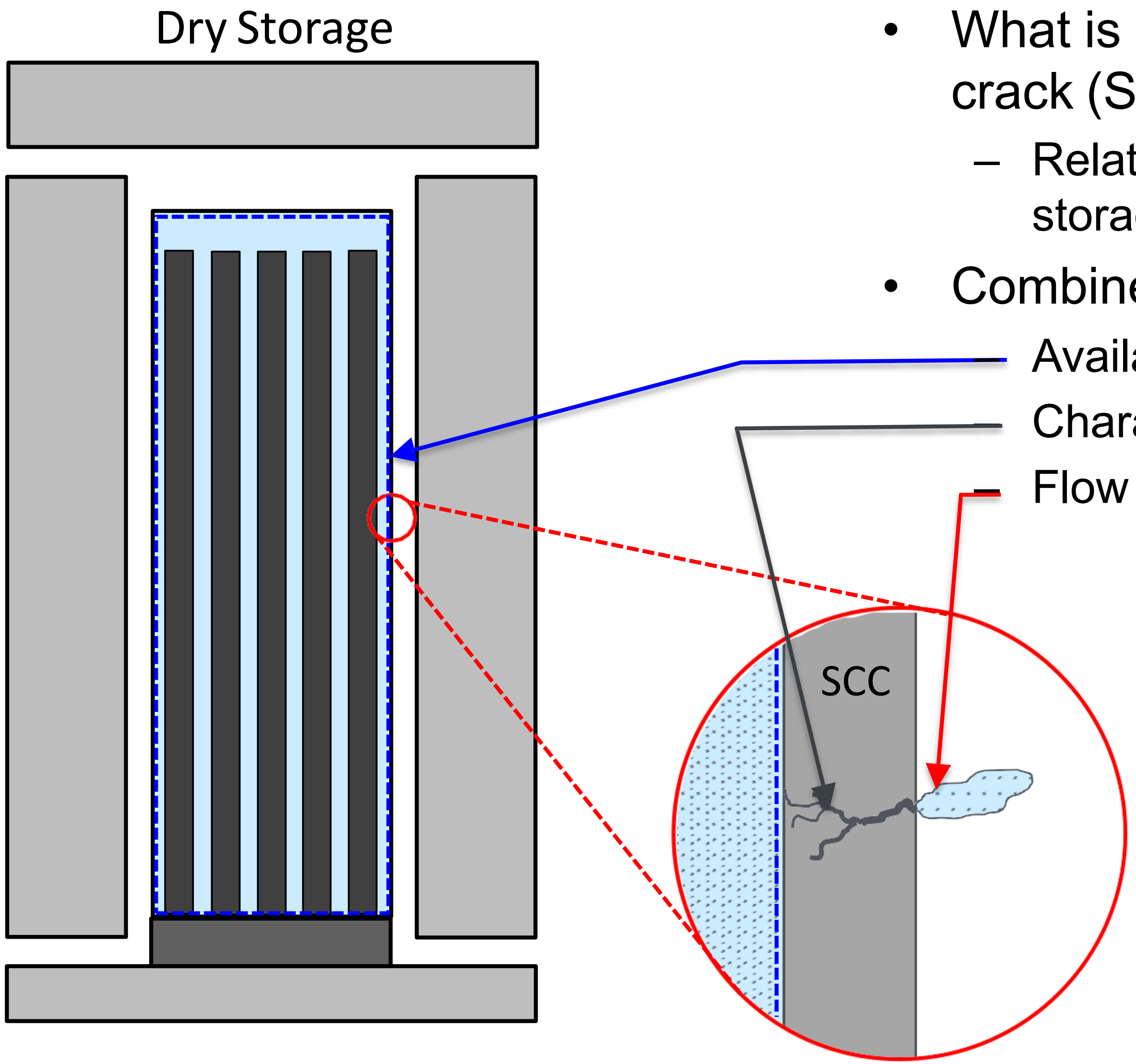
- Difficult to identify cracks quickly and effectively.
- Coatings could be an effective option as:
  - Mitigation/Repair of cracks once they are identified
  - Application as a preventative measure



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 consequence of a through-wall crack?



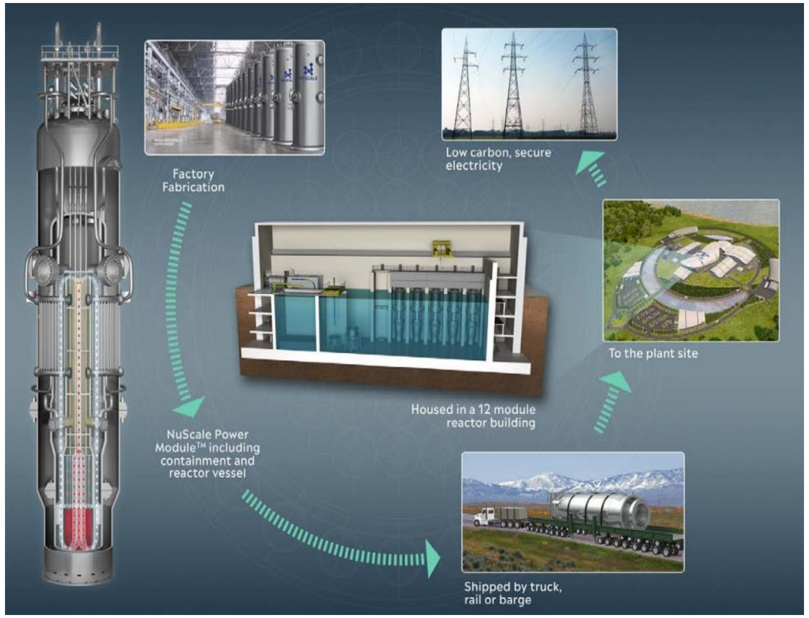
- What is the potential impact of a through-wall stress corrosion crack (SCC)?
  - Relatively low availability of mobile radionuclides under normal storage and transportation conditions
- Combined analysis needed from following topics
  - Available source term inside canister
  - Characteristics of SCC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

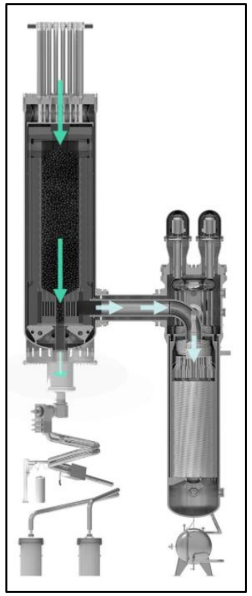
- Andrew Casella Pacific Northwest NATIONAL LABORATORY
  - GOTHIC modeling of canister and SCC flows
- Sam Durbin Sandia National Laboratories
  - MELCOR modeling of canister
  - Aerosol transmission testing
- Yadu Sasikumar OAK RIDGE National Laboratory
  - 1st principles modeling of SCC flow
- Stylianos Chatzidakis, Purdue University

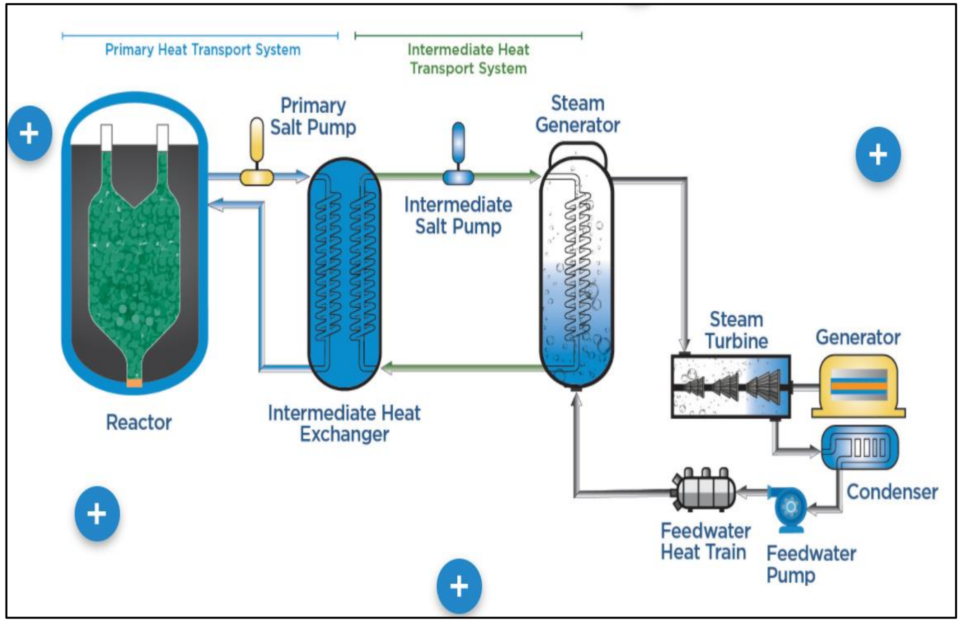
New Reactor Designs

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

Waste and safeguards issues are not being addressed yet.





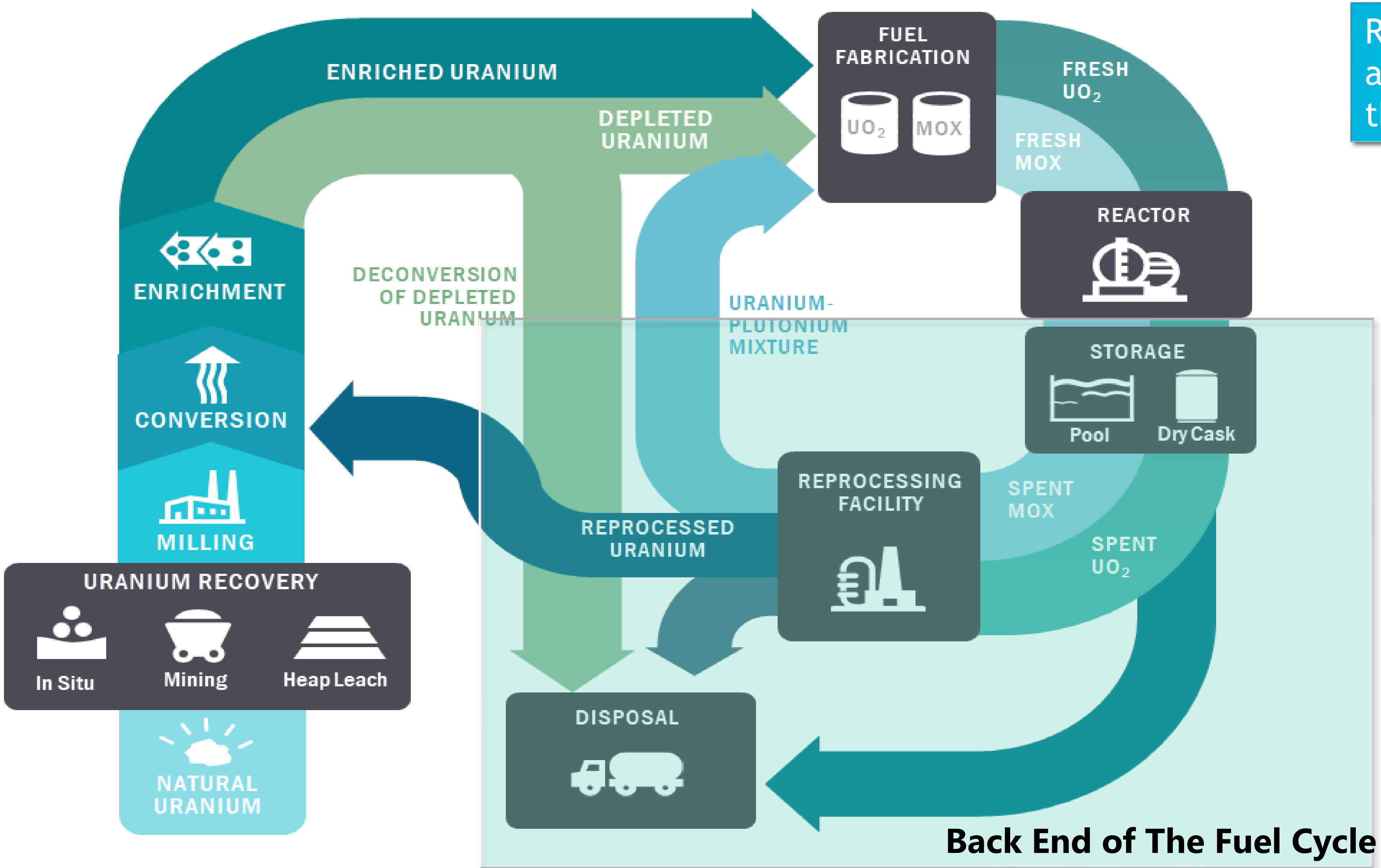


NuScale: received NRC design certification in January 2017. The original design is modular with each module producing 160 MWth, 50 MWe—the 12-pack plant will produce 600 MWe.

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

How Do We Keep the Cycle Going?



References are listed in the paper.