U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

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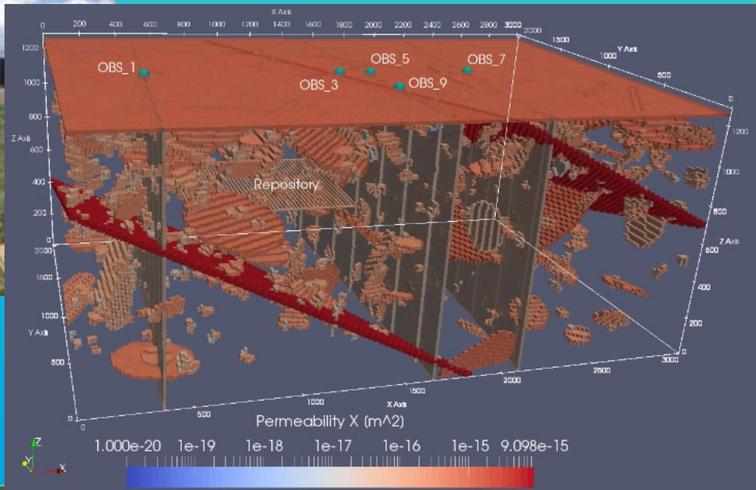

Cladding Degradation Modeling Development

NWTRB Winter 2022 Board Meeting

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Online Virtual Meeting

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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.

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Overview

- Source term processes in the Geologic Disposal Safety Assessment Framework
- Development of Cladding Degradation Model driven by
  - DPC Criticality Consequence Analyses
  - Safety Assessment needs for SNF degradation behavior, consistent with research roadmap (Sevougian et al. 2019)
- Cladding degradation processes included in model
- Recent major accomplishments
- Considerations for additional work
  - Treatment of important chemical interactions

Conceptual Framework for Source Term Processes in GDSA

- Radionuclide Inventory
- Radionuclide decay and ingrowth (Bateman equations)
- SNF instant release fractions
- Waste form degradation rate approaches
  - Instantaneous
  - Fuel Matrix Degradation Model (FMDM)
    - Radiolysis and major chemical boundary conditions
    - Surface area
  - FMDM Surrogate Mechanisms
  - Custom
    - Fractional dissolution rate
    - Rate based on specific surface area
- Waste package degradation
  - Canister vitality – timing of canister breach
  - Canister performance – performance of canister after breach (not yet implemented)

Cladding Modeling and DPC Criticality Consequence Modeling

- Criticality is dependent on SNF configuration
  - Assuming cladding fails when the waste package fails is not conservative for model analyses of postclosure criticality
  - Assess reasonable timing for loss of configuration
- Evaluate
  - Cladding degradation mechanisms
  - Basket hardware longevity
- Grid spacer degradation was identified as primary mechanism for configuration loss (i.e., permanent termination of postclosure criticality)
  - Model for failure of Zircaloy grid spacers from general corrosion was developed from cladding degradation work
  - Implementing that model into DPC criticality consequence model

Initial Screening of Mechanisms for Cladding Degradation for Criticality Consequence

Table 4. As-received Clad Degradation Mechanisms, Base Case and with Criticality.

	Alluvium		Shale	
Mechanism	**Base**	**Critical**	**Base**	**Critical**
General corrosion	too slow	too slow	too slow	•
Microbially influenced corrosion	unlikely	unlikely	unlikely	unlikely
Localized (radiolysis enhanced) corrosion	unlikely	unlikely	unlikely	unlikely
Localized (pitting) corrosion	unlikely	unlikely	unlikely	unlikely
Localized (crevice) corrosion	unlikely	unlikely	unlikely	unlikely
Enhanced corrosion from dissolved silica	unlikely	unlikely	unlikely	unlikely
Creep rupture	little/no effect	little/no effect	little/no effect	little/no effect
Internal pressurization of cladding	little/no effect	little/no effect	little/no effect	little/no effect
Stress corrosion cracking of cladding	unlikely	unlikely	unlikely	unlikely
Hydride cracking	unlikely	unlikely	unlikely	unlikely
Cladding unzipping (late WP breach)	too slow	too slow	unlikely	unlikely
Diffusion-controlled cavity growth	unlikely	unlikely	unlikely	unlikely
Localized (fluoride-enhanced) corrosion	•	•	unlikely	unlikely

Brady and Hanson 2020

- **General corrosion is described by two Arrhenius-type rate laws, one for the first phase of general corrosion (lasting a few years) and another for the second phase (Hillner et al. 1998)**
- **General corrosion rates from Hillner et al. (1998) are multiplied by 2 to account for effects of irradiation**

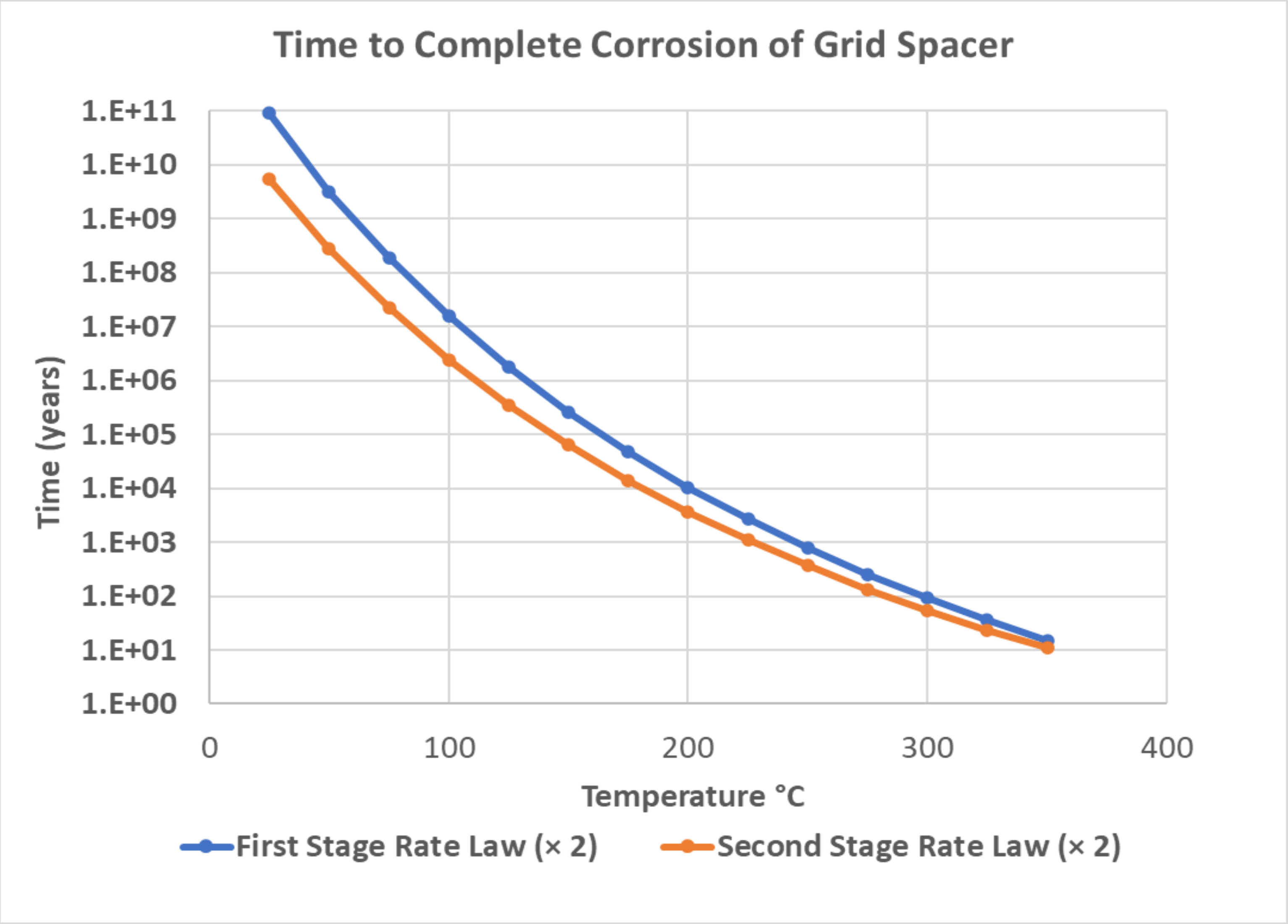
Comparison of 250°C failure times from General Corrosion

	Thickness (mils)	Failure Time (years)
Cladding	22.5	1,640
Grid spacer walls	10	366
Guide tubes	16	585

From Brady and Hanson (2020) using second-stage rate law from Hillner et al. (1998) × 2

- Grid spacer degradation was identified as likely failure mechanism for configuration loss
- Grid spacers are thinner and corrode on both sides
- At lower temperatures, corrosion rates are slower
- Temperature of 250°C is relevant to steady-state criticality in saturated shale environment

Grid Spacer General Corrosion Degradation Rate



Using Equations (6) and (7) from Hillner et al. (1998)

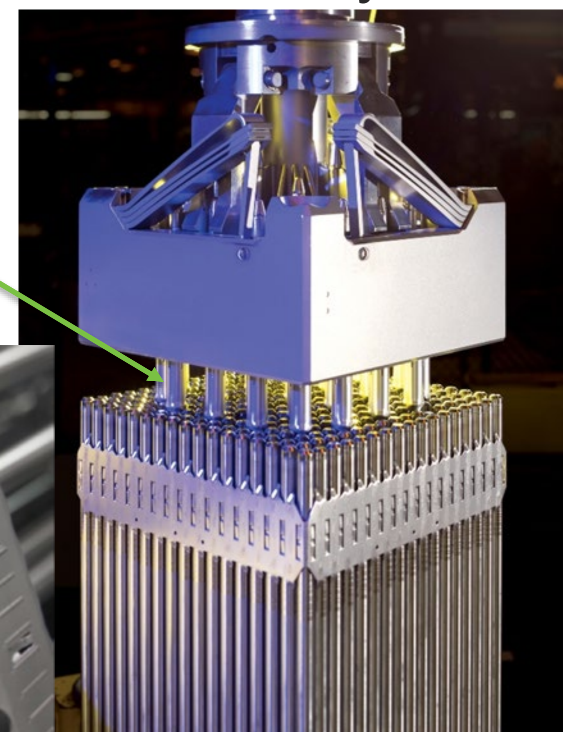
Additional Data Needs for Criticality Analyses

- For criticality analyses, degradation rates of the guide tubes/ tie rods/water channel, and grid spacers are necessary
  - Zircaloy, Inconel
- Relocation of rods (reduced pitch) or fuel dissolution may terminate criticality

Grid spacers

Example grid spacer showing thin-walled cells

Guide tubes



Photos from Westinghousenuclear.com

Concepts for Cladding Credit for Geologic Disposal Safety Analyses and Criticality

- A small percentage of cladding is failed upon emplacement
  - In-reactor failure/pool storage
  - Dry Storage
  - Handling/Transportation
- Additional failures occur in the repository
  - Mechanical
    - External (e.g., rockfall, seismic, etc.)
    - Internal (e.g., creep, internal pressurization, delayed hydride cracking, etc.)
  - Corrosion (e.g., general, localized, stress corrosion cracking, etc.)

OR

- Assume all cladding is failed upon emplacement (no credit)
  - Conservative for waste form degradation and dose calculations
  - May be optimistic/non-conservative for
    - Criticality assessments

International Perspective on Cladding Credit

- Finland- assumes water will penetrate the canister insert and fuel cladding in 1000 years upon canister breach
- Canada – no cladding credit
- Sweden (SKB 2011) – no cladding credit
  - "According to the Fuel and Canister process report, available data suggest a life of the cladding tubes of at least 100,000 years. Although Zircaloy is highly resistant to uniform corrosion, due to its potential susceptibility to local corrosion in groundwaters and to hydrogen induced cracking, cladding is not assumed to constitute a barrier to radionuclide release from the fuel in SR-Site. However, even a cladding with small cracks or corrosion defects would offer a large mass-transport resistance for water to get into contact with the fuel and for dissolved radionuclides to exit into the canister void."
  - "No studies of corrosion rate of Zircaloy have been conducted by SKB…..penetration of the cladding tubes is estimated to require 400,000 years at a tube thickness of 0.8 mm" (SKB 2010)

Review of Cladding Credit U.S. History

- Prior to Total Systems Performance Assessment (TSPA) – Viability Assessment (VA) for Yucca Mountain, there was no consideration of protection of the fuel by cladding and all fuel in a drip zone was available to dissolve.
- TSPA-VA
  - Initial failed cladding percentage: 1.25%
  - Cladding failure mechanisms
    - Mechanical (rockfall)
    - Corrosion (assumed 10× – 1,000× smaller than the corrosion rate of Alloy 22)
  - Peer Review (Budnitz et al. 1999) found "credit taken for spent fuel cladding may be optimistic, considering the potential effects of hydrogen embrittlement" and recommended obtaining additional experimental data for "…Zircaloy cladding when they are experiencing corrosive conditions" to address large uncertainties resulting from lack of data or quality of data.

Review of Cladding Credit U.S. History (Cont'd)

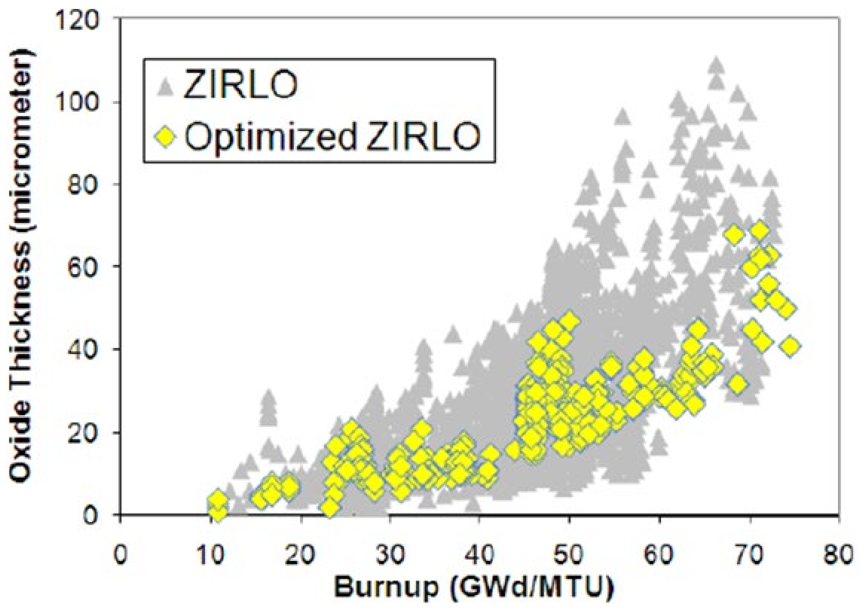
- TSPA-SR (Yucca Mountain Site Recommendation)
  - Initial failed cladding percentage: 0.0155% - 1.285% (median 0.0948%) [Siegmann 2000] (average 2.2 failed rods/failed assembly)
  - Cladding failure mechanisms
    - Examined in features, events, and processes (FEP) analyses
    - Mechanical (rockfall, severe earthquake)
    - Creep
    - Stress corrosion cracking (SCC)
    - Localized corrosion from dissolved fluoride
  - Cladding remains a significant barrier up to 100,000 years and beyond
  - Peer Review (NEA 2002): The IRT "…found one process (effects of the degradation of basket components on cladding integrity) that was not taken into account and which could compromise the performance of the cladding. *The issue of cladding performance is important because it is one area of possible optimism and because it has a major effect on system performance beyond 10,000 years. Thus further efforts are recommended to strengthen confidence in this area.*"

Review of Cladding Credit U.S. History (Cont'd)

- TSPA-LA (Yucca Mountain License Application)
  - Initial failed cladding percentage: log uniform distribution 0.01%-1.0%
  - Cladding failure mechanisms
    - Cladding failed at emplacement splits axially instantaneously upon waste package failure
    - Rockfall- cladding failure starts when both the waste package and drip shield failure fractions reach 20% and continue with uniform distribution to 50%, with cladding failure increasing linearly to 100% rod failure when an additional 50% of the waste package patches are open. (100% fuel exposure in a failed rod)

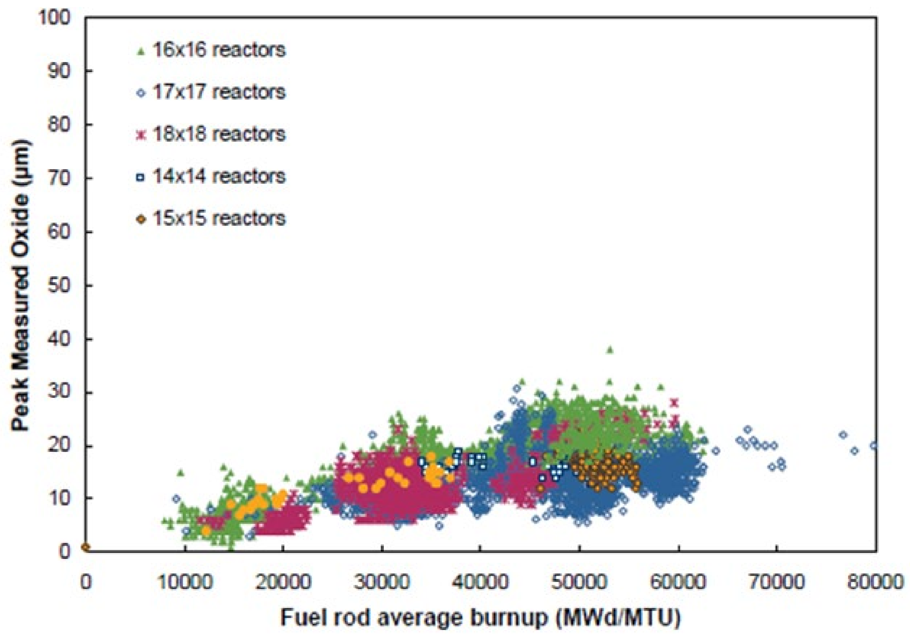
What Has Changed?

- Development of more corrosion resistant alloys (M5®, ZIRLO®, Optimized ZIRLO™)
- Accident tolerant fuels (e.g., Cr-coated cladding)
- Industry effort/focus to achieve zero failures



ZIRLO®

Pan et al. 2013



M5®

Mardon et al. 2010

Industry Practice: Significant Decrease in Fuel Failures

U.S. PWR fuel rod failure rate:
- **2010 Reload: $1 * 10^{-4}$ per rod**
- **2015 Reload: $8 * 10^{-6}$ per rod**

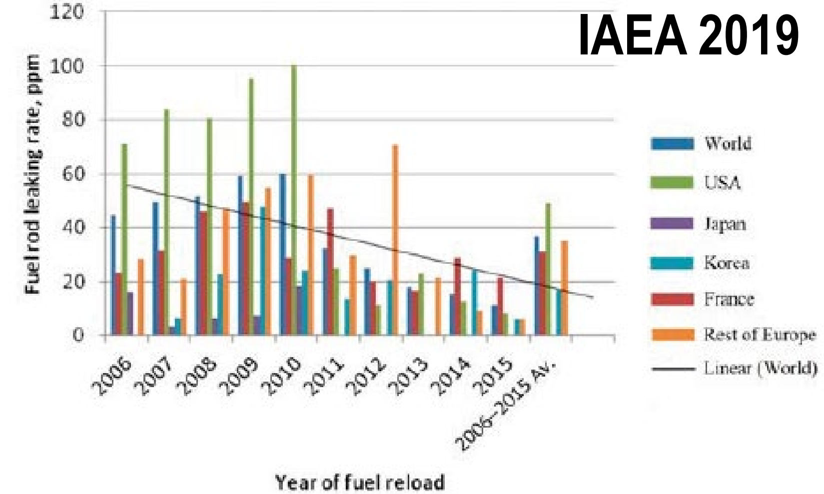
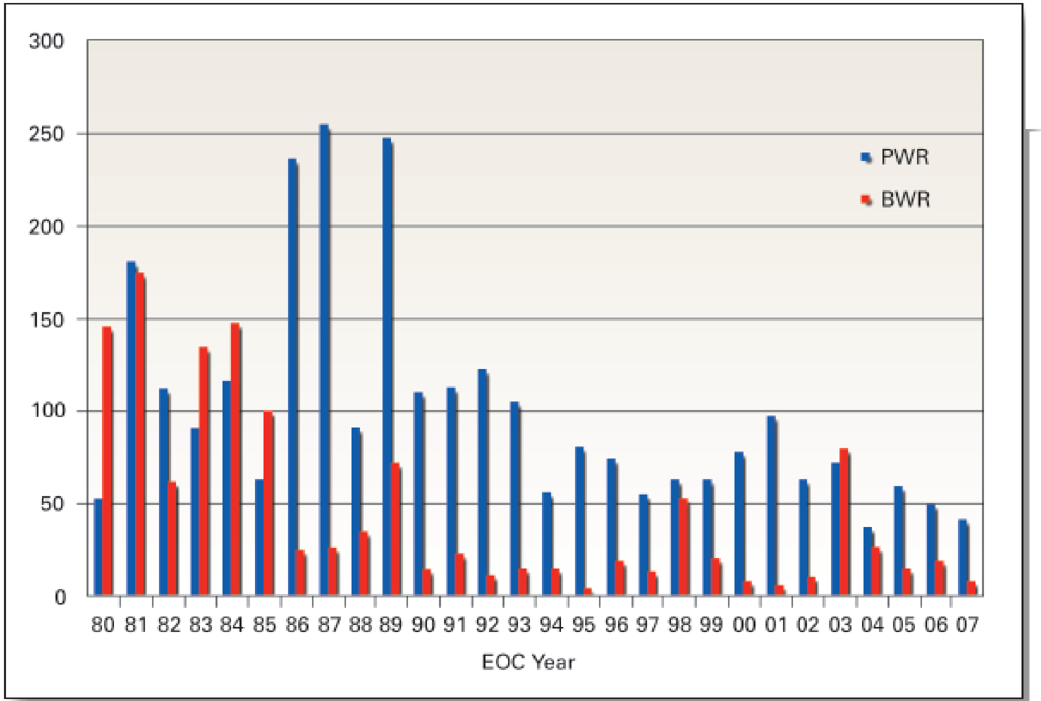


FIG. 3. PWR FR failure rates in 2006–2015. Linear extrapolation is for world averages (ppm means 1×10^6).



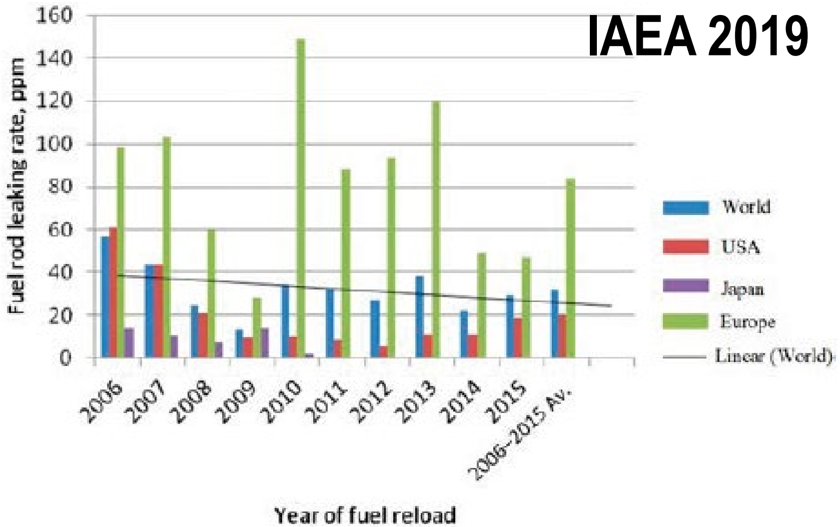
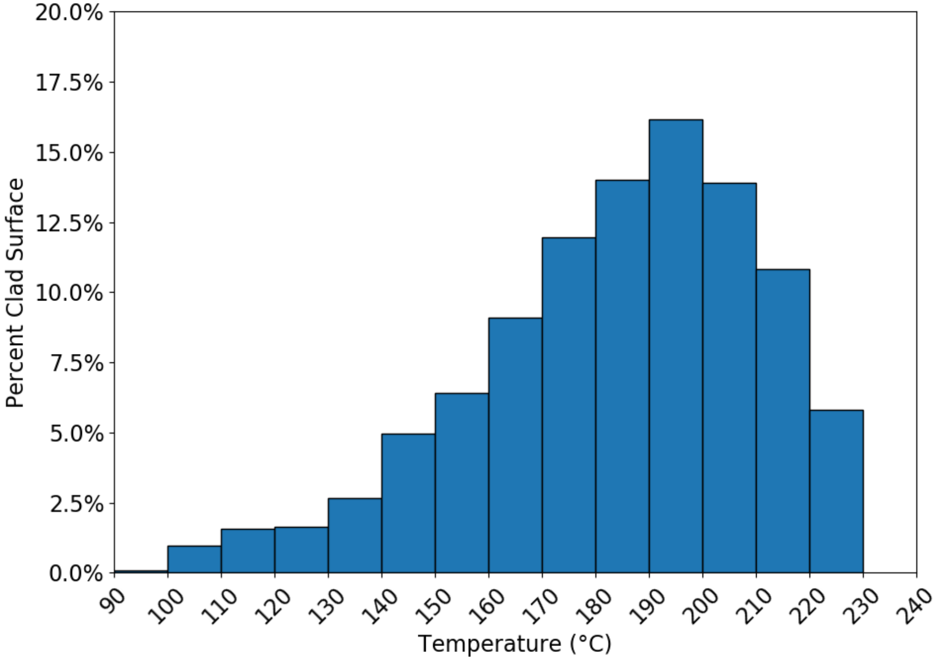


FIG. 8. BWR FR failure rates in 2006–2015. Linear extrapolation is for world averages.

Fuel failures trending downward (EPRI 2008)

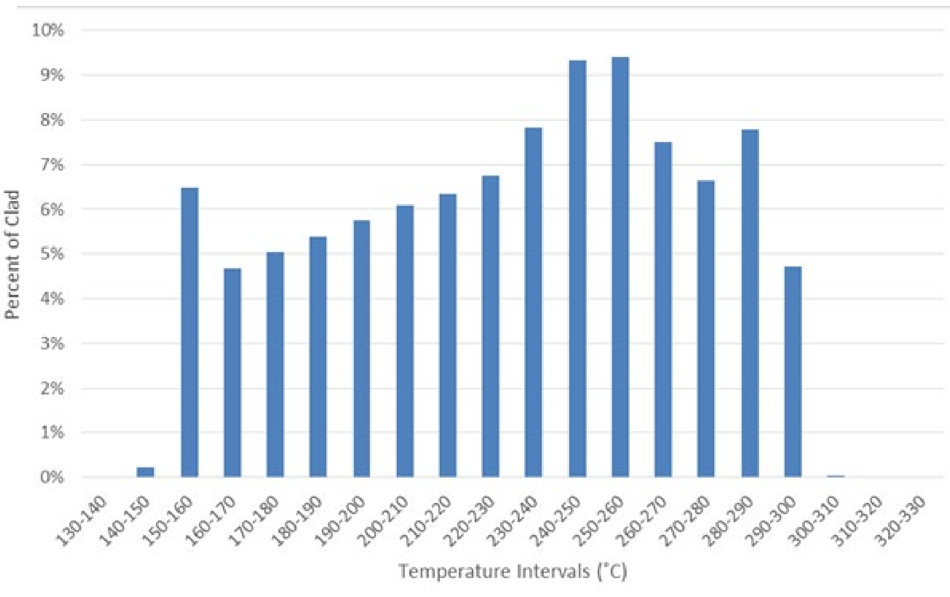
SFWST Work in Dry Storage and Transportation (1)

High Burnup Demonstration Cask (Fort et al. 2019)



- Cladding temperatures much lower than expected

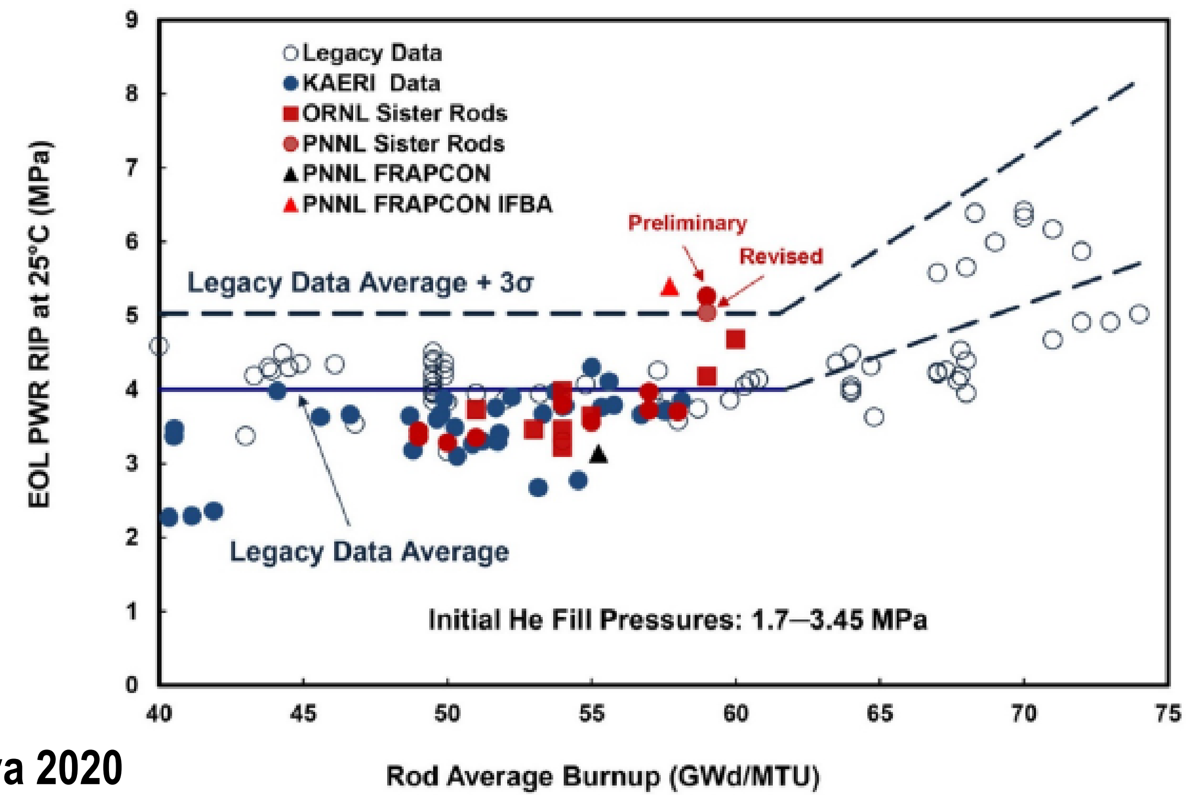
High Heat Load Vertical Canister (Fort et al. 2016)



- Only a small fraction of the cladding approaches the peak cladding temperature

SFWST Work in Dry Storage and Transportation (2)

- Modern fuels have much lower end-of-life rod internal pressure → hoop stress <90 MPa at 400˚C → no impact of hydride reorientation on mechanical properties (sibling pin testing), minimal creep, SCC, or delayed hydride cracking

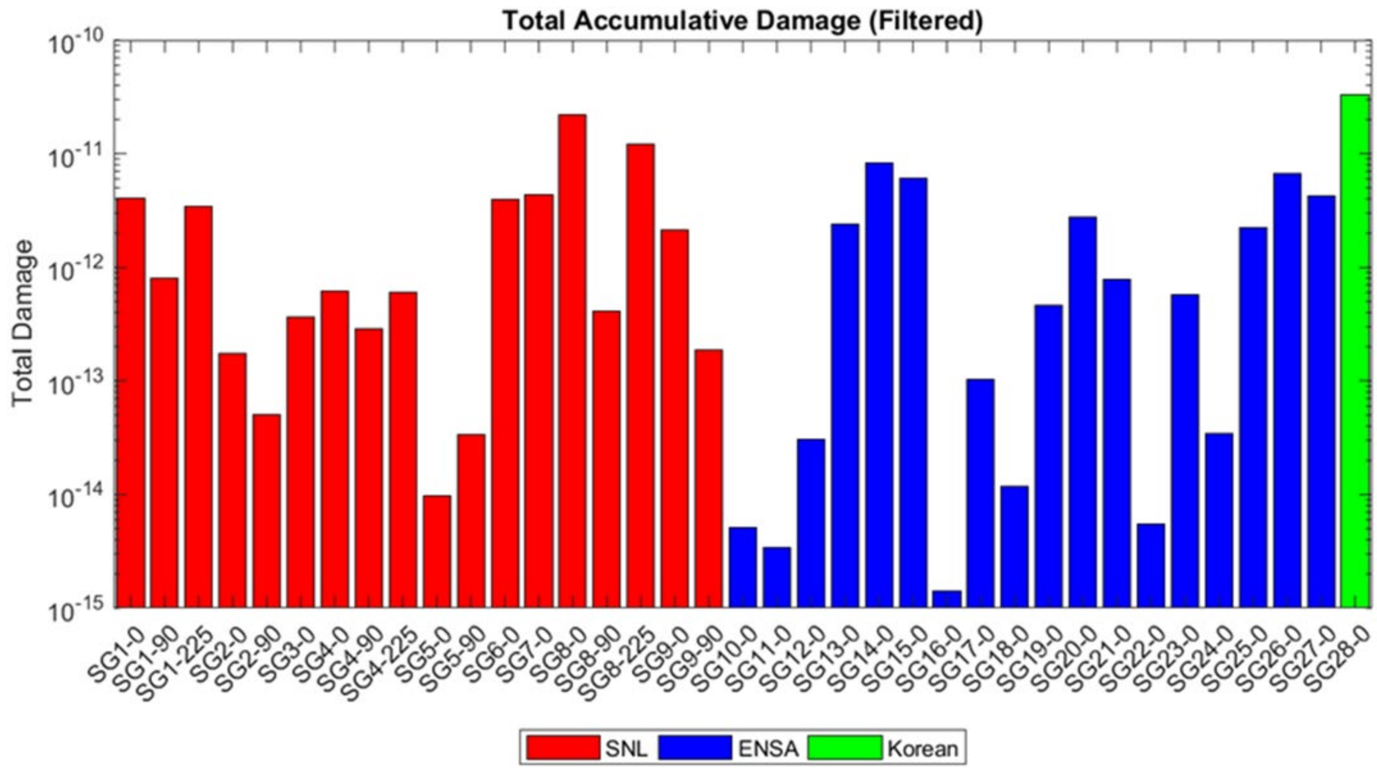


Billone and Burtseva 2020

Figure 80: End-of-life (EOL) rod internal pressure (RIP) data extrapolated to 25°C for fuel rods with standard UO_2 fuel pellets clad in Zry-4, LT Zry-4, ZIRLO®, and M5®.

SFWST Work in Dry Storage and Transportation (3)

- External loads from handling and normal conditions of transport are minimal (Kalinina et al. 2018)
- Strain energy from maximum shock event (railcar coupling at 8 mph) comparable to the kinetic energy of one raindrop



10,000,000,000+ trips of 2,000 miles before fatigue failure would occur (Klymyshyn et al. 2018)

Industry and Regulatory Activities

- EPRI has sponsored Phenomena Identification and Ranking Table (PIRT) exercises for
  - Decay Heat – Review of Current Status and Recommendations for Future Needs (3002018440 2020)
  - Thermal Modeling (3002018441 2020)
  - Exercise for Used Fuel Cladding Performance (3002018439 2020)
  - Exercise for Spent Fuel Cladding Gross Rupture (3002020929 2021)

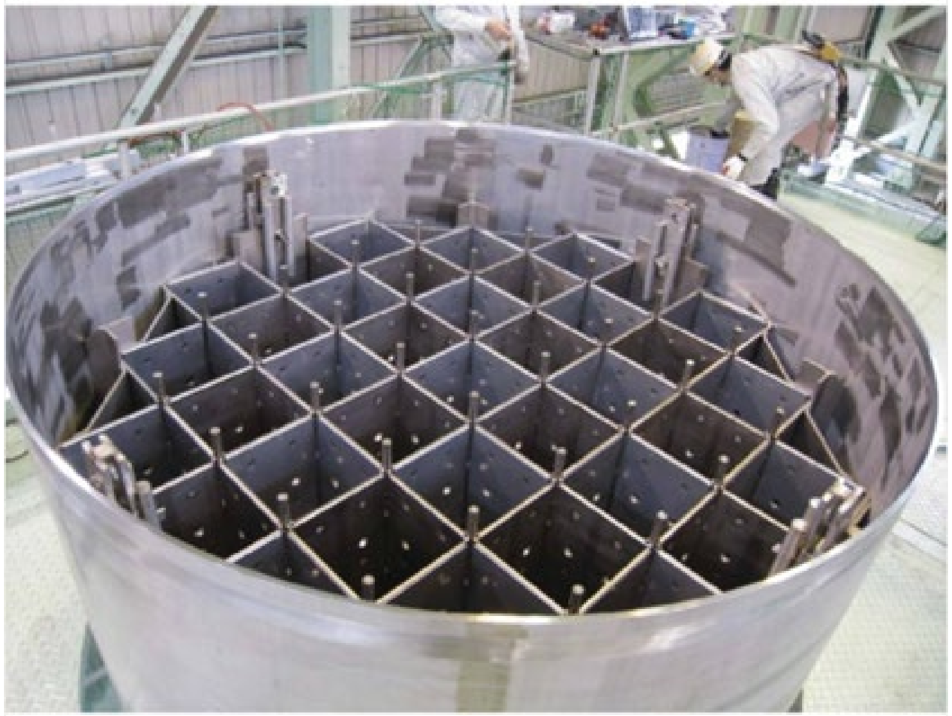
- Nuclear Regulatory Commission has issued
  - Managing Aging Processes In Storage (MAPS) Report, NUREG-2214, 2019
  - Dry Storage and Transportation of High Burnup Spent Nuclear Fuel, NUREG-2224, 2020

Open Issues Being Pursued for Cladding Degradation Model for Safety Assessment and Initial Test Planning

- Sufficient and high-quality data to reduce uncertainties
  - Zircaloy-2, Zircaloy-4, ZIRLO®, Optimized ZIRLO™, M5®, ATF
- Long-term testing to validate extrapolations from short-term tests
  - General corrosion (oxidation) especially for the critical shale case and T>150℃
- Irradiated vs unirradiated cladding modeling and testing (irradiated degrades 2-20× faster; IAEA 1998)
  - Possible factors (Olander and Motta 2021)
    - Internal heat flux
    - Hydride rim
    - Radiation-induced changes to cladding and oxide microstructure
    - Water radiolysis

Open Issues Being Pursued for Cladding Degradation Model for Safety Assessment and Initial Test Planning (Cont'd)

- Effects of degraded waste package materials, including baskets (e.g., stainless steel with boron, aluminum, metal matrix composites [B_4C/Al], etc.) on water chemistry, potential galvanic coupling, and mechanical impacts on cladding
- Fluoride-enhanced corrosion
  - Alluvium, T<100℃, pH<3.2, and dissolved fluoride > 5 ppm



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Questions?