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Challenges and Solutions for Safe Management of Spent Nuclear Fuel

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ANS Savannah River Chapter Dinner Meeting, March 19, 2024

Introduction

- Scope: Extended storage of spent nuclear fuel (SNF) from present design Research Reactors (RR) and from Power Reactors (PR)
- De facto extended storage
- See paper in Journal of the South Carolina Academy of Science for additional information

Winner of the 2021 Governor's Award for Excellence in Scientific Research

The Nuclear Fuel Cycle: Safe Management of Spent Nuclear Fuel

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The aim for storage of spent nuclear fuel (SNF) either in wet or in dry storage systems is to ensure general safety objectives are met throughout a desired storage period. Staff at the Savannah River National Laboratory (SRNL), in collaborations with partners at other national laboratories, industry research organizations, and the University of South Carolina (UofSC), have performed materials aging testing and analyses, and have established nuclear materials aging management programs to support extended periods of safe storage of research reactor (RR) SNF and of commercial power reactor (PR) SNF pending ultimate disposal. Several example challenges include susceptibility of aluminum SNF from research reactors to corrosion in poor quality water (wet storage). In dry storage, aluminum SNF can release hydrogen via radiolysis of the hydrated oxides on the aluminum cladding. Austenitic stainless steel canisters used for dry storage are susceptible to chloride-induced stress corrosion cracking (outside-in attack) that threaten the confinement boundary provided by the canister. This paper further describes these challenges, among others, and the formulated solutions to support extended safe storage of SNF.

Introduction

The nuclear fuel cycle for fission reactors spans the set of functions and processes from the initial mining of uranium through to the permanent disposal of the spent fuel itself, or, if reprocessed to recover useful species, a waste form for disposal in a repository (see Figure 1). An important stage in the back end of this cycle is the storage of the spent nuclear fuel (SNF) which can be in a wet storage system (e.g., a pool or water basin) or in a dry storage system (e.g., stainless steel canisters with radiation shielding overpacks on a concrete pad outside).

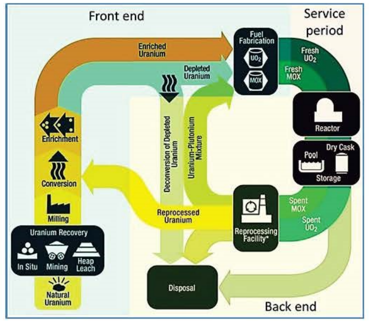


Figure 1. Stages in a Generic Nuclear Fuel Cycle for a PR with Reprocessing [courtesy of U.S. Nuclear Regulatory Commission]

Figure 2 shows examples of commercial power reactor (PR) fuel and research reactor (RR) fuel and their wet and dry storage systems. Following reactor service, the SNF is discharged to a pool for cooling, for both power reactors (PR) and research reactors (RR). The SNF can remain in pool storage for additional cooling and shielding of the attendant decay radiation. In the U.S., PR fuel was originally intended to be stored in the water pool several years prior to reprocessing. However, the U.S. has followed a "once-through" (i.e., no reprocessing) nuclear fuel cycle strategy since the late 1970's, and this has led to interim storage in pools at full capacity or soon-to-be full pools at most of the U.S. reactor sites, and in dry storage systems owned by utilities and licensed by the U.S. Nuclear Regulatory Commission (NRC). At present, over 80,000 metric tonnes of heavy metal (MTHM) of SNF have been discharged from PR in the U.S., of which nearly half is stored in

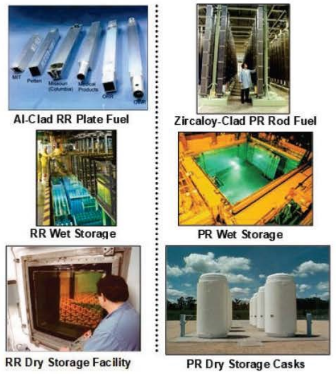


Figure 2. Research Reactor (RR) and Power Reactor (PR) Fuel in Storage Systems

dual-purpose canisters[1] (DPC) made of stainless-steel numbering over 3000 DPCs [1].

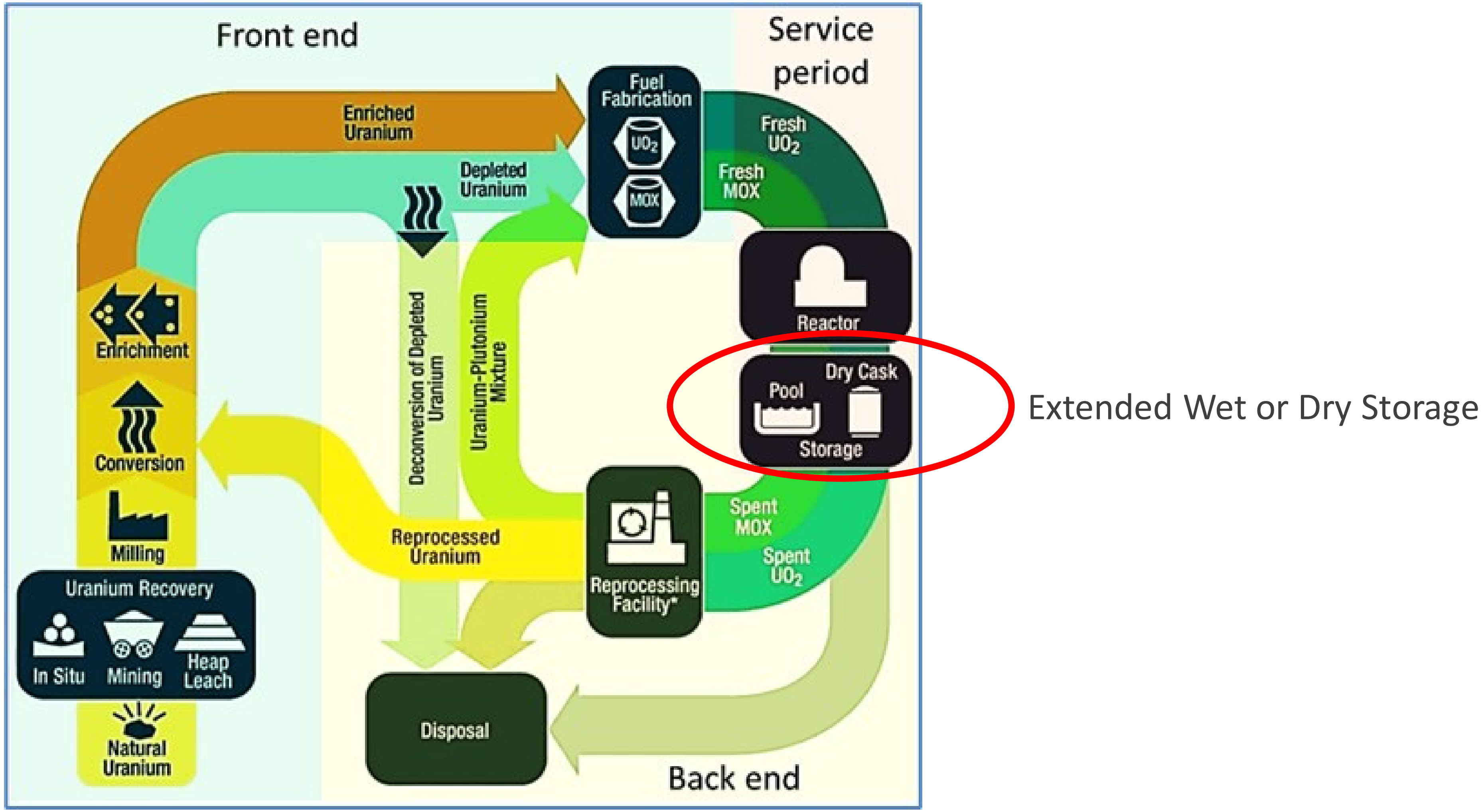
The U.S. Department of Energy - Environmental Management (DOE -EM) office is responsible for the receipt and storage pending disposition of spent nuclear fuel that was used in research and test reactors worldwide that contains U.S. origin and certain non-U.S. origin enriched uranium. This foreign and domestic RR fuel is primarily aluminum-based, aluminum-clad fuel that is being stored in L Basin, a water basin at the Savannah River Site (SRS) in South Carolina. Additional aluminum fuel, the majority of which originated from the Advanced Test Reactor, is in dry storage in the Irradiated Fuel Storage Facility (IFSF) at the Idaho Nuclear Technology and Engineering Center (INTEC) at the Idaho National Laboratory (INL).

The lack of a federal geologic repository as the ultimate end state for the SNF from PR and RR has led to de facto extended storage with no certain end date.

[1] The DPC would be multi-purpose for storage, transportation, and disposal

https://scholarcommons.sc.edu/jscas/vol20/iss1/7

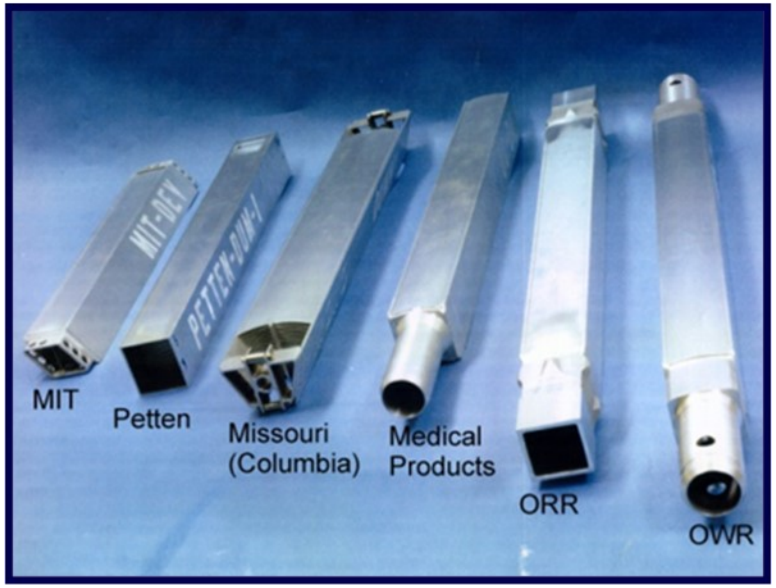
Nuclear Fuel Cycle (Fission Reactors)



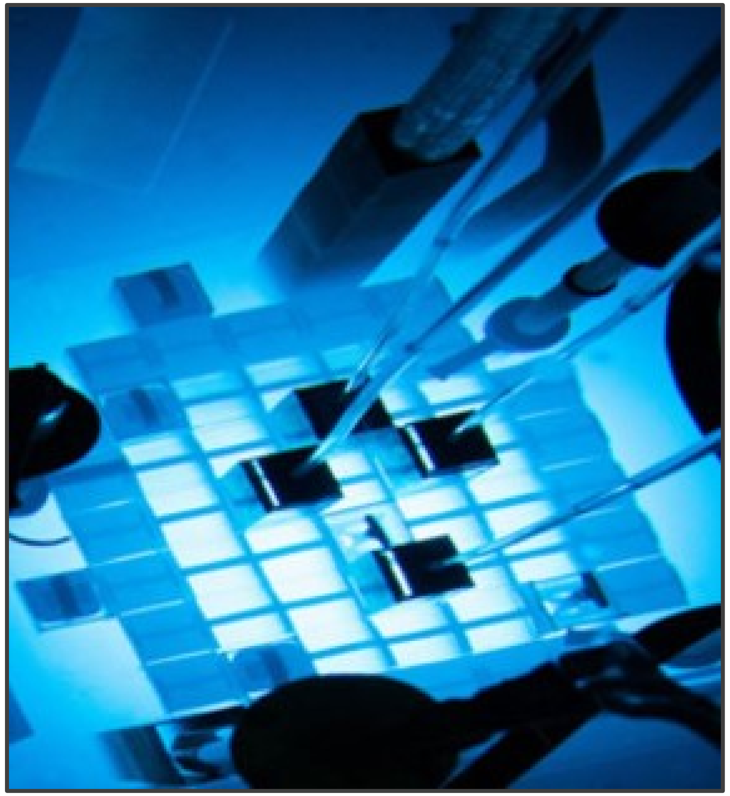
Stages in a Generic Nuclear Fuel Cycle for a PR with Reprocessing [courtesy of U.S. Nuclear Regulatory Commission]

Description of RR and PR Fuel

Research Reactor Fuel



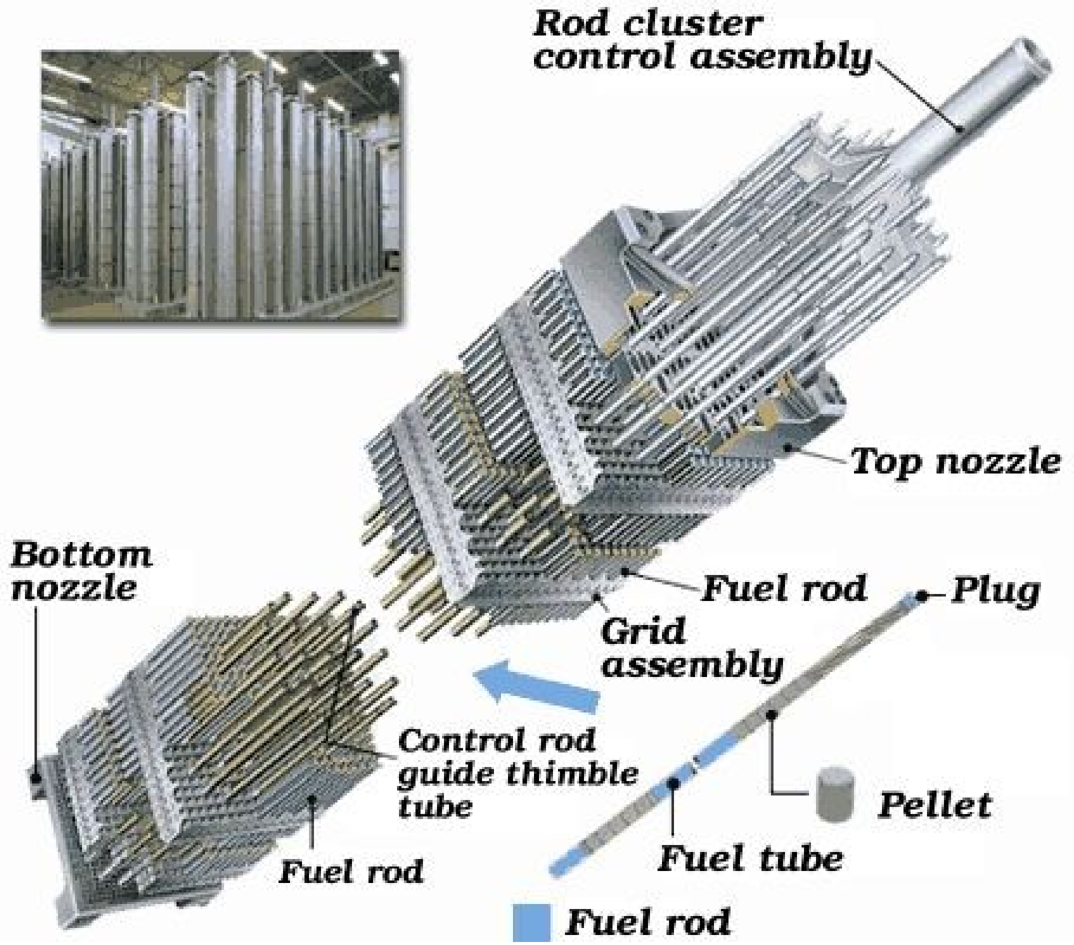
Materials Testing Reactor (MTR) design fuel
Aluminum-clad, aluminum-based plates



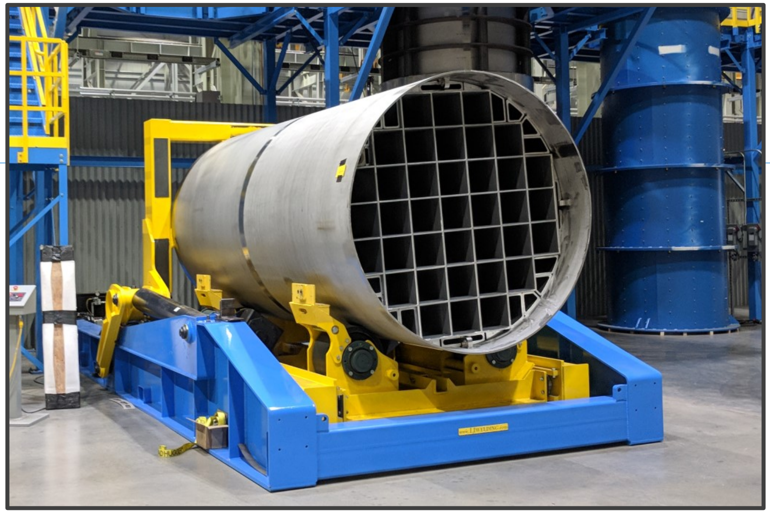
226 Research Reactors in operation, 840 total in 70 countries worldwide (IAEA RR Database)

Spent Nuclear Fuel from RR Reactors in Vertical Tube Storage in L Basin

Power Reactor Fuel



Assembly with pins/rods of UO_2 Pellets in Zircaloy Cladding



Multipurpose Canister (courtesy of Holtec International)

Holtec HI-STORM System (courtesy of Holtec International)
~ 4000 canisters being stored in U.S. at present

Safety Functions for Wet or for Dry Storage of SNF

- Maintain criticality safety
- Maintain cooling of the fuel
- Maintain radiation shielding
- Maintain confinement
- Maintain retrievability (on canister or fuel basis)

Met by the Structures, Systems, and Components of the storage system with specifications and limits (e.g., peak cladding temperature for the fuel) and by establishing Aging Management Programs (e.g., Inservice Inspection programs)

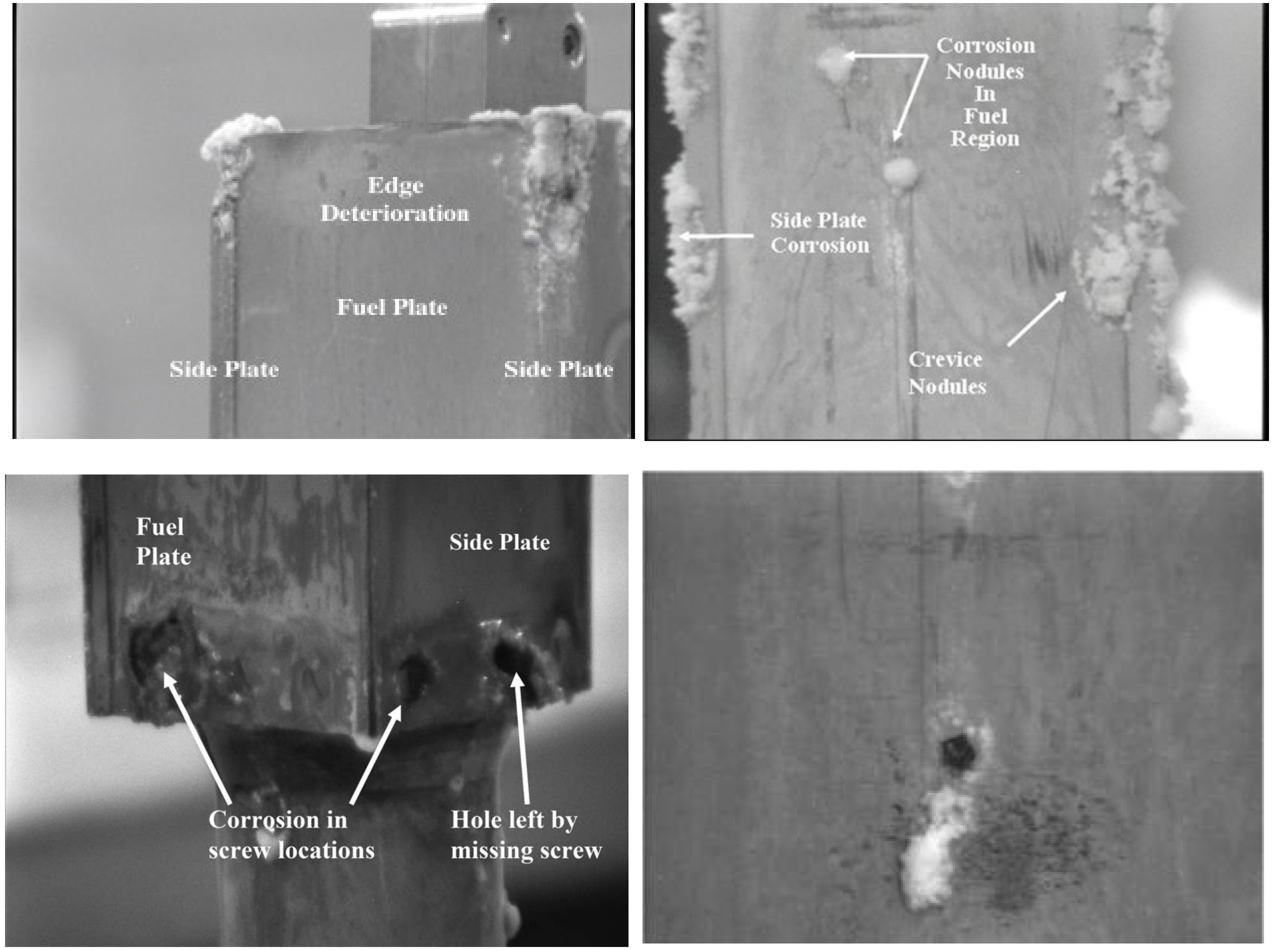
Safety functions derived from U.S. NRC Standard Review Plan for dry storage and IAEA safety standards for RR and PR

Challenges and Solutions for Wet and Dry Storage of RR Fuel

RR Fuel in Wet Storage – Challenge is Corrosion Attack to Aluminum and Impact

Corrosion types for metals in water storage

- General Corrosion Pitting Corrosion
- Crevice Corrosion Galvanic Corrosion
- Intergranular Corrosion Stress Corrosion Cracking
- End-Grain Attack
- Erosion-Corrosion
- Blister Formation (Filiform Corrosion)
- Microbial Corrosion
- Sediment-Induced Corrosion



Corrosion attack on aluminum spent fuel in poor quality water

RR Fuel in Wet Storage – Establish Water Quality Limits

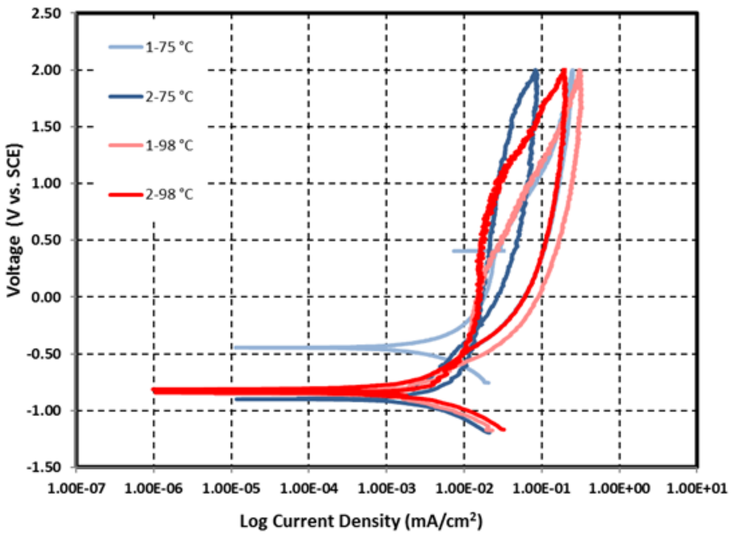
Water quality parameter limits and chemistry monitoring prescribed by IAEA for aluminum materials in research reactor systems

Table 1. Recommended physical-chemical parameters, limits, and monitoring frequencies for water in fuel decay and storage basins

PARAMETER	VALUE (LIMIT)	MONITORING FREQUENCY
pH	4.5 to 7	weekly
Conductivity	< 10 µS/cm	weekly
Solids	< 5 mg/l	Every 6 months
Cu Concentration	< 0.1 mg/l	Every 6 months
Cl Concentration	< 0.1 mg/l	Every 6 months
Nitrate (NO_3^-), mg/l	< 10 mg/l	Every 6 months
Sulphate (SO_4^{2-}), mg/l	< 10 mg/l	Every 6 months
Fe Concentration	< 1.0 mg/l	Every 6 months
Al Concentration	< 1.0 mg/l	Every 6 months
Temperature	< 45°C	monthly
Radioactivity level (*)	(see note below)	Weekly
Turbidity (**)	(see note below)	

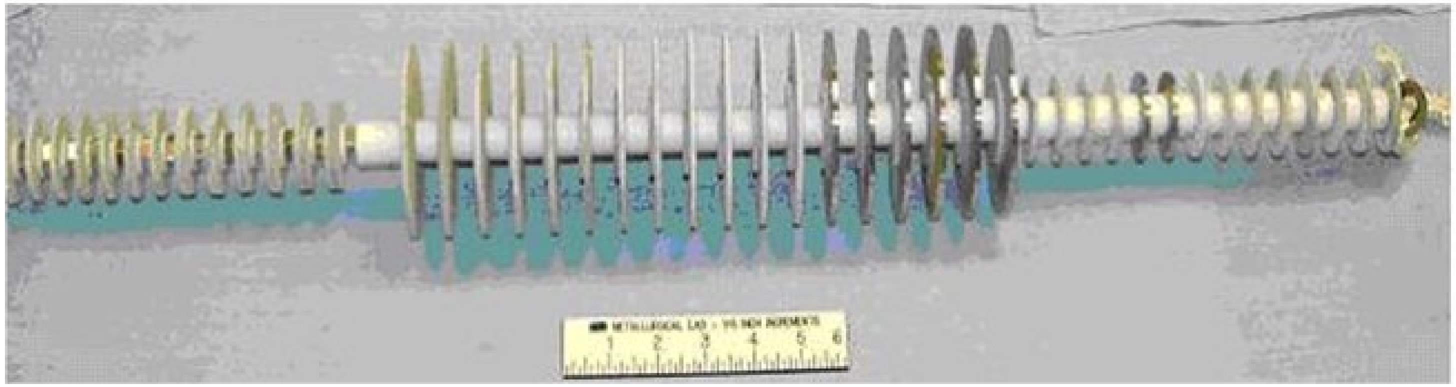
(*) Water Radioactivity level and the presence of radioisotope species should be measured each time a water sample is drawn or one time per week. A gamma scan is recommended to measure the presence of radioisotopes that would have come from failed fuel (e.g. Cs-137). No specific limits are set. The presence of radioisotope species should be evaluated on case-by-case basis. Measurement of the activity from filters and resin columns should be performed to detect the presence of leaking fuel.

(**)Turbidity should be reduced, as necessary, to provide visual clarity in the water system.

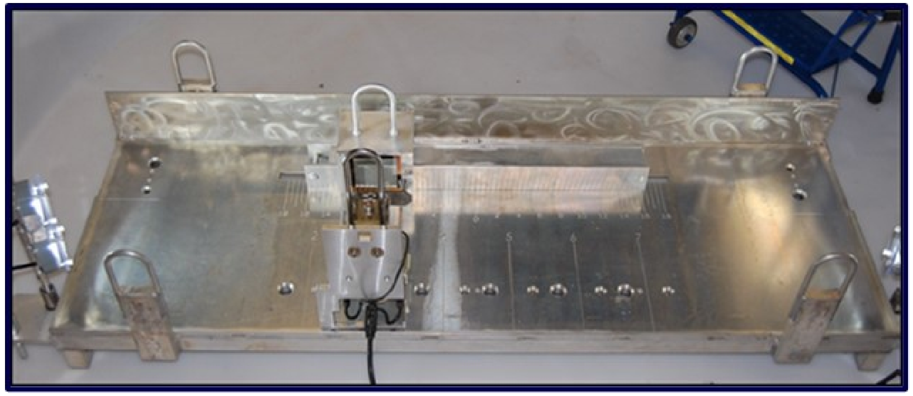


Corrosion testing – OCP, LPR, CPP can be used to evaluate water chemistry aggressiveness

RR Fuel in Wet Storage – Corrosion Monitoring; Inservice Inspection

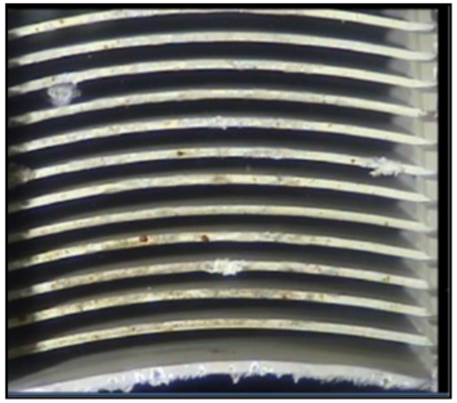


Corrosion Coupon Rack – Coupon designs can be used to evaluate all types of corrosion attack



Fuel Examination Table use in L Basin

Pitting corrosion on fuel plate

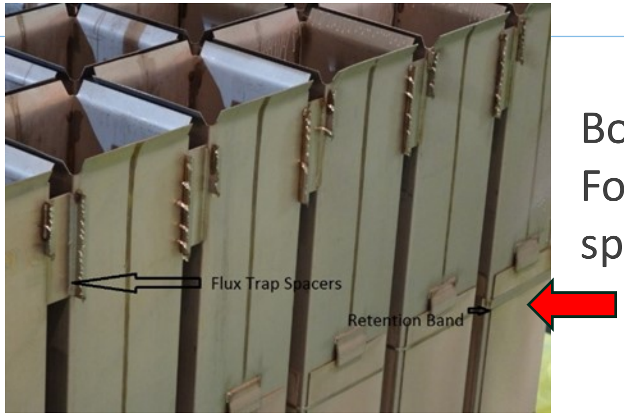


End grain attack

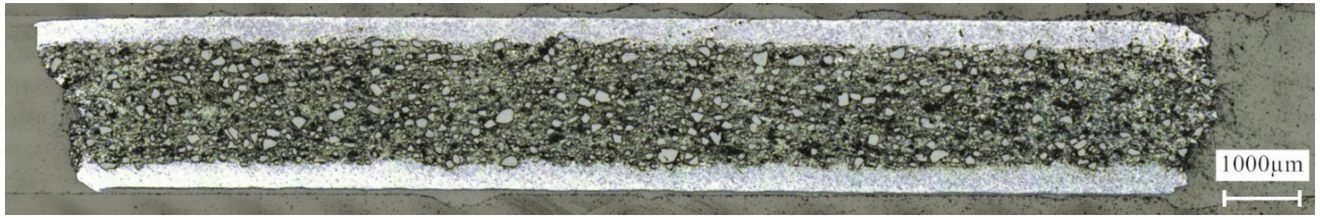
Corrosion Monitoring

Inservice Inspection

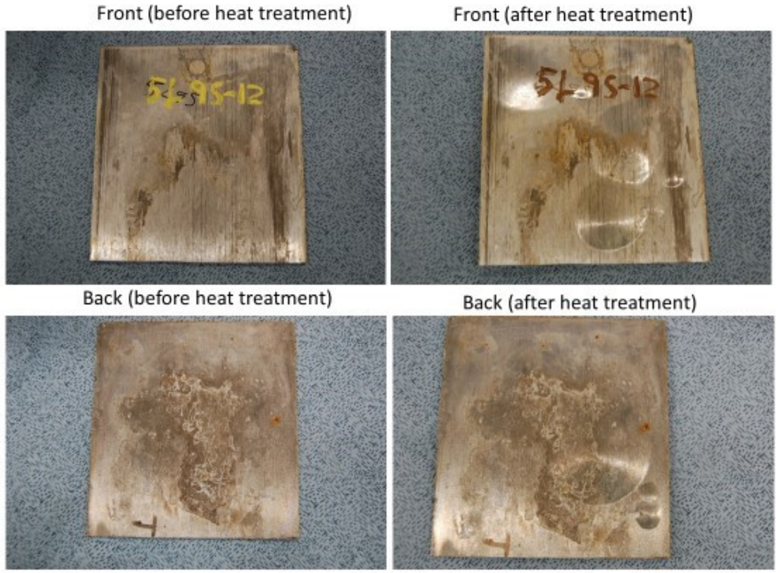
PR Wet Storage of Neutron Absorber Material Panels – Challenge is Blistering

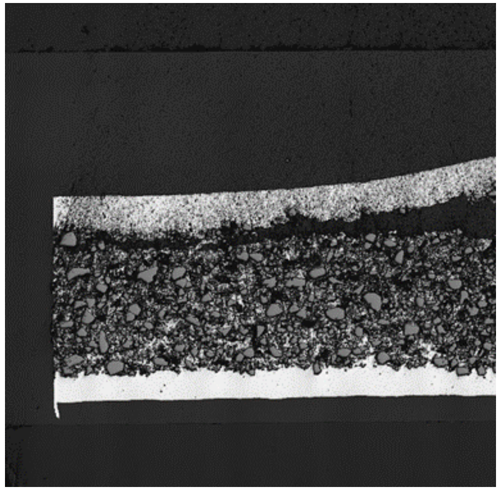


Boral®, a NAM, is credited For criticality control in spent fuel storage pools

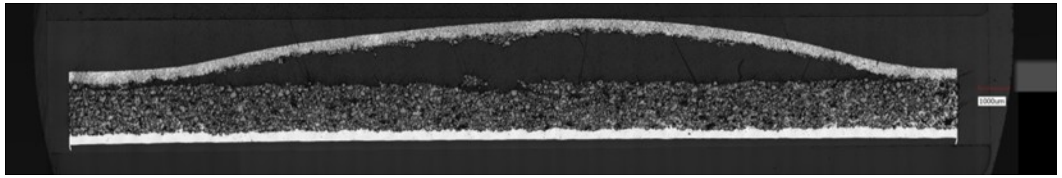


B_4C-Al composite material bonded between two thin sheets of aluminum cladding





Corrosion testing in water chemistries and temperatures of PWR and BWR spent fuel pools including off-normal upset conditions showed corrosion not significant to cause loss of B_4C



Neutron Absorber Materials In BWR and PWR Pools suffered several instances of gross blistering in service. Pictures and micrographs of forced blistering

Transition Wet to Dry Storage

Transition Wet to Dry Storage – Standard Guide Developed

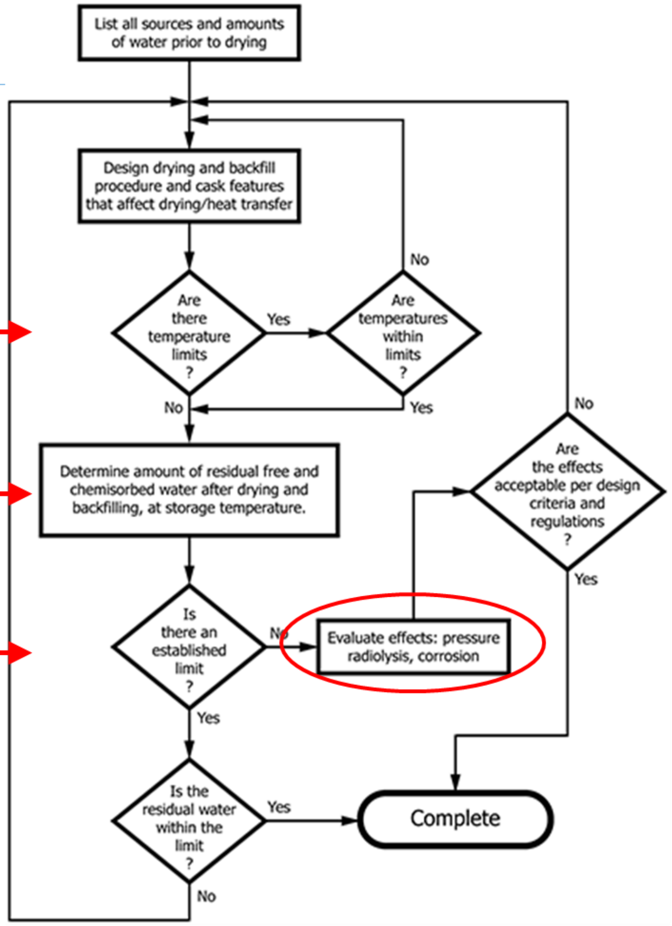
- ASTM C1553-21 Drying Guide:
  - How to dry?
  - Sufficiency of dryness?
  - How to measure dryness?
- Residual Water Sources:
  - Free
  - Physisorbed
  - Chemisorbed
- Dryness Criterion:
  - 30-min hold time with < 4 × 10^{-4} MPa (<3 torr)
  - Corresponds to ~10 ml free water

Check if there is a temperature limit to drying process:

Example: 400°C for zircaloy rods; 250°C for aluminum fuel*

Determine the amount of residual water (free, physisorbed, and chemisorbed) after a drying process

Evaluate effects of residual water for the SNF-in-canister storage system

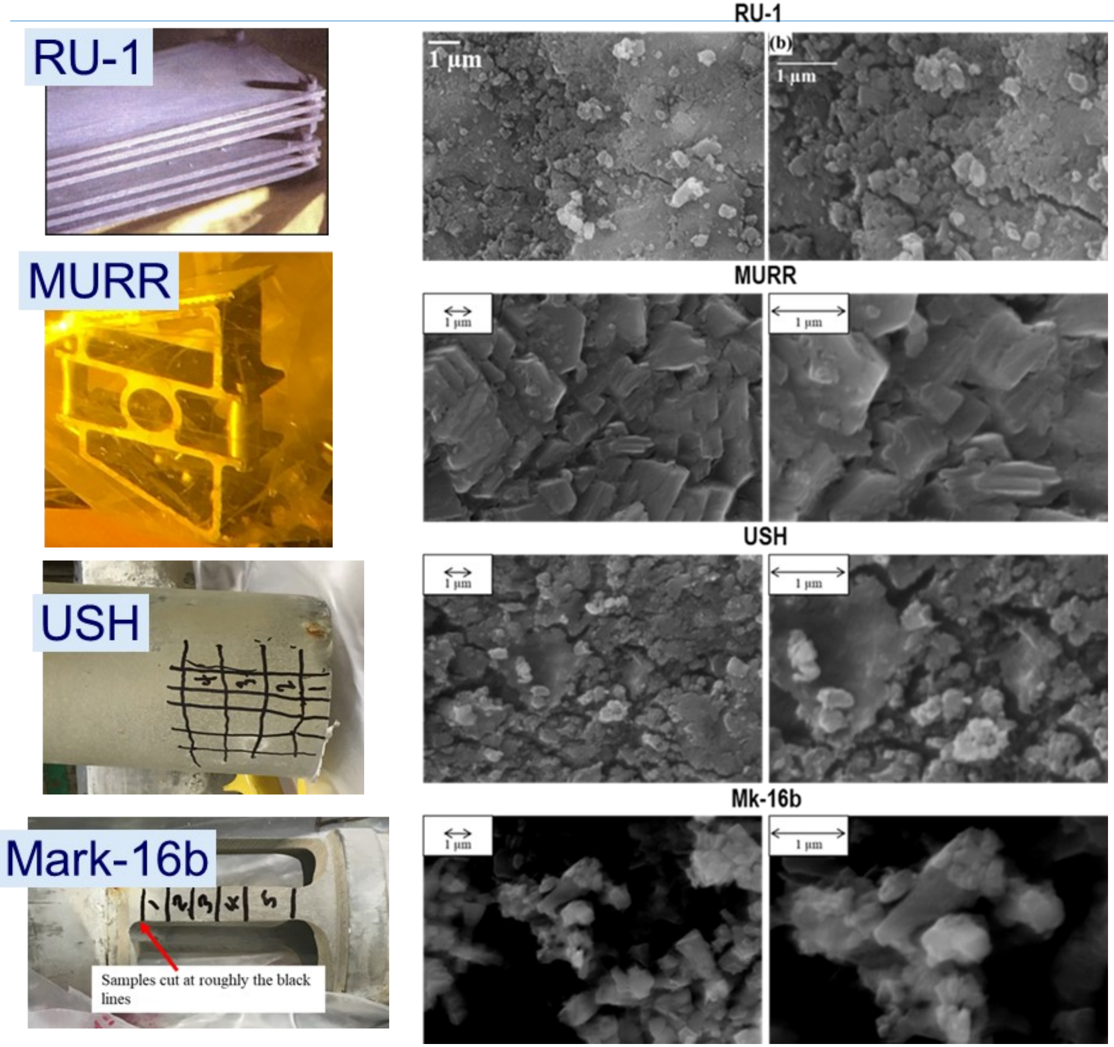


ASTM C1553, Figure 1

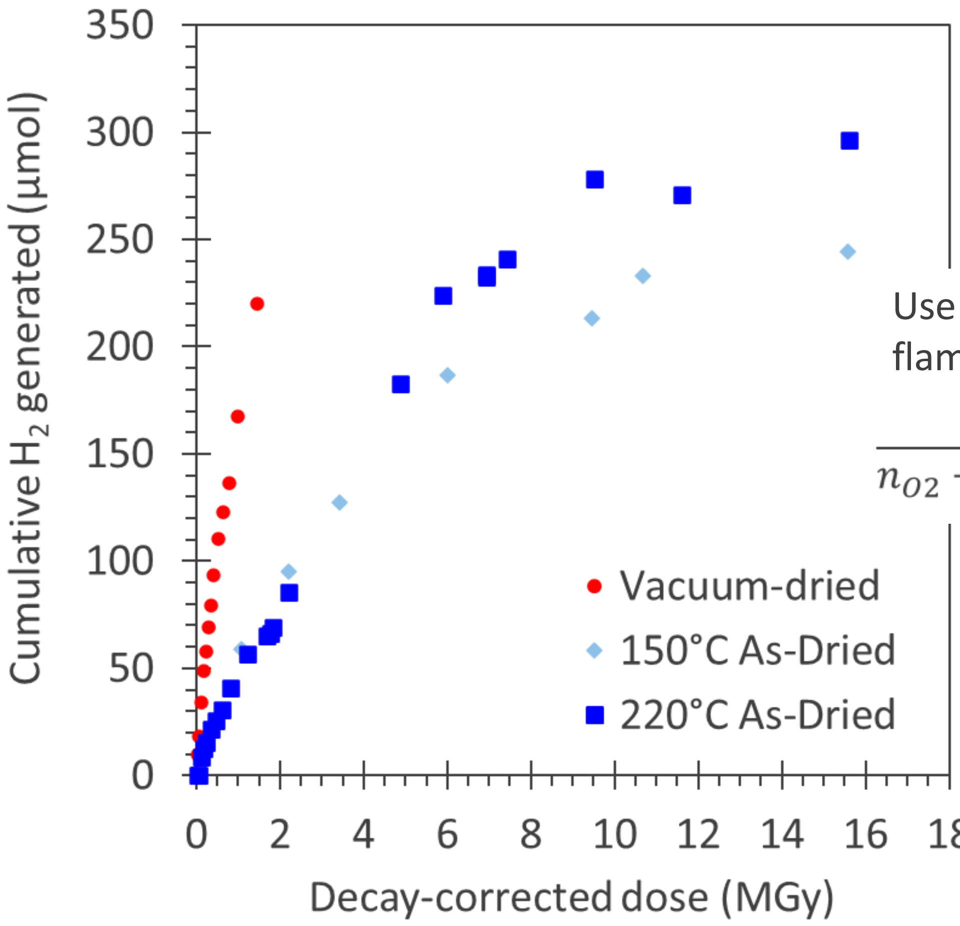
See d'Entremont, et. al., in *Nuclear Technology*, https://doi.org/10.1080/00295450.2023.2226519

Challenges and Solutions for Dry Storage of RR Fuel

RR Fuel in Dry Storage – Challenge/Solution for Radiolytic Hydrogen Generation



Hydrated oxides on aluminum claddings due to service



Radiolytic H_2 generated from lab-grown oxides on aluminum

Use oxygen control as flammability criterion:

$$\frac{n_{O2}}{n_{O2} + n_{H2} + n_{He}} = 0.015$$

Challenges and Solutions for Dry Storage of PR Fuel

PR Fuel in Dry Storage – Challenge of Radial Hydride Reorientation, Embrittlement of Cladding

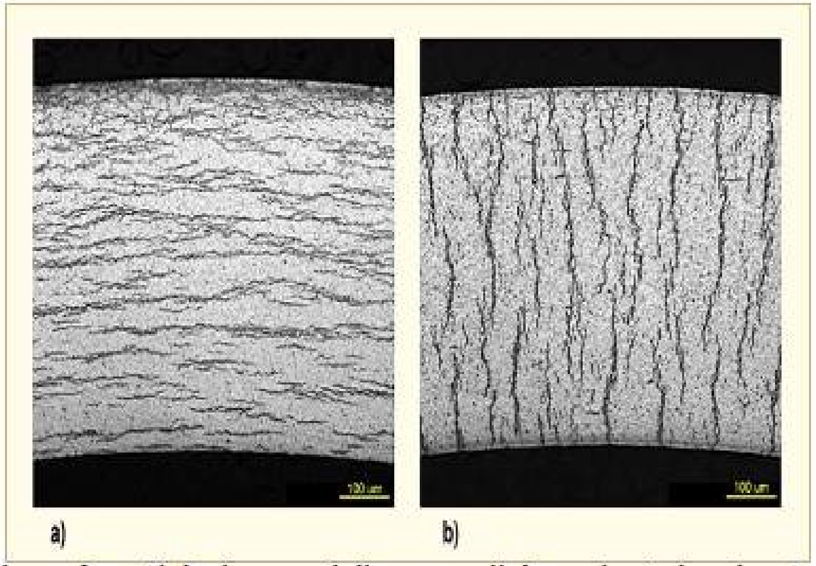
Corrosion during reactor operation: $Zr + 2H_2O \rightarrow ZrO_2 + 4H$

Zirconium hydride, δ-hydrides ($ZrH_{1.59}$) form

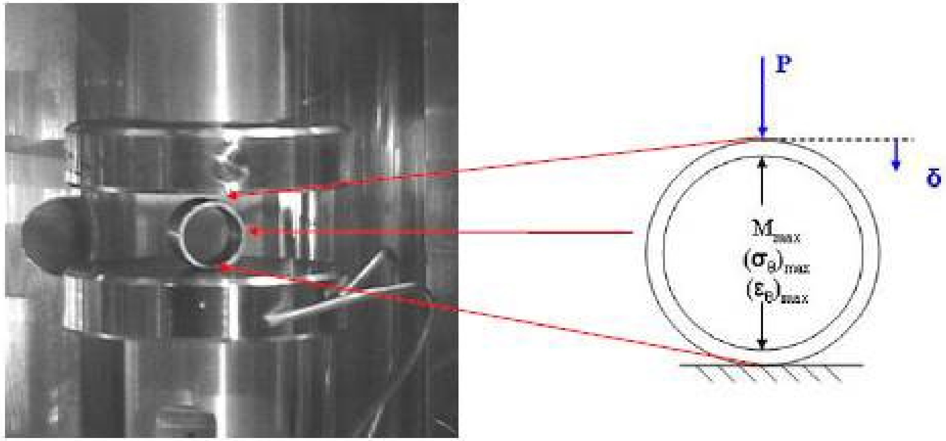
Fuel rod compressed:
by 2200 psi, PWR
by 2200 psi, BWR

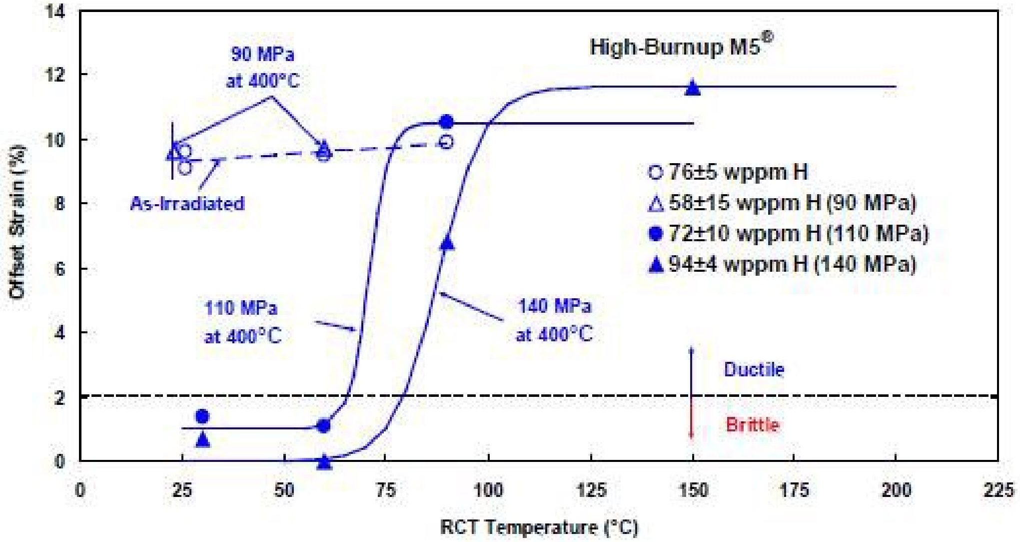
Hydrogen is redissolved at high T. Re-precipitated at high hoop stress in clad:

At 400°C, 200 ppm H in Zr
90 MPa = 13 ksi



circumferential (tangential) radial, reoriented under stress

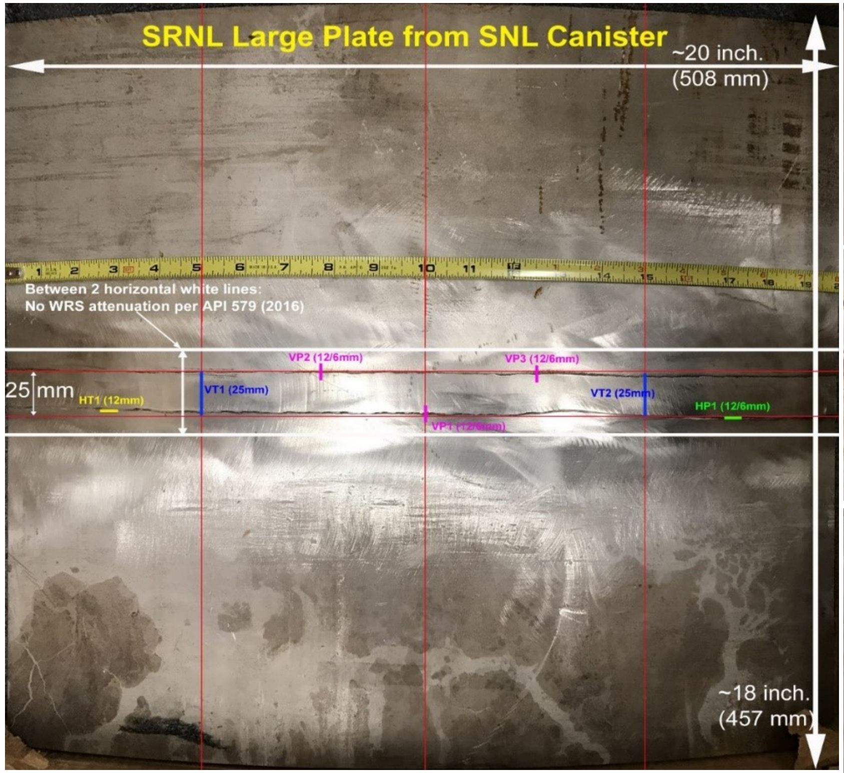


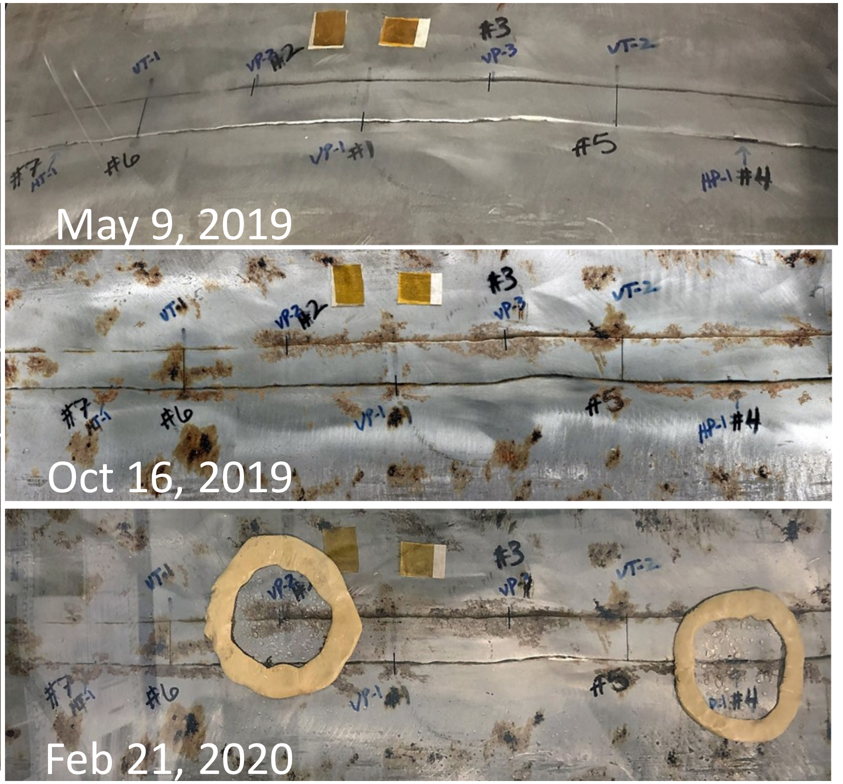


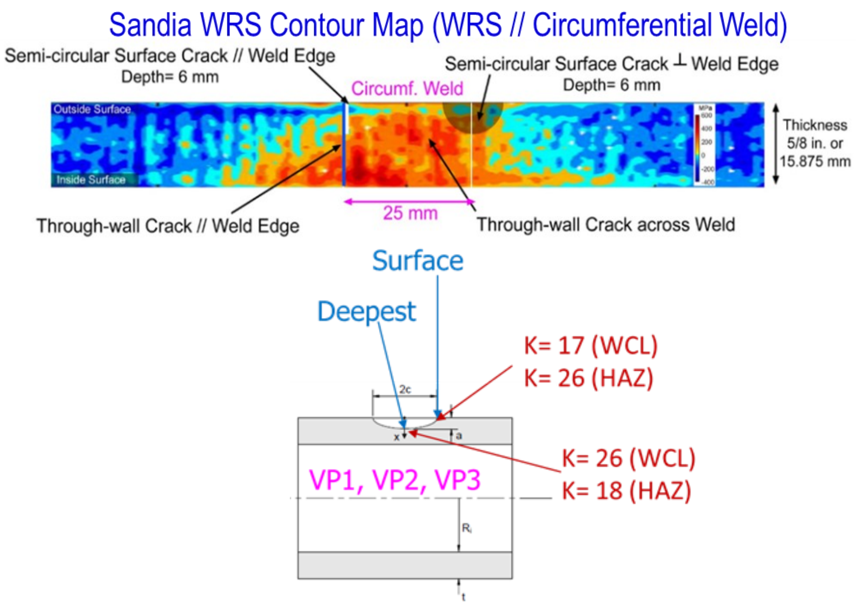
The solution:
the results from the High Burnup Demonstration Cask experiment showed very low temperatures (< 250°C peak).
Thus the cladding Is not subject to radial hydride reorientation

PR Fuel in Dry Storage – Challenge of Chloride-Induced Stress Corrosion Cracking of the Stainless Steel MPC (Outside-In Attack) – SRNL Large Plate Test

Concern: Marine Salt Deposits, Deliquesce and Form Brine to Cause CISCC on MPC

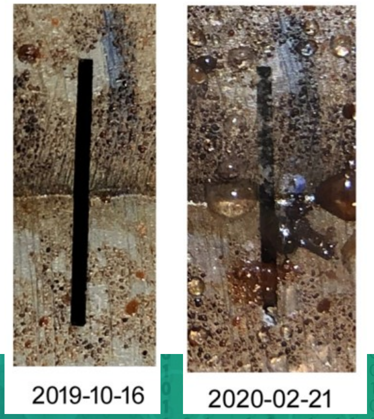






- 20” x 18” x 5/8” Plate from Canister
- Pre-machined defects
- Applied sea salt loading, let deliquesce

- Two-years exposure, including additional salt
- No cracking from machined defects
- No crack initiated



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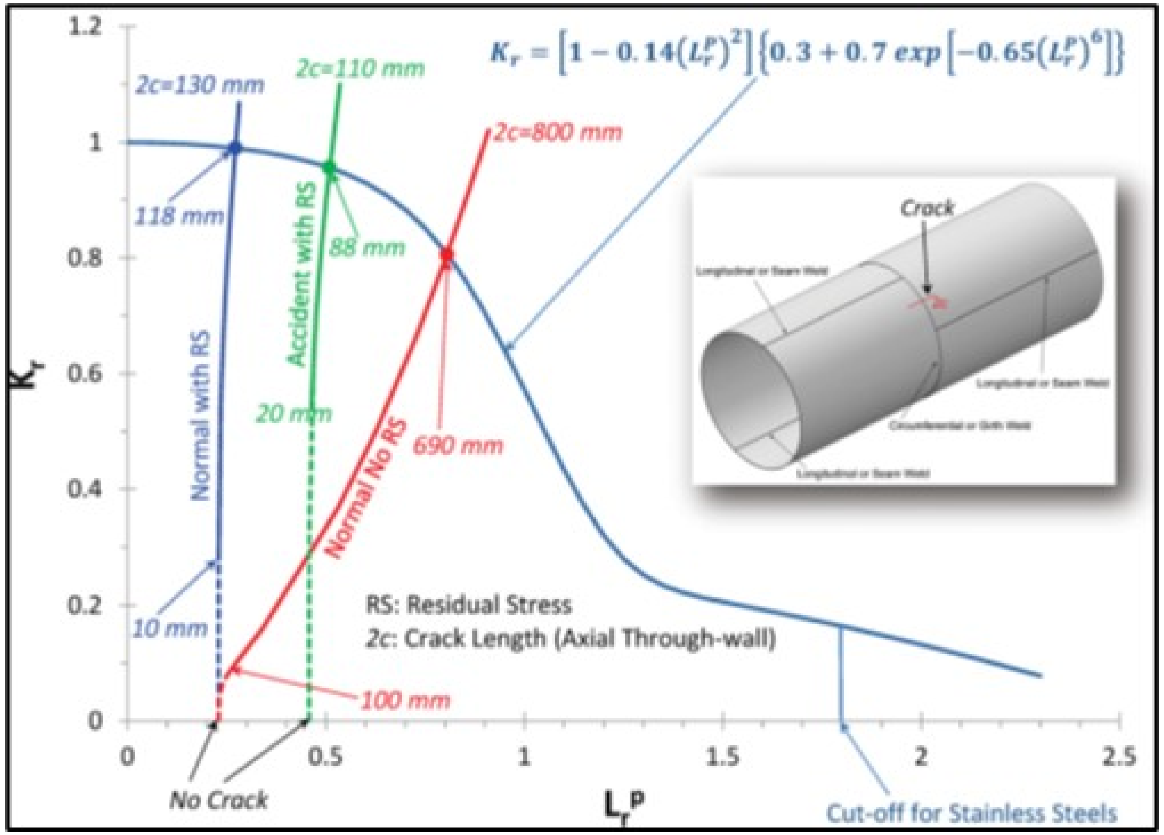
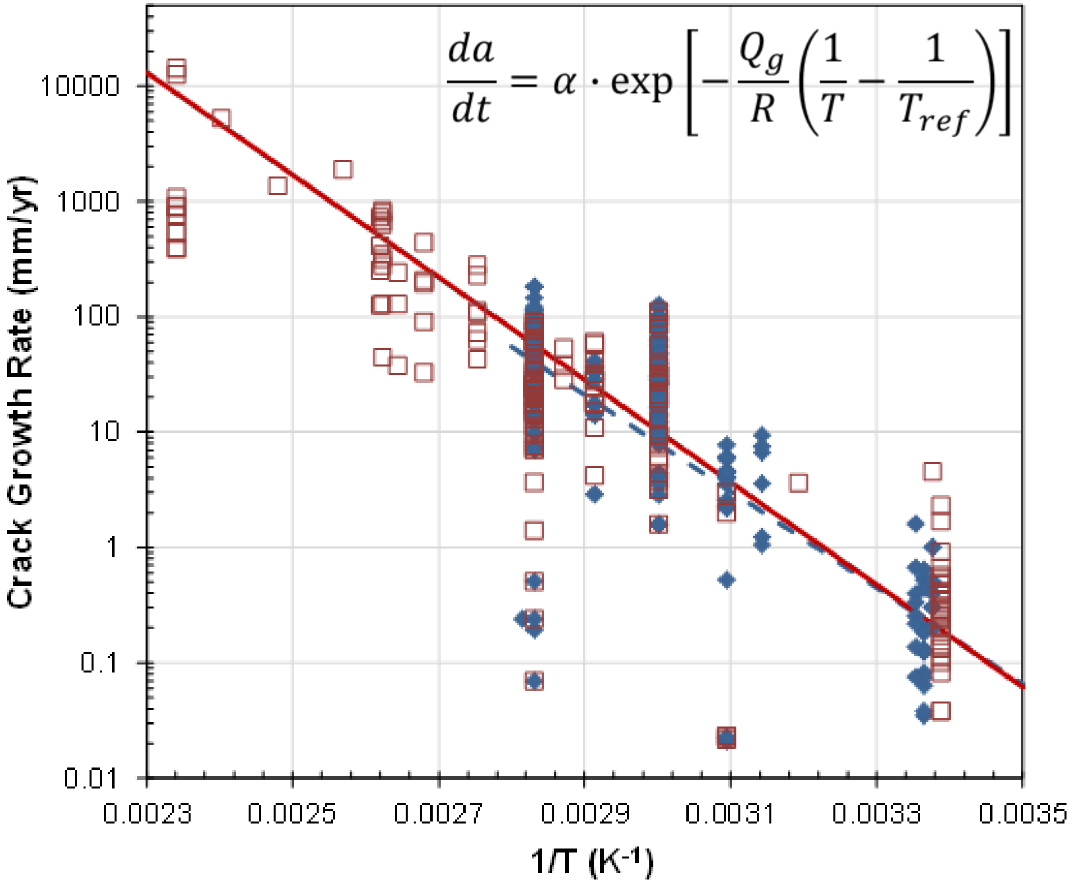
PR Fuel in Dry Storage – Solution to Chloride-Induced Stress Corrosion Cracking – ISI (ASME N-860)



Flaw Stability Determination (Normal, Accident, Residual Stress Loadings)



Crack Growth Rate

Summary

- Solutions have been developed for safe extended storage of SNF, both RR and PR (maintain safety objectives) – SRNL played an important role
  - Challenges because of materials aging of the SNF and/or the SSCs of the storage system – address through limits/controls and/or Aging Management Programs
- Thank you for attending this ANS-SR meeting!