



EPRI Used Fuel and High-Level Waste Program

China Workshop

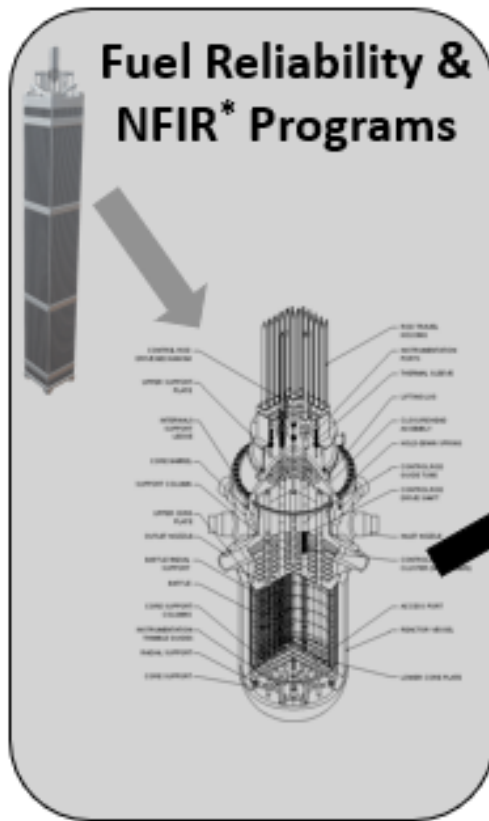


Dr. Joe Faldowski, DBA, PMP
Sr. Program Manager

China Workshop
October 13-15, 2025

UFHLW Program Scope

UFHLW Program



Wet Storage Fuel & NAM



Dry Storage Fuel & System



Transportation and Disposition System & Cycle

Cross-Cutting Initiatives

* Nuclear Fuel Industry Research

UFHLW Team



Industry experience: Orano
Contact: jfaldowski@epri.com

Joe Faldowski

Program Oversight



Hatice Akkurt

Criticality
Cross-cutting
Decay Heat
ESCP

Industry experience:
Schlumberger, Oak Ridge
Contact: hakkurt@epri.com



Ricardo Torres

**Spent Nuclear Fuel
Research**
Gross rupture TR
AFPM
HBU tollgate support

Industry experience:
NRC, PNNL
Contact: rtorres@epri.com



Keith Waldrop

**Cladding
Performance**
Cross-cutting
Bolted Cask Testing

Industry experience:
Duke Energy
Contact: kwaldrop@epri.com

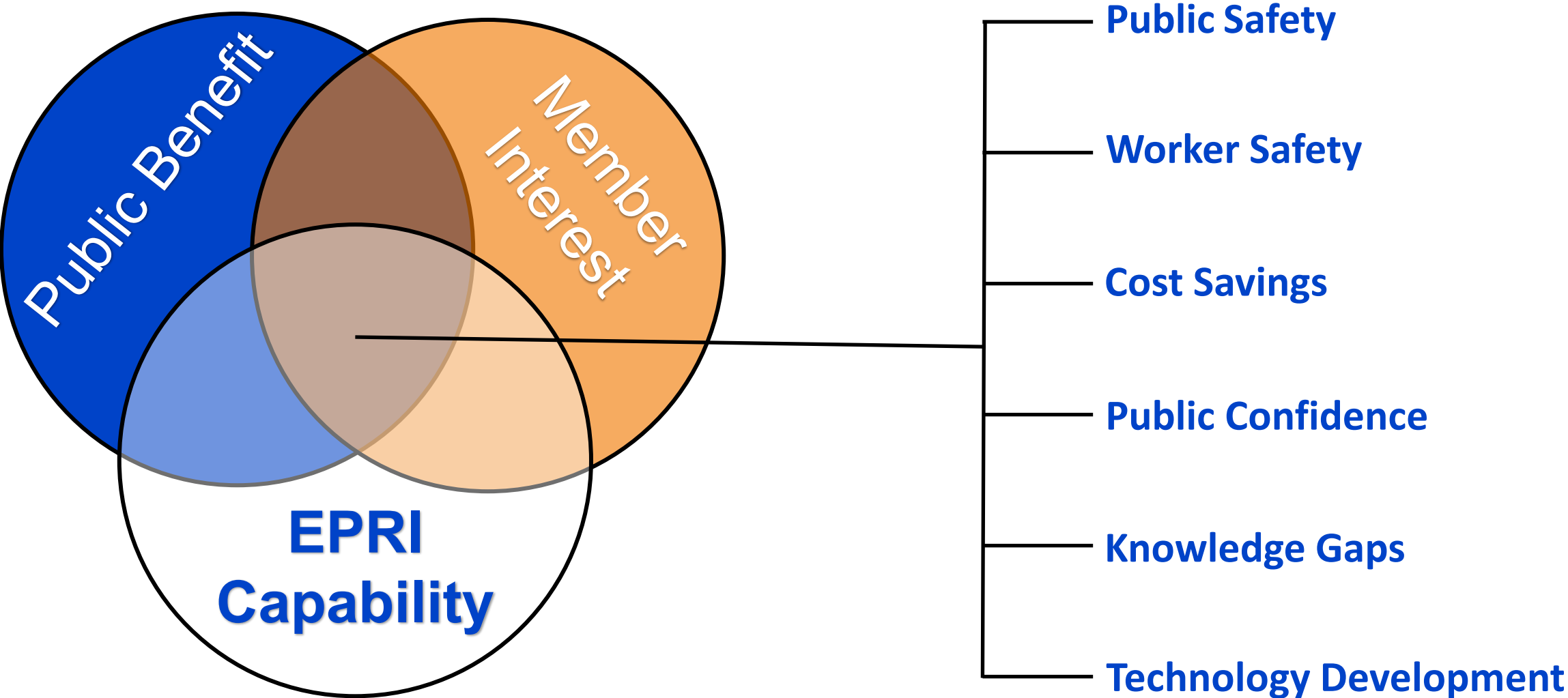


Laura
McManniman

**Disposition &
Transportation**
Cross-cutting
Adv Rxs
Int'l Engagement

Industry experience:
IAEA, Sellafield Ltd
Contact:
lmcmanniman@epri.com

Defining the EPRI Global Role in Used Fuel & High-Level Waste



UFHLW Key Engagements

2025

Extended Storage Collaboration Program (October)

- EPRI Offices - Charlotte, North Carolina
 - Dates: October 27-30, 2025

2026

Nuclear Advisory Meeting (February)

- - Sheraton Grand at Wild Horse Pass — Phoenix, AZ
 - Dates: February 9-12, 2026

Nuclear Advisory Meeting (February)

- - Sheraton Grand at Wild Horse Pass — Phoenix, AZ
 - Dates: August -, 2026

Extended Storage Collaboration Program (October)

- EPRI Offices - Charlotte, North Carolina
 - Dates: October, 2026

2026 UFHLW Proposed Portfolio

Aging Management of Dry Fuel Storage Components

- Canister surface environment sampling
- Canister Storage PRA
- xLPR Canister Module "V&V"

Used Fuel Cladding Performance During Storage & Transportation

- High Burnup Research Project
- HBU Tollgates Alternatives
- Gross Rupture Definition 
- Alternate Fuel Performance Metrics
- International Cladding Collaborations (NFIR, SCIP)
- Fuel Cladding Analysis

Used Fuel Criticality Control During Storage & Transportation

- ATF/HBU/HE SFP Criticality
- i-LAMP: Industrywide Learning Aging Management Program 
- Neutron Absorber Materials / NAUG 
- Metamic Performance Evaluation 
- NAM Research Summary
- SFP NAM In-situ Measurement Tool

Disposition

- Total System Performance Assessment Model Update
- Advanced LWR Fuel Impacts on Storage, Transport, Disposal

Cross-Cutting Research

- Extended Storage Collaboration Program 
- Rod Release Fractions
- Decay Heat Measurements and Validation 
- UNFSTANDARDS Enhancements
- DSS Dose Modeling
- Bolted Cask Testing
- International Thermal Modeling 

 Continuing  On Hold  New in 2026

 Topics being discussed this week

UFHLW Deliverables Report - Published

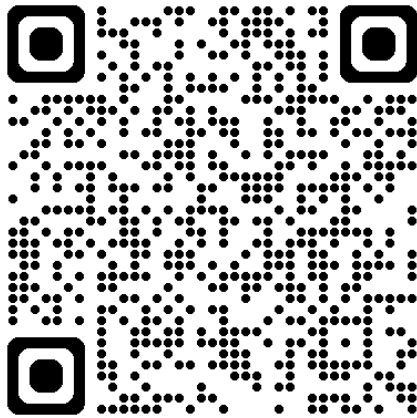
ID	NAME	PUBLISHED DATE
3002031701	Program on Technology Innovation: Transportation of Spent Nuclear Fuel, Considerations for High Burnup Light Water Reactor Fuels, Accident Tolerant Fuels, and Advanced Reactor Fuels	03-Jul-2025
3002033076	Summary Report of TPC Dry Storage Hot Test at Chinshan Nuclear Facility	27-May-2025
3002028998	Canister Cleaning, Contamination Sampling, and Gas Detection Demonstration	15-Apr-2025
3002029312	Spent Fuel Dry Storage Cask Opening: Operational Experiences	26-Mar-2025
3002029436	Welding and Repair Technology Center: Extended Storage Collaboration Program Industry Progress Report on Canister Mitigation Technologies	26-Nov-2024
3002026549	Spent Fuel Decay Heat Measurements at Clab: Description of Decay Heat Measurements from 2003 - 2021 Under EPRI-SKB Collaboration	16-Oct-2024

UFHLW Deliverables Report - Upcoming

ID	NAME	PUBLISHED DATE
3002032043	ESCP Aging management working group meeting summary: Key recommendations for path forward	30-Sep-2025
3002032045	ESCP International Thermal Modeling Report	24-Oct-2025
3002031997	Evaluation of Radioactive Material Released During Used Fuel Canister Drying	21-Nov-2025
3002031995	Development of Oxide Block Fabrication Technology to Enhance Efficiency in Spent Nuclear Fuel Storage: Current Status	21-Nov-2025
3002032044	ATF/LEU+/HBU workshop summary report	21-Nov-2025
3002031986	High Burnup Dry Storage Research Project Update	21-Nov-2025
3002031987	Dry Cask Storage System Welded Canister Inspection Capability Studies	26-Nov-2025
3002023975	Accelerated Corrosion Tests to Evaluate the Long-Term Performance of Boral in Spent Fuel Pools: Results from Five Year Tests	12-Dec-2025
3002032294	Program on Technology Innovation: Innovative Options for Spent Fuel Waste forms	23-Dec-2025

UFHLW Deliverable Quick Guide

- The Quick Guide is a catalog that concisely presents 20 years of Program Deliverables
 - Organized by topic
 - Downloadable
 - Available on the program page at EPRI.com



[UFHLW Program Catalog](#)



Extended Storage Collaboration Program (ESCP)



Hatice Akkurt, PhD
Senior Technical Executive

China Workshop
October 13-15, 2025

Extended Storage Collaboration Program (ESCP)

Mission

- Enhance the technical bases to ensure continued safe, long term used fuel storage and future transportability

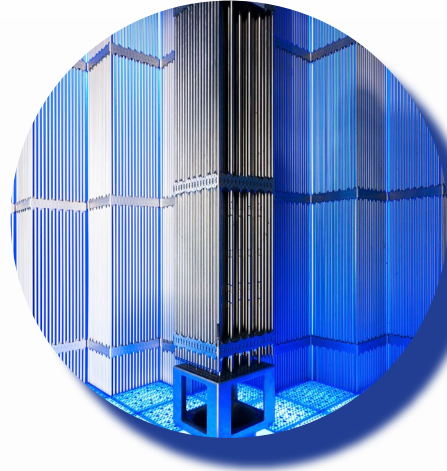
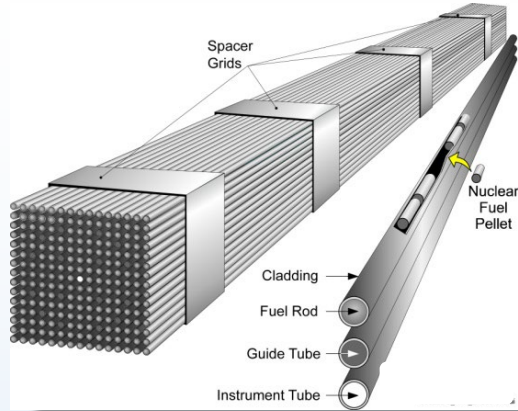
Goals

- Bring together US and International organizations engaged with active or planned R&D in used fuel area
- Share information
- Identify common goals and needs
- Identify potential areas of “formal” collaborations

Phases

- **Phase 1:** Review current technical bases and conduct gap analysis for storage systems
- **Phase 2:** Conduct experiments, field studies, and additional analyses to address gaps
- **Phase 3:** Long-term performance confirmation

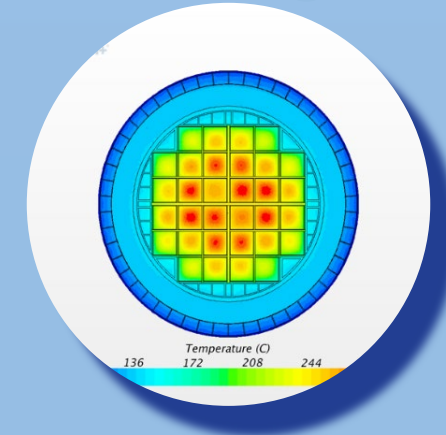
Managing Extended Storage of Used Fuel: Technical Challenges



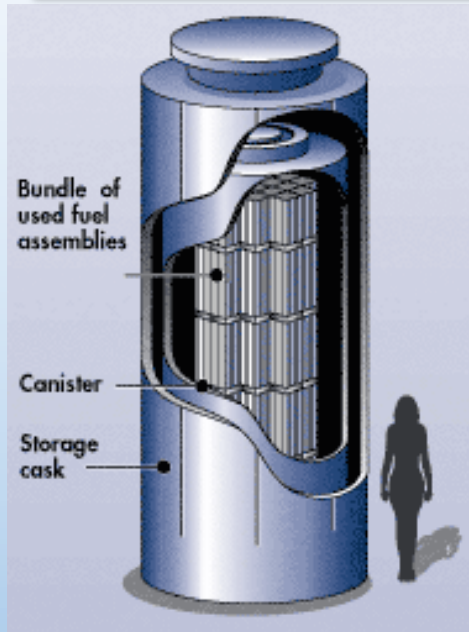
**Fuel Integrity:
Existing Fuel,
ATF/LEU+/HBU,
Advanced Reactors**



**Aging
Management of
Dry Storage
Systems**



**Accuracy of
models: Thermal,
decay heat, and
dose models**



ESCP: Collaborative R&D to Inform and Transform

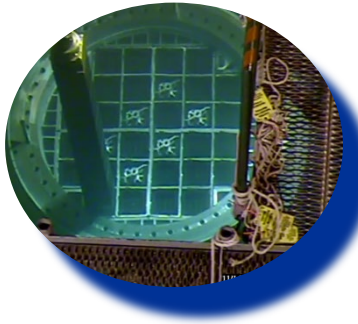
ESCP is a collaborative forum for addressing global challenges



ESCP Fuel Subcommittee Activities

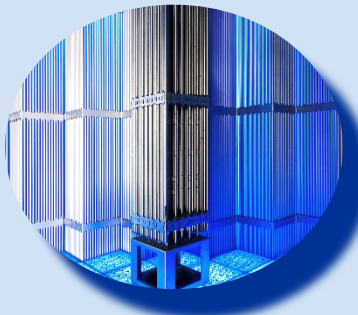
Spent Fuel Integrity R&D

[EPRI HBU Demo video on YouTube:](#)



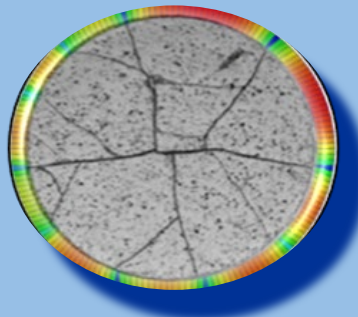
EPRI/DOE High Burnup (HBU) Demonstration Program

- ✓ Demonstrate high burnup fuel performance
- ✓ Supports dry storage license renewals



Improved Performance Margins

- ✓ Measured temperatures much lower than estimated
- ✓ Identified performance margins exist
 - ✓ Multiple PIRTs since HBU Demo loading

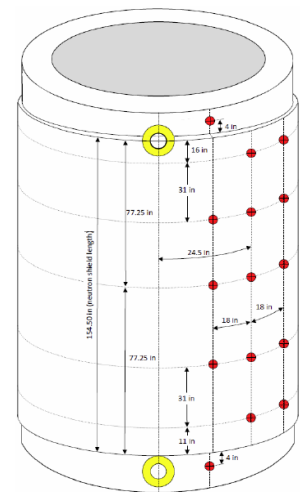


Key High Burnup Fuel R&D Findings

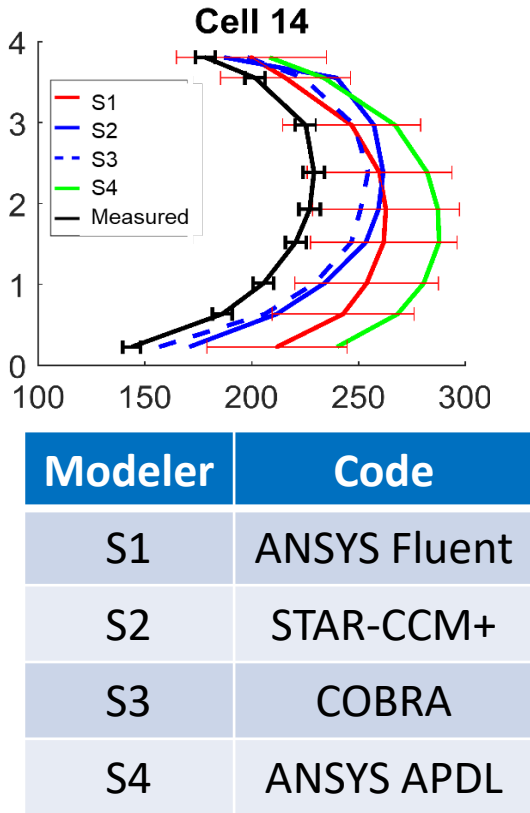
- ✓ High burnup fuel more robust than originally understood
- ✓ Dry storage and transportation are safe



HBU Demo showed measured temperatures are much lower



Parameter	FSAR	LAR	Best-Estimate	HBU Cask Meas.
PCT	348°C	318°C	254-288°C	229°C
Total Heat Load	36.96 kW	32.934 kW	30.456 kW	30.456 kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?



- HBU Demo Measurement results published in EPRI report 3002015076
- HBU Demo Blind Benchmarking Thermal Results published in EPRI report 3002013124
- Both reports are publicly available

Phenomena identification and Ranking Table (PIRT) Activities

Fuel

- Published in EPRI report, 3002018439, in 2020
- Led to the Gross Rupture PIRT,
 - New definition of GR that is more actionable
 - Published in EPRI report 3002020929
- Alternate Fuel metric PIRT is being finalized
 - Report will be published in March 2023
- Next steps, for regulatory review/implementation, are being discussed

Thermal Modeling

- Published in EPRI report, 3002018441, in 2020
- Need for evaluation of
 - Code-to-code variations
 - User-to-user variations
- Led to the international thermal benchmark project

Decay Heat

- Published in EPRI report, 3002018440, in 2020
- Identified gaps
 - Lack of measurement data for high burnup and short cooling times
- Recommended publication of “unpublished” Clab decay heat measurements
 - Due to high quality of measurements
- Led to SKB-EPRI joint project

Experts from many organizations (DOE Labs, NRC, vendors, utilities) participated in PIRTs
Reports are publicly available from [epri.com](https://www.epri.com)

ESCP Fuel Subcommittee Activities

Existing Fuel

- Annealing
- PIRTs and next steps
- Fuel release fractions (for consequence)

ATF/LEU+/HBU

- Recommended test plan developments
- Needs for back-end

Advanced Reactors

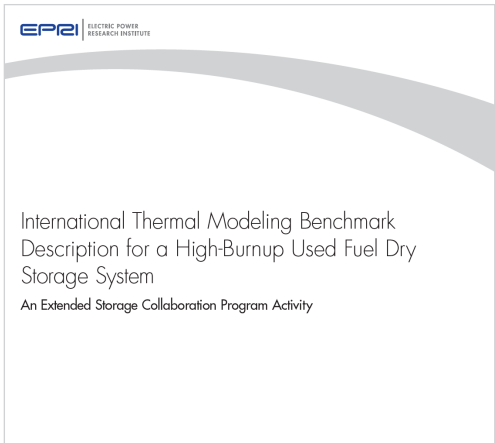
- Back-end needs
- Coordination of activities by vendors, NRC, and other organizations (NEA)

Current ongoing activities and plans discussed



ESCP Modeling & Benchmarking Activities

ESCP International Thermal Modeling Project



EPRI report, **3002018498**, provides a description of the benchmark:

- Based on publicly available information
- Includes a recording of the description

EPRI report, **3002023976**, provides Phase I results

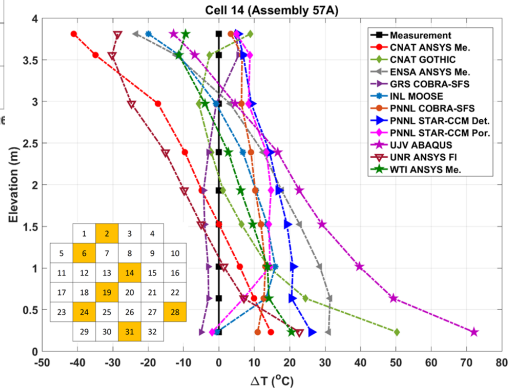
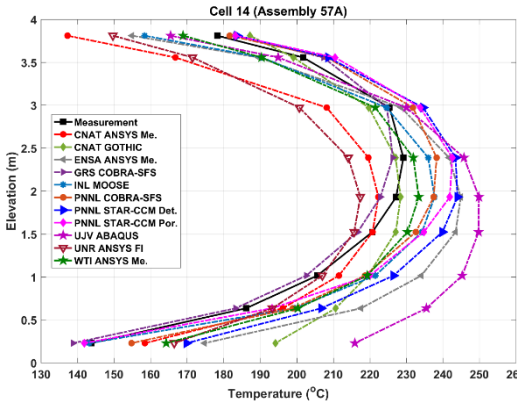
- Both reports are publicly available



Observations:

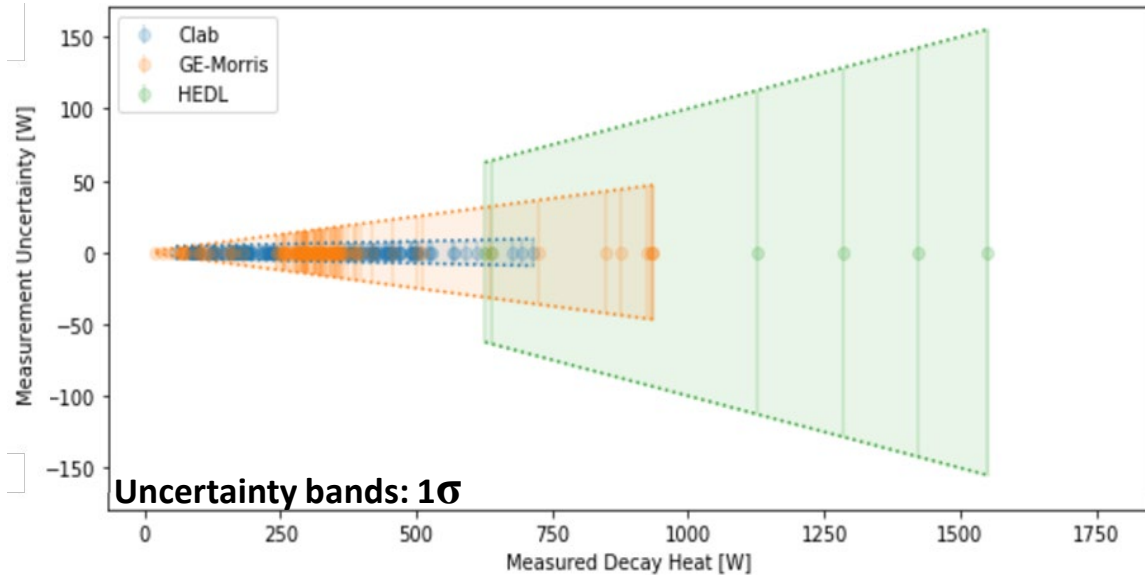
- Wide variation in temperature predictions
 - Between different codes
 - Between different organizations, using the same code
- No correlation between computational time, details of the model and accuracy of the results

Solution Method	Code(s)	Organization(s)
Finite Element Method (FEM)	ANSYS Mechanical	CNAT ENSA WTI
	ABAQUS	UJV
Finite Volume Method (FVM)	ANSYS Fluent	UNR
	GOTHIC	CNAT
	STAR-CCM	PNNL
Finite Difference Method (FDM)	COBRA-SFS	GRS PNNL
	MOOSE	INL

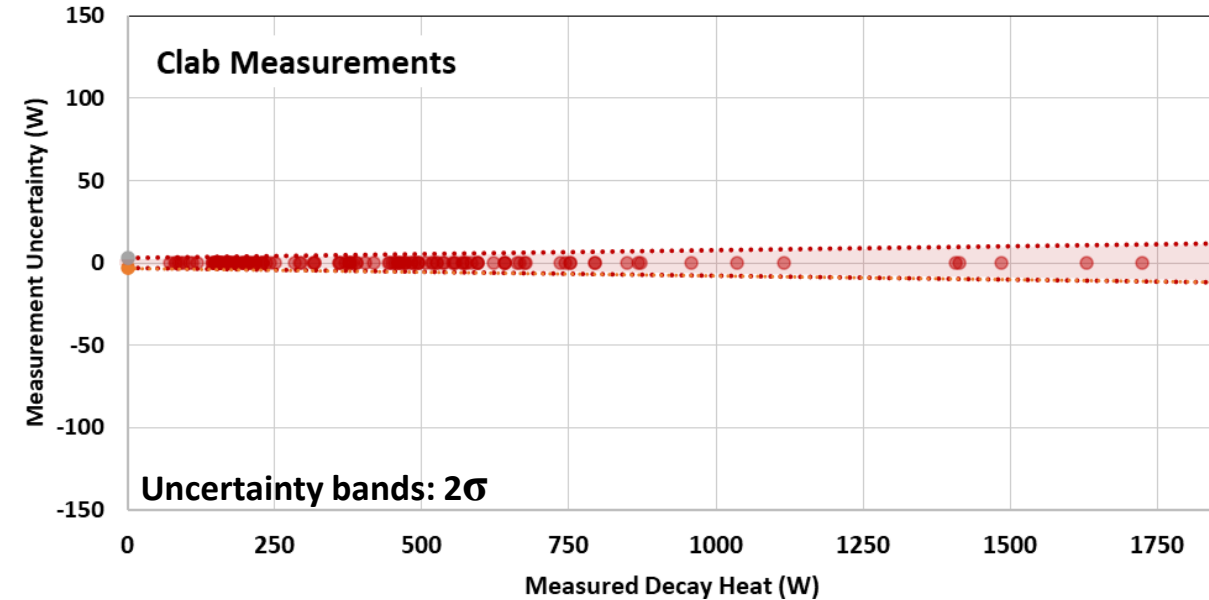


Eight organizations from four countries using seven codes and 11 solutions with different solution approaches. Phase I is complete; Phase II is ongoing

Extending Validation Range for Decay Heat and Reducing Measurement Uncertainty



- **HEDL:** Large measurements uncertainty; no other measurements for high DH range → can't be taken out of validation set yet
- **GE-Morris:** Measurement quality issues at higher DH; no other measurements → can't be taken out of validation set yet
- **CLAB:** Low measurement uncertainty; focus on low DH

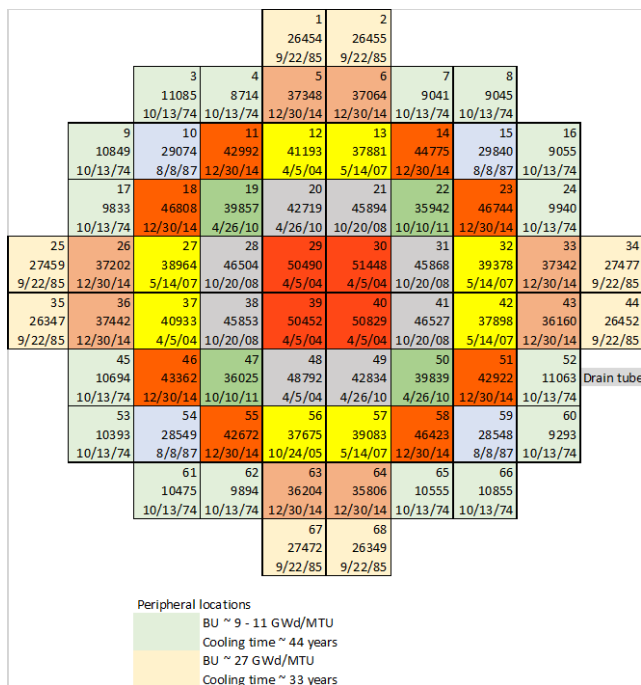


- Over 120 new DH measurements that are not published yet
- High quality data → better validation set → decrease DH uncertainty and increase margins for global industry

EPRI initiated a collaborative project with SKB to publish unpublished CLAB measurements; perform new measurements to close the gaps - ESCP Decay Heat Task group members, and other interested collaborators, will perform review and participate in potential blind benchmark for new measurements

Radiation Dose Benchmarking

Radiation dose measurements from three loaded canisters are available from two sites for modeling



Benchmark description, based on publicly available documents, and assumptions will be provided to participants

Blind Benchmark

- EPRI will not release the measurement data until the completion of benchmark project
- Actively participating organizations:
 - USA: INL, ORNL, PNNL
 - Sweden: SKB
 - Japan: NMRI
 - Germany: GNS
 - Spain: ENSA
- Project kick-off meeting in February 2023
- Results will be published in a publicly available EPRI ESCP report

ESCP Modeling and Benchmark Subcommittee Activities

Decay Heat

- Validation report review
- Blind benchmarking when new measurements available (after calorimeter upgrade)

Dose Modeling

- Blind benchmarking activity ongoing
- Expecting to complete this year
- Participants include:
 - USA: ORNL, PNNL, SBC
 - Japan: NMRI
 - Germany: WTI/BGZ
 - Spain: ENSA

Thermal Modeling

- International thermal modeling activity ongoing
- Report in preparation
- Next steps need to be discussed

ESCP modeling subcommittee will produce one report in 2025 and one report in 2026

**ESCP Aging Management of DSS
(Presented under Aging Management Presentation)**



ESCP Focus Areas - Next 2-3 Years

Forward Looking ESCP Focus Areas for Next 2-3 Years

Fuel

- Phase II sister rod testing
- Transport of HBU Demo cask and opening
- Increased focus on ATF/HE/HBU and back-end effects
- Increased focus on Advanced Reactors and back-end issues

Aging Management and Canister Integrity

- Mitigation and repair techniques development
- Demonstration via field tests
- Acceleration of consequence studies

Modeling & Benchmarking

Thermal:

- Completion of international thermal modeling project
- Gathering more benchmark data during inspections

Dose:

- Blind benchmarking activity for dose modeling

Decay Heat:

- Completion of decay heat reports
- New measurements and potential for blind benchmark

Collaborative R&D to Inform and Transform

Summary

- ✓ ESCP is a forum that enables collaborative development of innovative solutions for spent fuel management
- ✓ Recent cooperative **R&D with DOE and NRC reduced dry storage and transportation concerns** of high burnup fuel
 - ✓ Research shows continued long-term storage of commercial spent fuel is **safe with larger performance margins**
- ✓ ESCP is continuing to enable the development of **improved aging management guidelines** with inspection, repair, and mitigation technologies as well as consequence analysis
- ✓ ESCP is increasing its activities in modeling and benchmarking to enable better performance in predictions

2025 Upcoming ESCP Deliverables

- **3002032043**, ESCP Aging management working group meeting summary: Key recommendations for path forward, December 19, 2025.
- **3002032045**, *ESCP International Thermal Modeling Report*, October 24, 2025

2025 Publications to Date

- H. Akkurt, J. Faldowski, R. Kelly, J. Burns, R. Granaas, J. Kessler, D. Dunn, *“ESCP Dry Storage System Aging Management Roadmap,”* Proceedings of PATRAM 2025, July 2025.
- Hatice Akkurt and Maik Stuke, *“ESCP International Thermal Modeling Benchmark Project Results,* Proceedings of PATRAM 2025, July 2025.
- Hatice Akkurt and Maik Stuke, *“ESCP International Thermal Modeling Project: Comparison of PCT and External Surface Temperature Values with Varying Sensitivity Parameters”* accepted for inclusion in IHLRWM 2025 conference proceedings, November 2025.

Save the Dates: ESCP2025 Meeting

October 27-30, 2025
EPRI Charlotte, NC

If you are interested in presenting at ESCP 2025 or have suggestions for topics that should be included in the meeting, reach to hakkurt@epri.com



TOGETHER...SHAPING THE FUTURE OF ENERGY®

Overview of EPRI Research on Neutron Absorber Materials



Hatice Akkurt, PhD
Senior Technical Executive

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Spent Fuel Pool (SFP) Neutron Absorber Material (NAM) Aging

- **The safety function** – maintain subcriticality margin in the SFP

Is the safety function still met?

- **The aging issue** – some NAMs have degraded

Boraflex: Severe, up to local total loss of absorber

Carborundum: Moderate, gradual washout of absorber

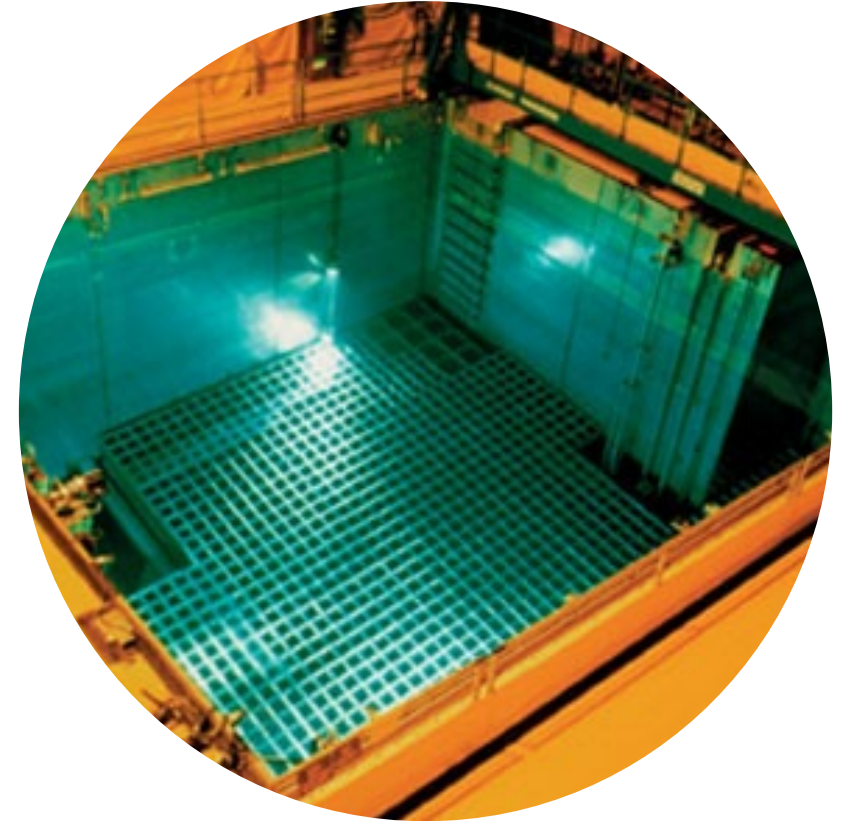
BORAL®: Blistering, pitting and surface corrosion

Others: Pitting and thinning

- **The regulatory issue** – reasonable assurance of safety

If fueled, must have assurance of SFP NAM effectiveness

Life of the SFP may be longer than life of the plant



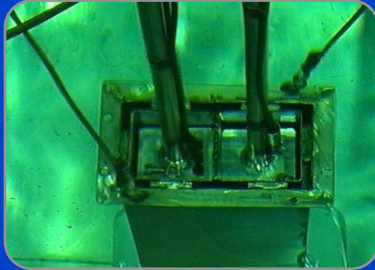
SFPs with neutron absorber materials need a NAM aging management program (AMP)

Spent Fuel Pool (SFP) Neutron Absorber Material (NAM) Monitoring



1. Coupon Monitoring

- Many SFPs have no coupons
- Many SFPs have few coupons left



2. In situ Measurements (Existing tool: BADGER)

- Expensive
- SFP logistic issues and dose
- Can be inaccurate and lead to false degradation*



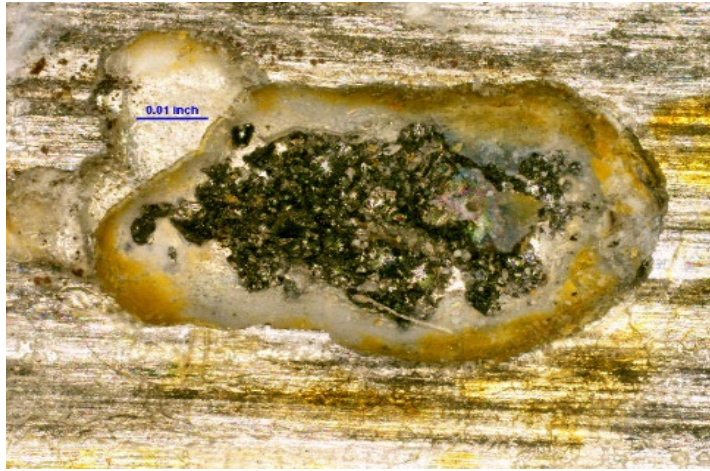
3. Cutting NAM panels from rack modules

- Very expensive
- May lead to rack module damage (left with cells that can't be used)
- Plant and SFP logistic issues and dose

***Zion comparative analysis performed blind comparison of in-situ and actual panels, which showed false degradation predicted by in-situ measurements**

NAM Degradation Mechanisms and Potential Concerns

1. Pitting



Pit picture with 100x magnification; pit reached absorber material

2. Blistering



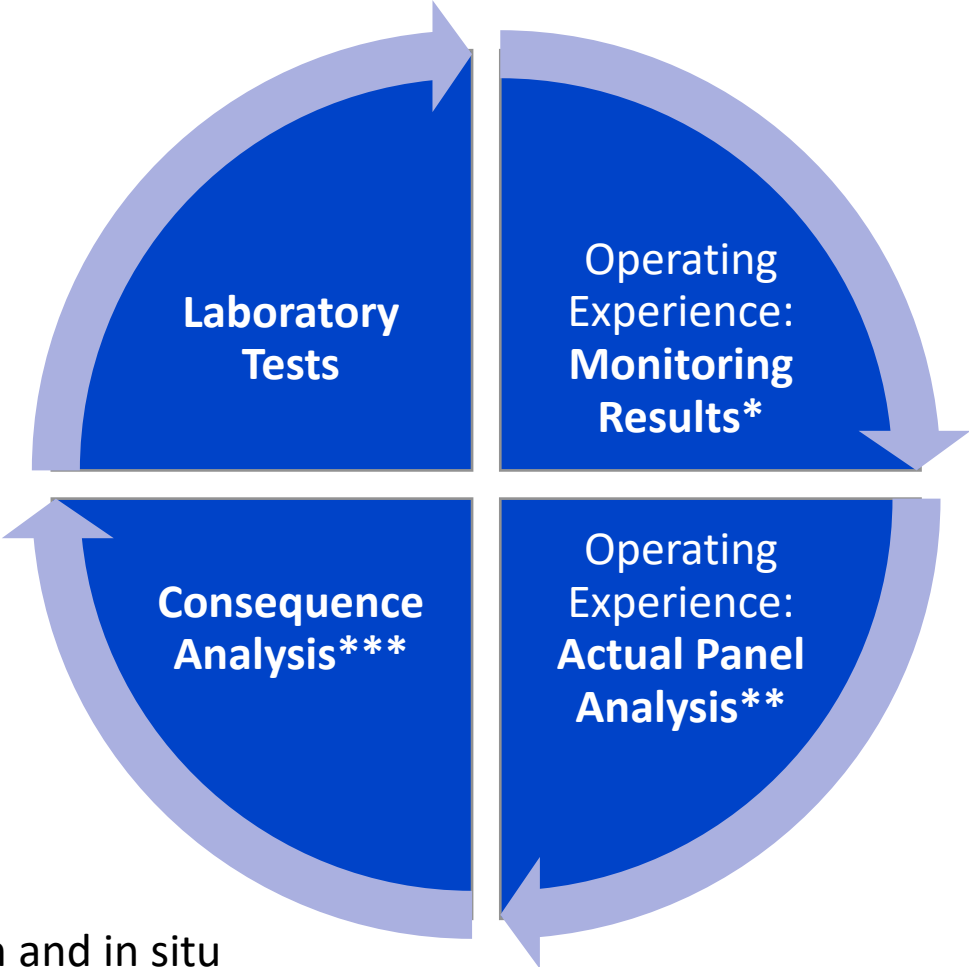
Blistering is only **applicable to absorber materials with cladding** (i.e., Boral, Maxus, etc.)

For a given neutron absorber material, aging effects in SFPs are a function of:

1. Type and vintage of the material
2. Time in the SFP
3. SFP water chemistry
4. Temperature
5. Cumulative neutron dose
6. Cumulative gamma dose

For different materials, significance of parameters vary (i.e., effect of gamma dose for Boral versus Boraflex)

Path to Establishment of Technical Basis for Effective Aging Management Programs



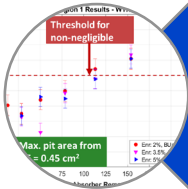
*Coupon and in situ
**Panels from Zion & Operating SFP
***Evaluation of impact of blister and pits on SFP reactivity



Laboratory: Accelerated Corrosion Test (to be published soon 3002023975)



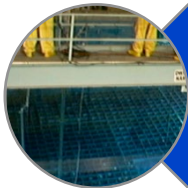
Actual panels, coupons, and in-situ measurements from SFP: Zion comparative analysis (3002008196 and 3002008195)



Modeling and Simulation: Evaluation of Impact of Blister and Pits (3002013119)



Evaluation of Panels from an Operating SFP (3002018497)



i-LAMP proposal (3002013122) and i-LAMP final report (3002018497)

To date, work has been published in 7 EPRI reports and ~20 papers

List of references included at the end



Zion Comparative Analysis Project

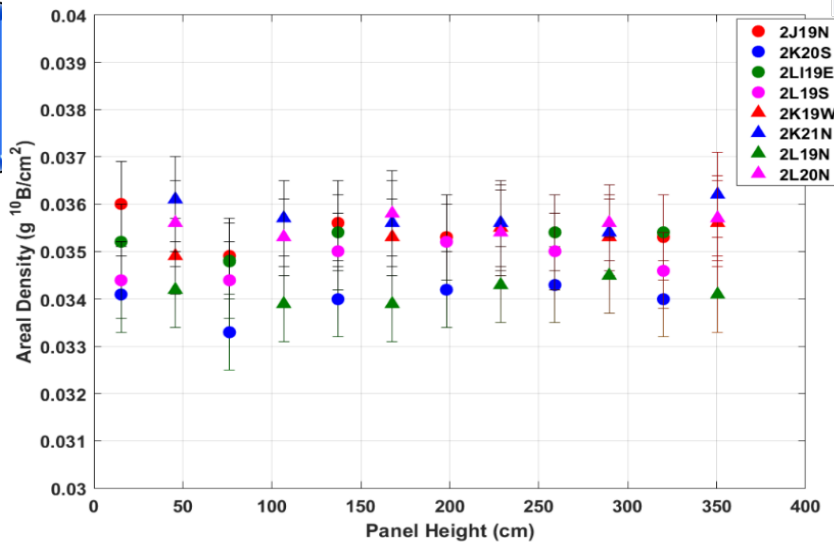
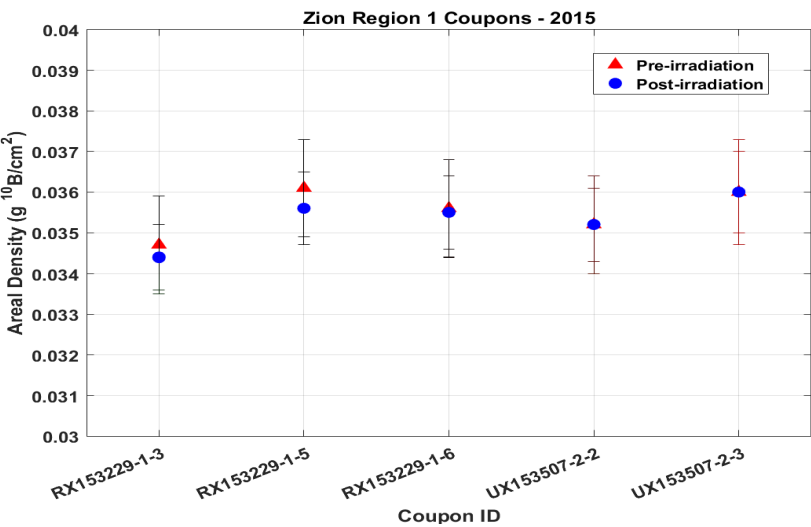
Zion Comparative Analysis project – Key Findings



Zion Panels

Zion Coupons

Zion In-situ Measurements

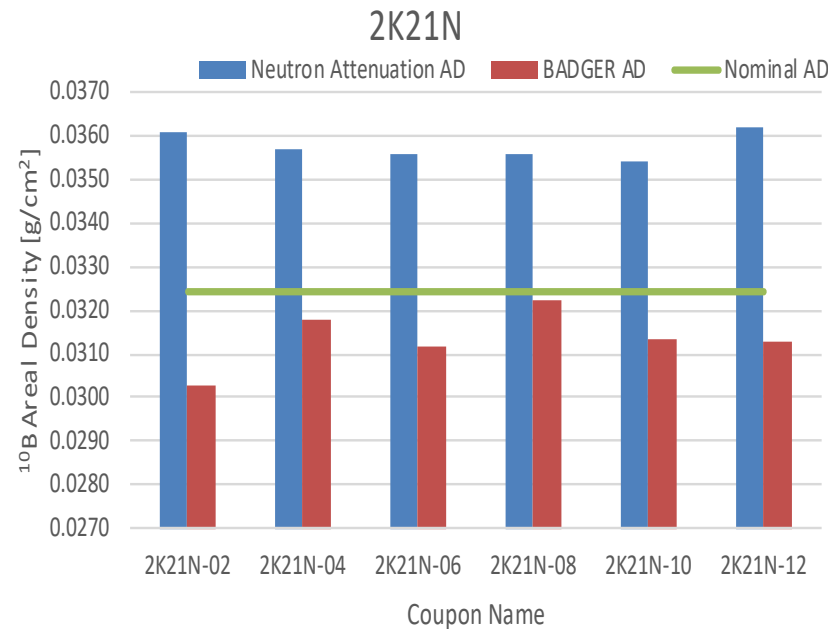
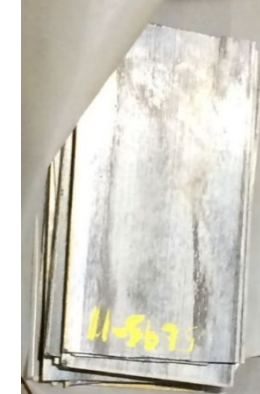
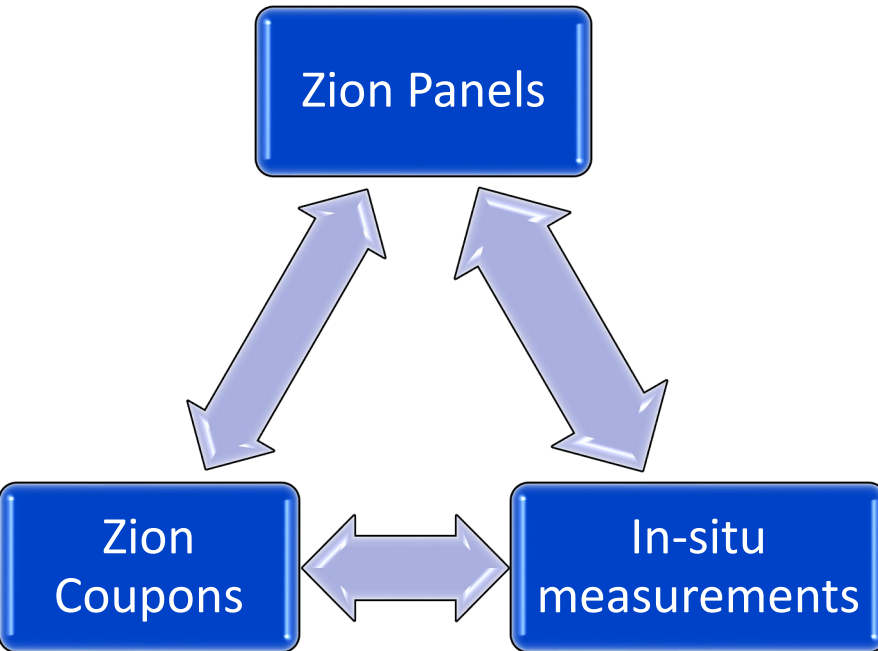


Zion Panel Sample ID	Region	Total Number of Pits	Zion Coupon ID	Region	Total Number of Pits
2J19N-5	1	28	RX153229-1-3	1	182
2L19N-4	1	47	RX153229-1-5	1	255
2L19S-1	1	25	RX153229-1-6	1	131
5L9E-1	2	16	UX153507-2-2	1	176
5L9S-9	2	34	UX153507-2-3	1	155
5L9S-11	2	33	RZ150433-1-3	2	121
5M7E-9	2	10	RZ150433-1-4	2	257
5M7S-12	2	19	RZ150433-1-6	2	203
5M12E-6	2	40	SZ151748-1-4	2	149
2J19N-5	1	28	RX153229-1-3	1	182

1. Good agreement between panel and coupon areal densities
2. No axial height dependence for areal density for panels (radiation and temperature impacts are minimal)
3. Coupons show more pits compared to panels

Coupons represent panels in a conservative manner

Zion Comparative Analysis project – Key Findings



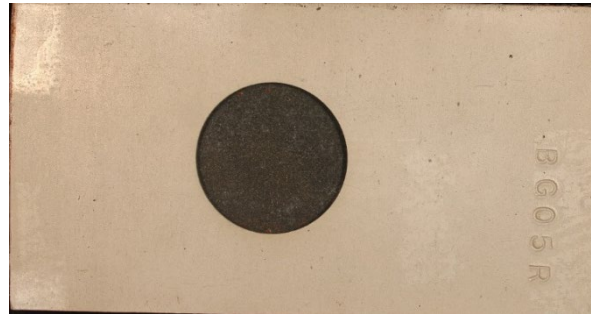
4. In situ (BADGER) measurements underpredict Areal Density → Implies false degradation

One of the key recommendation after Zion was to re-insert coupons into SFP without heat drying to avoid losing remaining coupons across the industry. This approach is now accepted by the NRC and implemented by the industry

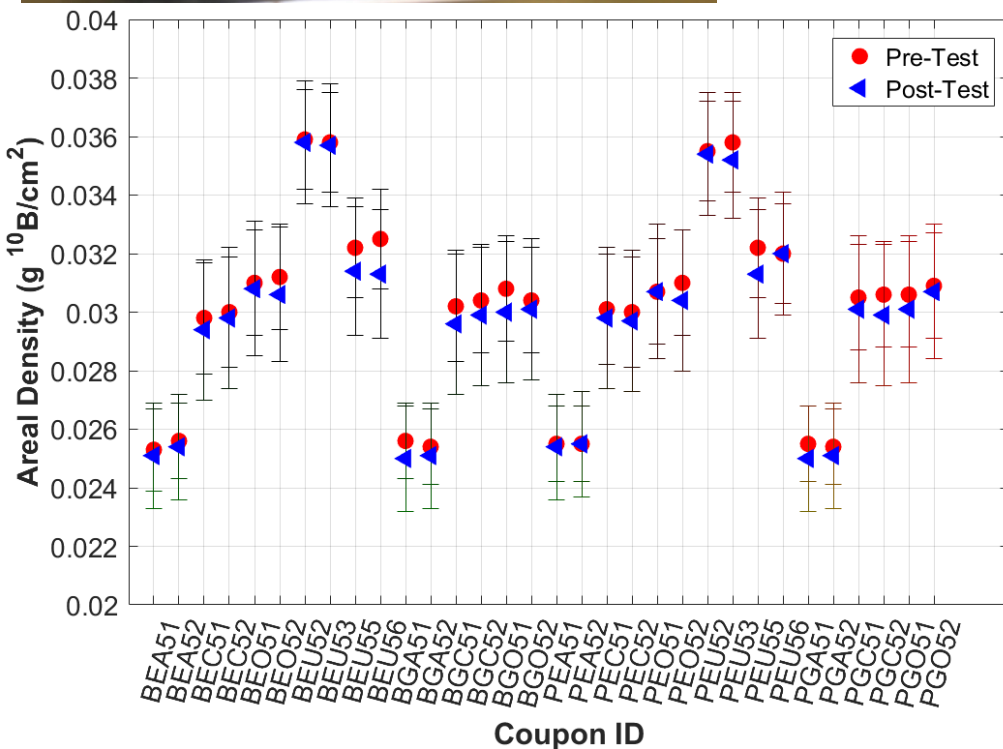


Accelerated Corrosion Project

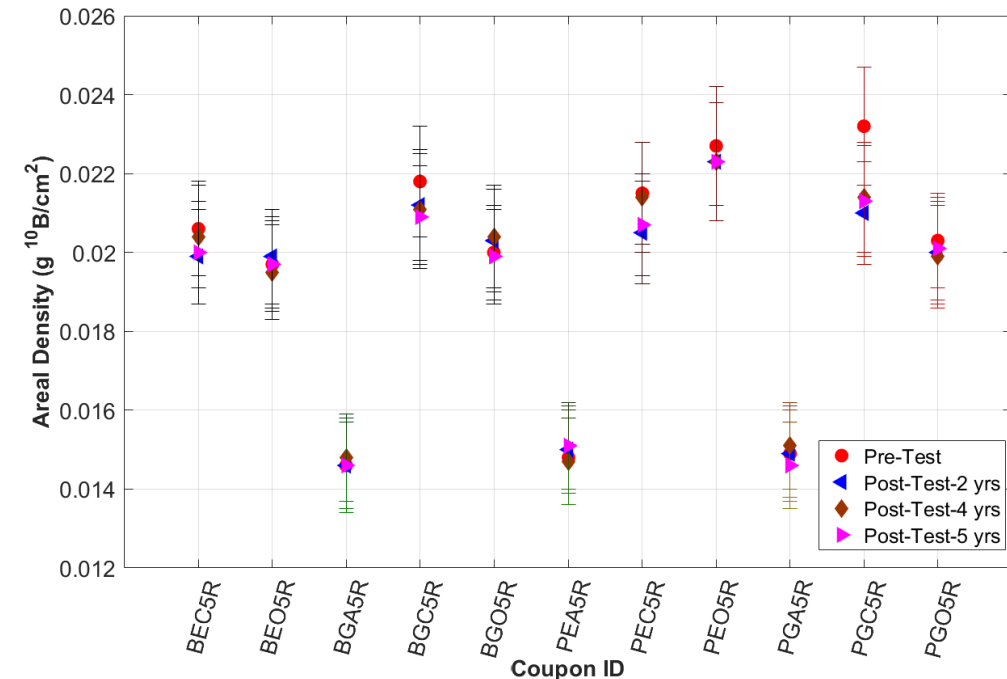
Accelerated Corrosion Tests – Key Findings



Clad removed coupon



- No statistically significant change in Areal Density values for Year 5 coupons
- No statistically significant change in Areal Density for Year 1-4 coupons either

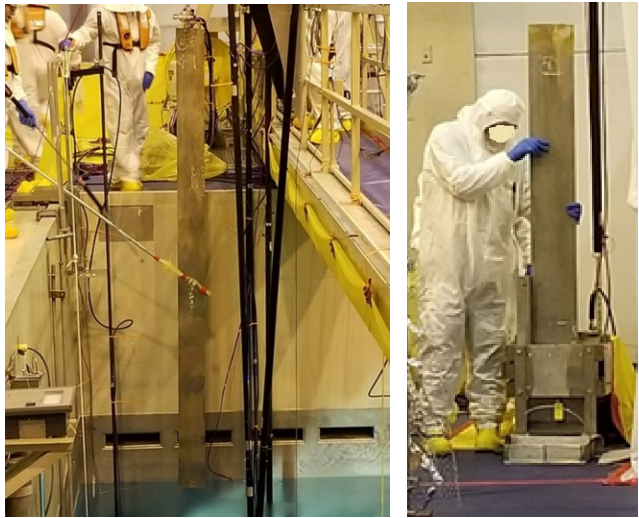
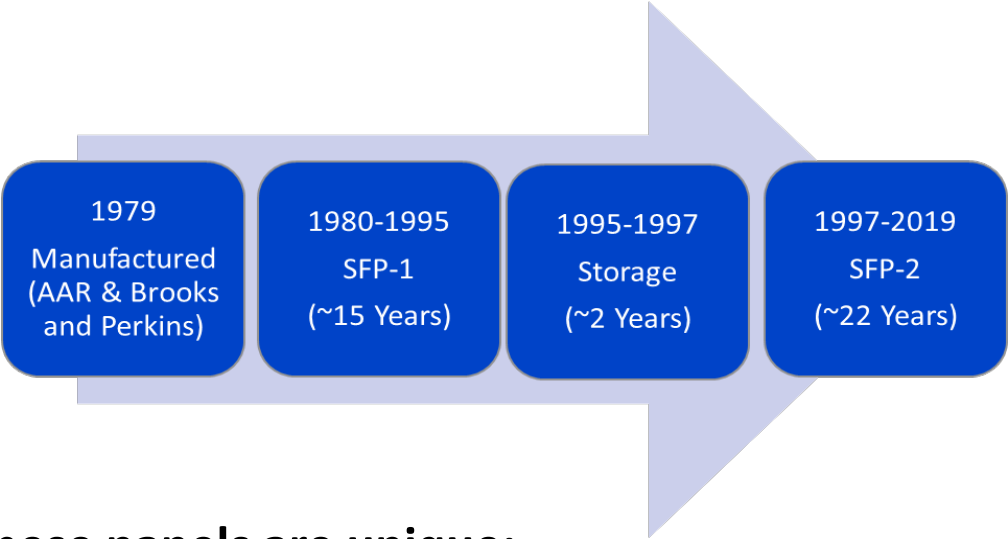


- Even for clad removed coupons, no statistically significant change in AD over time
- Considered extending the project beyond 5 years, although coupons are in great condition, corrosion test baths degraded



Evaluation of Panels from an Operating SFP

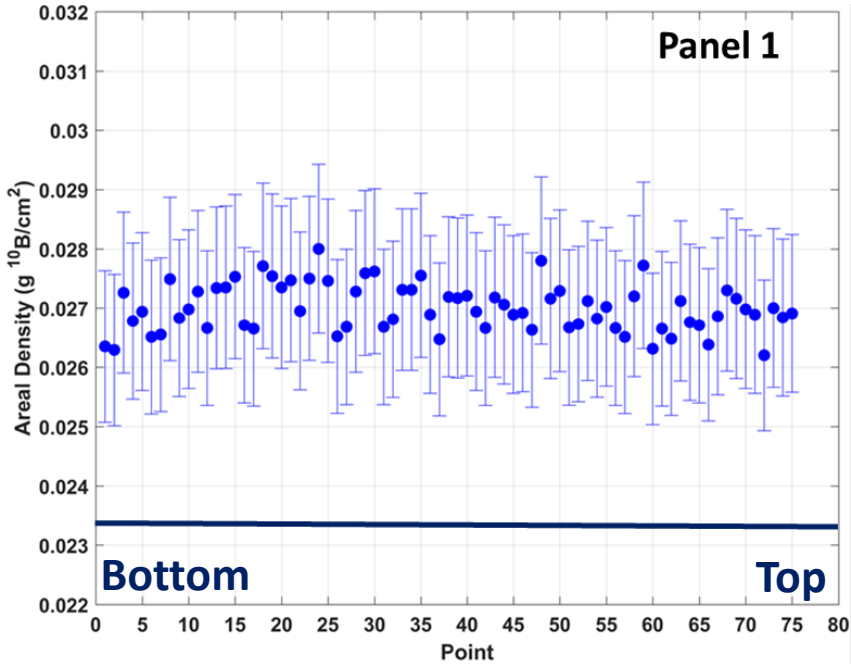
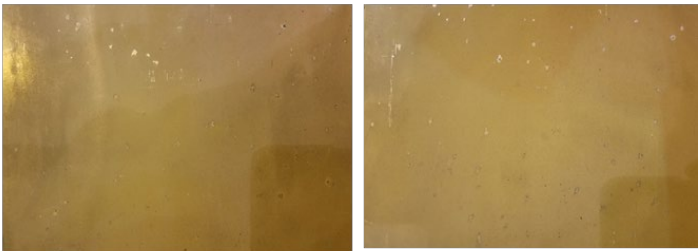
Evaluation of Panels from an Operating SFP – Key Findings



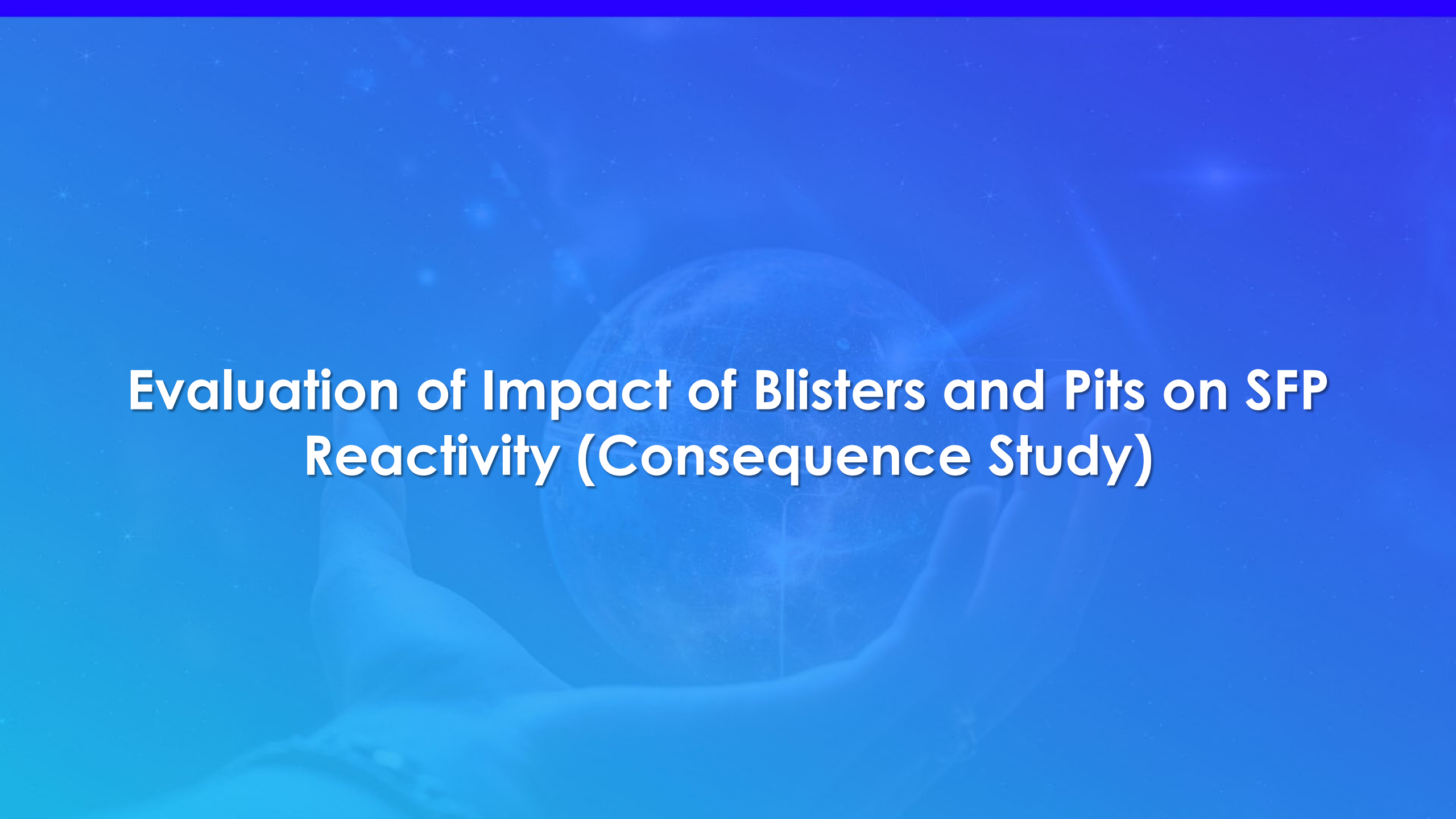
- Panels are in very good condition
- **No blisters**
 - Despite being considered most susceptible to blisters due to age
 - General flow patterns, scratches but no gross degradation

These panels are unique:

1. Age and vintage (considered most susceptible for blistering)
2. Used in two SFPs
3. Storage time in between two pools (dry)
4. Long service time (~40 years)

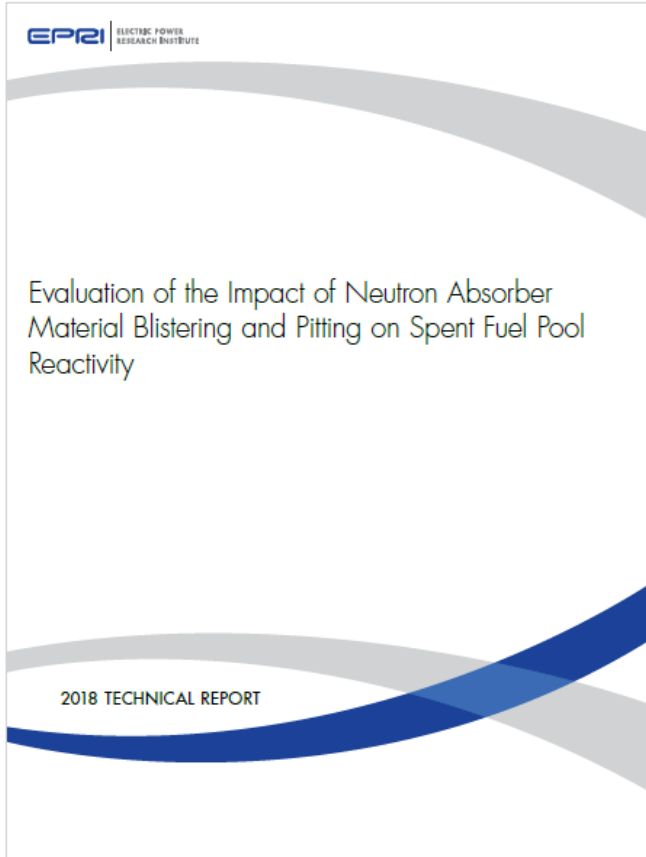


1. No loss of absorber material
2. Areal density (AD) values higher than minimum certified (AD)
3. No clear dependence to variation in axial height → No impact of temperature and radiation variations



Evaluation of Impact of Blisters and Pits on SFP Reactivity (Consequence Study)

Evaluation of the Impact of NAM Blistering and Pitting on SFP Reactivity – Key Findings



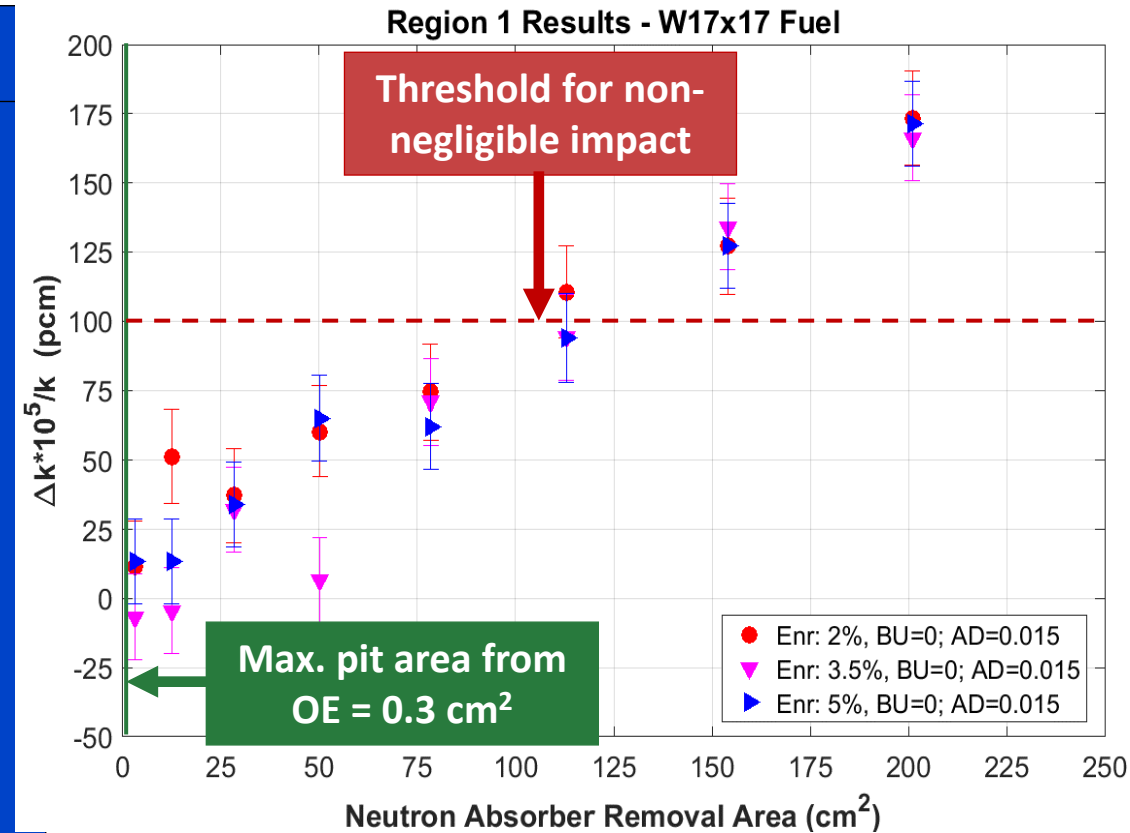
Objectives

Perform simulations and analysis to evaluate

- Impact of pits on reactivity
- Impact of blisters on reactivity

Perform analysis to determine

1. Impact based on operational experience (OE) to date
2. The bounds when impact become non-negligible



EPRI report, **3002013119**, *Evaluation of the Impact of Neutron Absorber Material Blistering and Pitting on Spent Fuel Pool Reactivity*, May 2018.

Based on extensive simulations, pits observed to date have no statistically significant impact on reactivity (need to be >300X larger and in worst location)

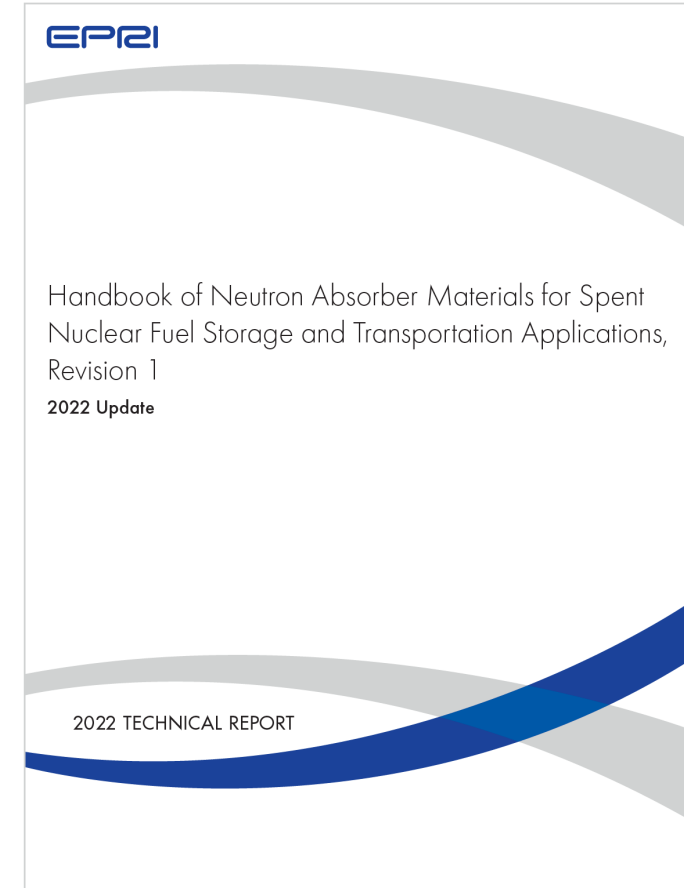


Neutron Absorber Materials Handbook

Neutron Absorber Materials (NAM) Handbook

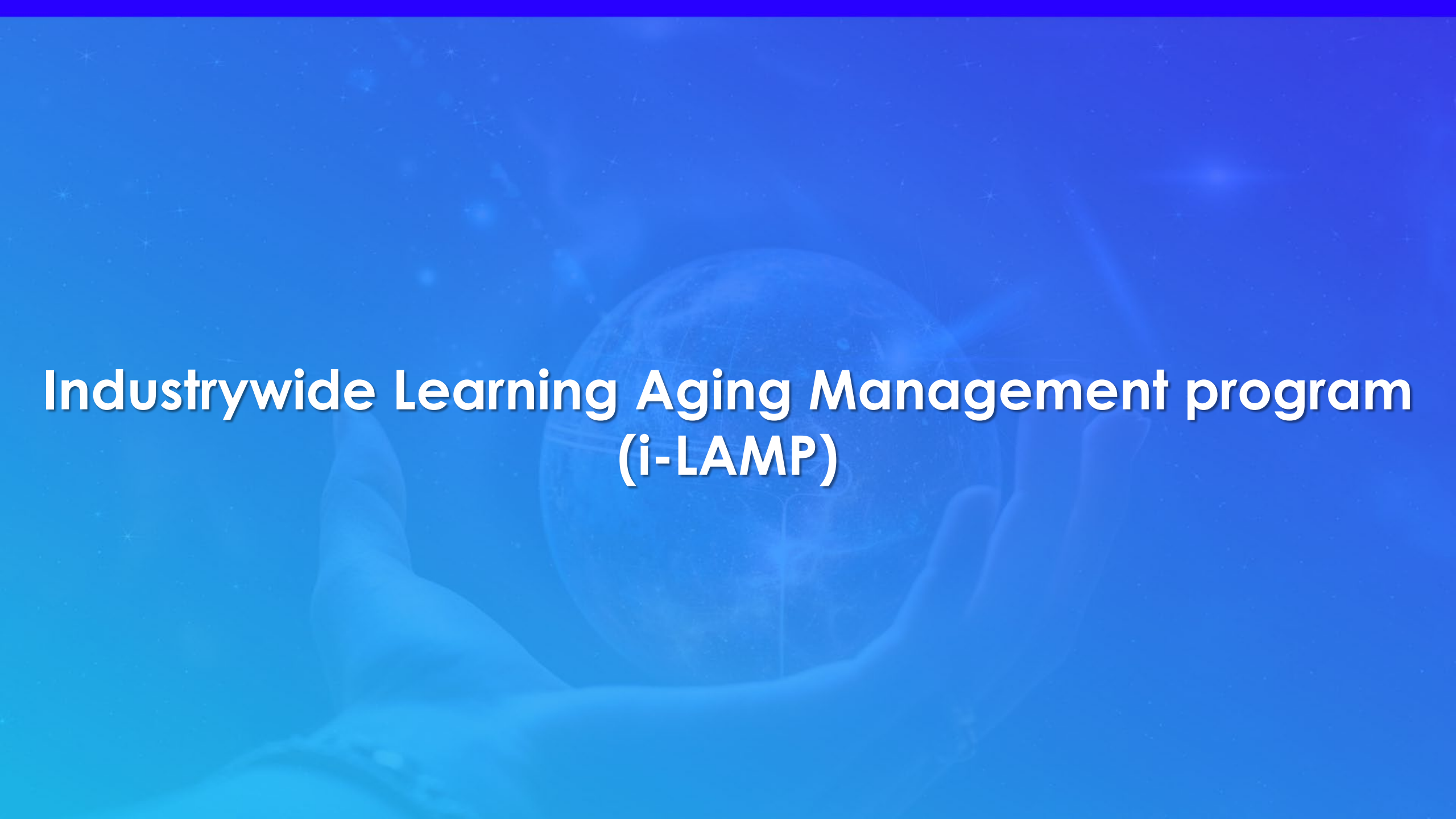
Handbook includes:

1. The properties of neutron absorber materials in wet storage (spent fuel pool), dry storage, and transportation.
2. Summarizes the United States regulatory and industry guidance, based on documents published by the U.S. Nuclear Regulatory Commission (NRC), Nuclear Energy Institute (NEI), EPRI, and other industry organizations.
3. Summarizes non-US experience in wet and dry storage
4. Material properties, qualification testing, and industry experience are provided for 16 neutron absorber materials
 1. Data and information obtained through vendor surveys
 2. Publicly available documents



EPRI report **3002018496**, Revision 1 published in March 2022. Report is publicly available from [epri.com](https://www.epri.com)

NAM Handbook serves as consolidated reference for products used throughout the industry



Industrywide Learning Aging Management program (i-LAMP)

i-LAMP: Industrywide Global Learning Aging Management Program

Global program – Initial focus is on BORAL®

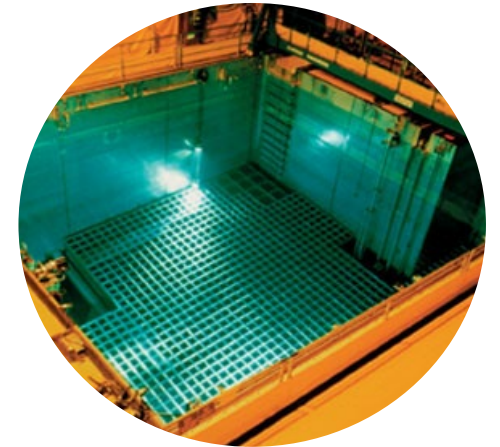
- NAM specifications (type, vintage)
- NAM history (installation and manufacturing years)
- SFP water chemistry history
- NAM performance (coupon monitoring)

Sibling Pool Process – If No Coupons

- Identify sibling(s)
- Commitment to i-LAMP for AMP
- Periodic data updates (“learning”)
- Periodic sibling performance update



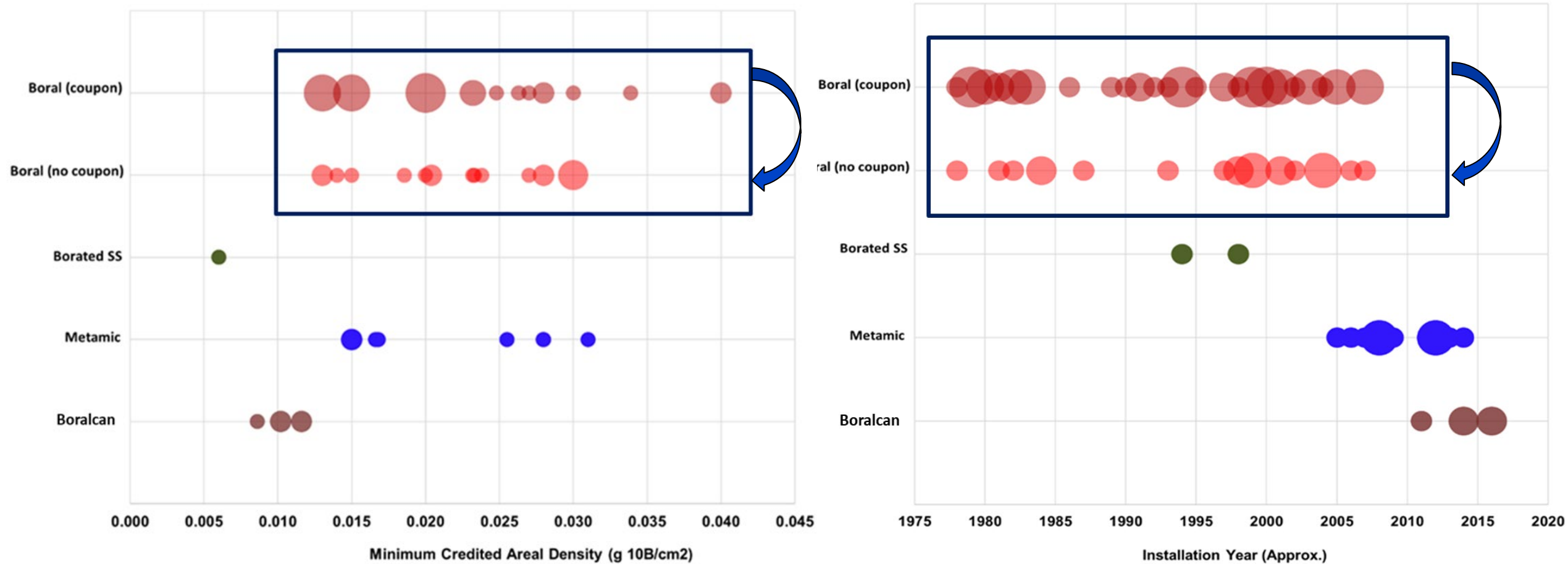
SFP With Coupons



SFP Without Coupons

EPRI's research over the past ~8 years informed establishment of technical basis and implementation plan for i-LAMP

SFP Neutron Absorber Material (NAM) Status



Areal Density: For Boral, all SFPs without coupons are bounded by SFPs with coupons

NAM Age: Not all but majority of SFPs without coupons are bounded. Surrogate identified for two exceptions with unique histories.

i-LAMP Databases

SFP Water Chemistry

- pH
- Conductivity
- Chloride (Cl) concentration
- Fluoride (F) concentration
- Sulfate (SO₄) concentration

Additionally, for PWRs

- Boron (B) concentration
- Sodium (Na) concentration

Few SFPs measure Al; in future may recommend all SFPs to measure Al

SFPs with Coupon

- Pool name
- Rack installation year
- Rack type (egg crate versus flux trap)
- Stainless steel encapsulation or not
- Coupon unique ID number
- Coupon analysis year(s), if the same coupon is analyzed multiple times
- Dimension data (pre-characterization and post-irradiation)
 - Height, width, thickness
 - Weight
 - Areal density values (pre-characterization and post-irradiation)
 - Pit and blister data
 - Pictures

SFPs w/o Coupon

- Pool name
- Rack installation year
- Rack type (egg crate versus flux trap)
- Stainless steel encapsulation or not
- Dimension data
 - Height, width, thickness
- Weight
- Areal density values

EPRI is the owner of these databases. Databases are live and updated as new data comes

Necessary Elements for i-LAMP Long Term Success



EPRI report **3002018497**, published in August 2022. Report is publicly available

- Maintain existing coupon inventory
 - Return coupons to SFP after periodic testing
 - Prior typical utility practice was to discard
 - **Transfer coupons to a sibling SFP after decommissioning**
- Update coupon monitoring data
 - **Provided by utilities to EPRI after periodic testing**
 - EPRI identification of adverse trends
- Maintain and update water chemistry data (**sent by utilities to EPRI**)
- Standardization of coupon analysis
- Expand program to additional NAM types (Metamic and Boralcan)

i-LAMP data, need, and commitment is global

i-LAMP: Industrywide Learning Aging Management Program

i-LAMP has two primary objectives:

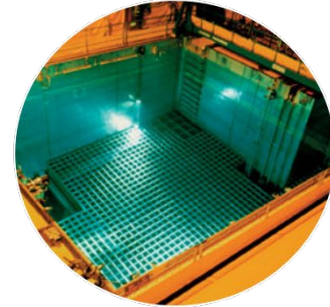
1. Using sibling data for SFPs without coupons
2. Analyze global industry data for trends to identify any potential issues in a timely manner



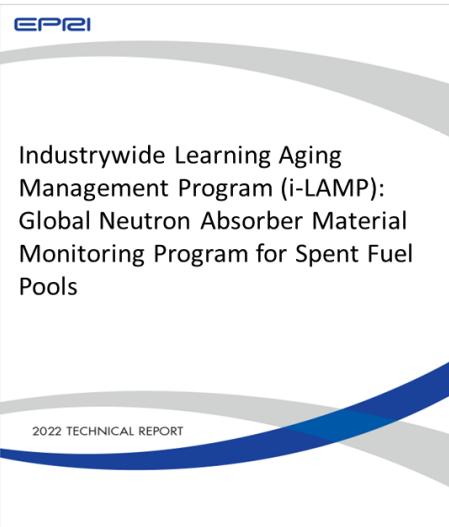
SFP With Coupons

Siblings

Similar NAM Specifications
Similar Water Chemistry
Similar NAM Vintage

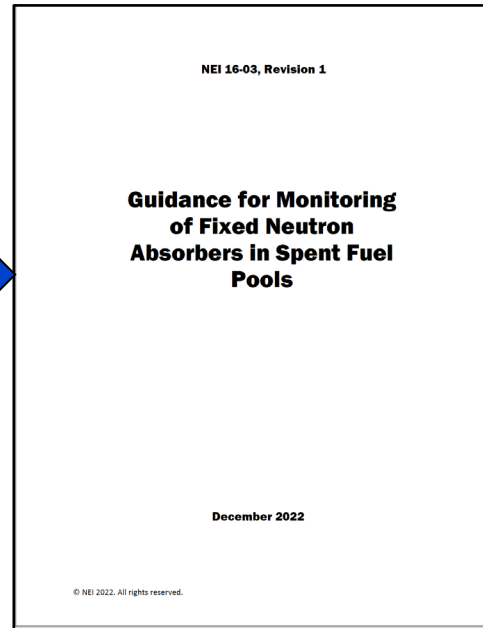


SFP Without Coupons



EPRI report **300201897**
Publicly available

Included in NEI 16-03
Rev.1 as 3rd option



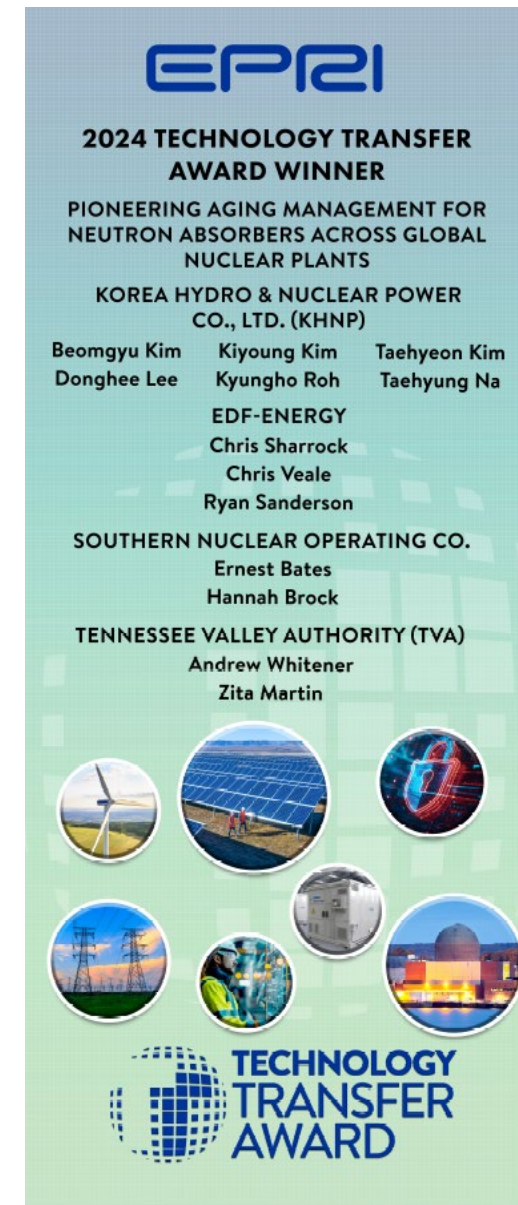
Regulatory review is complete.

- Final SER issued January 30, 2024.
- NEI 16-03-A Rev. 1 submitted in March 2024.
- i-LAMP implementation by utilities is ongoing.

To date, i-LAMP is mainly focused on Boral, for regulatory purposes. i-LAMP will be extended to other materials (Metamic and Boralcan)

i-LAMP Implementation – 2024 TTA Award Winners

- **EDF** – Implemented i-LAMP for Sizewell, using surrogate approach, even before the NRC review was complete with the agreement from their regulator
- **TVA** – Removed panels with unique history since commitment was made prior to i-LAMP proposal but shared extra samples with EPRI and industry and now part of i-LAMP
- **Southern** – Installed extra samples from TVA since Vogtle and Watts Bar had similar unique histories
- **KHNP** – Have coupons but participated in i-LAMP for regulatory issues

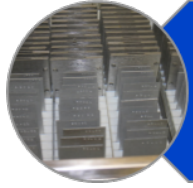


Congratulations to EDF, TVA, Southern, and KHNP for TTA



2025 Activities & Focus Areas

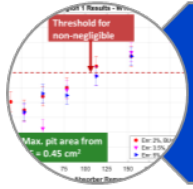
Overview of EPRI Research on Boral Over the Past Decade



Laboratory: Accelerated Corrosion Test (to be published soon 3002023975)



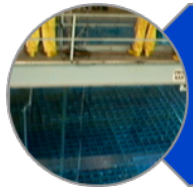
Actual panels, coupons, and in-situ measurements from SFP: Zion comparative analysis (3002008196 and 3002008195)



Modeling and Simulation: Evaluation of Impact of Blister and Pits (3002013119)



Evaluation of Panels from an Operating SFP (3002018497)



i-LAMP proposal (3002013122) and i-LAMP final report (3002018497)

- EPRI performed significant amount of work to **evaluate Boral performance for long term operation**
- To date, work has been **published in 7 EPRI reports and >25 papers**, including 2 journal articles.
- To date, Boral did not show any significant degradation based on
 - Lab test results
 - Analysis of actual panels removed from two SFPs
 - Operating experience to date using coupon results from over 40 years
- This work has been used as the **foundation for i-LAMP development** and other **regulatory interactions by the utilities (GL2016-01 closure)**

EPRI will prepare a summary report that provides key findings from these projects and prepare a recorded video with slides – Aims for knowledge transfer, especially for new staff training

2025 Activities & Focus Areas - Summary

i-LAMP Implementation & Databases

- Continue to work with utilities on i-LAMP implementation
- Development of templates for different implementation paths
- Maintain existing coupon inventory - Return coupons to SFP after periodic testing
- Share coupon results with EPRI & share water chemistries on a regular basis
- Improved databases

EPRI Reports/ NAUG

- Accelerated corrosion test - repeat tests conducted in August 2024.
 - Accelerated corrosion test report will be published by July 30, 2025.
- Overview of EPRI research on Boral over the past decade
 - Report and recording for knowledge transfer
- **NAUG 2025**
 - August 12-14, 2025
 - Included SFP Criticality Training
 - EPRI Washington, DC office

i-LAMP implementation and database construction will be the main focus areas for 2026



TOGETHER...SHAPING THE FUTURE OF ENERGY®

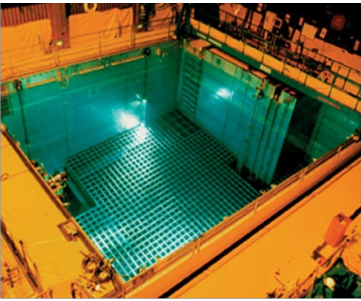
Decay Heat: EPRI-SKB Collaborative Project



Hatice Akkurt, PhD
Senior Technical Executive

China Workshop
October 13-15, 2025

Decay Heat is an Important Parameter That Impacts Entire Back-end Operation



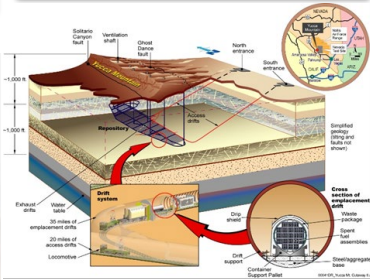
Spent Fuel Pool (SFP)

- SFP Heat Management
- Available storage capacity
- Outage management



Dry Storage & Centralized

- Loading
- Fuel/Cladding Integrity
- Canister Integrity



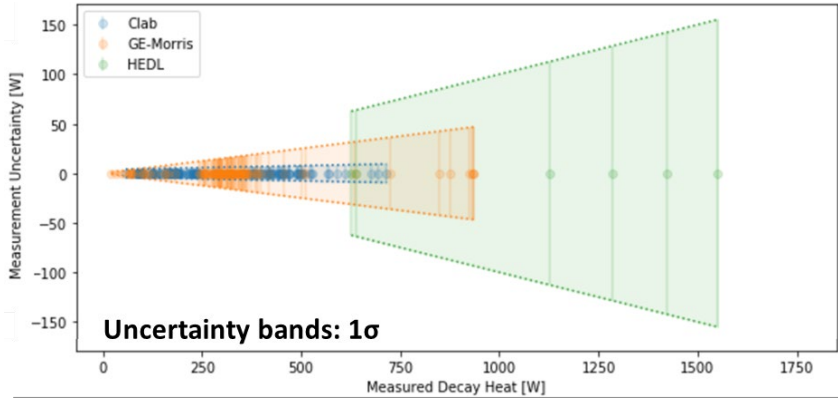
Disposal

- Heat load management
- Dictates number of casks or canisters that can be stored in repository

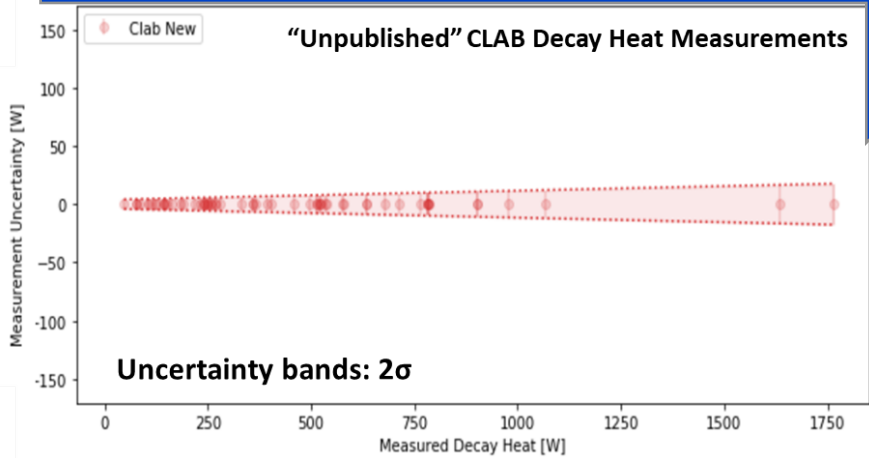


Transportation

- Transportation limits



Reasonably accurate estimation of decay heat, with low uncertainty, is important for the entire back-end operation



EPRI

2024 TECHNICAL REPORT

Spent Fuel Decay Heat Measurements at Clab

Description of Decay Heat Measurements from 2003–2021 Under EPRI-SKB Collaboration

EPRI report, 3002026549, published October 2024 and publicly available from [epri.com](https://www.epri.com)

Decay Heat Measurement Report Outline

1. Introduction
2. Background on Decay Heat Measurements
 - Decay heat PIRT and EPRI-SKB Collaborative agreement
3. Overview of Clab Decay Heat Measurements
 - Clab facility description
 - Calorimeter design
4. Evaluation of Decay Heat Uncertainty
5. Measured Decay Heat and Corresponding Uncertainties
6. Recommended Validation Set
7. Conclusions and Future Work
8. References

Appendices:

- A. Quality Control for Decay Heat Measurements
- B. Description of Gamma Leakage Model
- C. Fuel Assembly Description and Irradiation Histories
- D. Tabulated Values of Measured Decay Heat and Corresponding Uncertainties
- E. Comparison of Burnup and Decay Heat Values from R-05-62 and Current Study
- F. Description of Attachments
 - An Excel file, called
Clab_DecayHeatMeasurements_2003-2021.xls
 - A pdf file, called Fuel_Data.pdf

Comprehensive review and evaluation of Clab decay heat measurements along with all the supporting information, analyses, and data provided in detail for the use by global nuclear industry

Overview of BWR and PWR Fuel Assemblies (FA) versus Number of Measurements

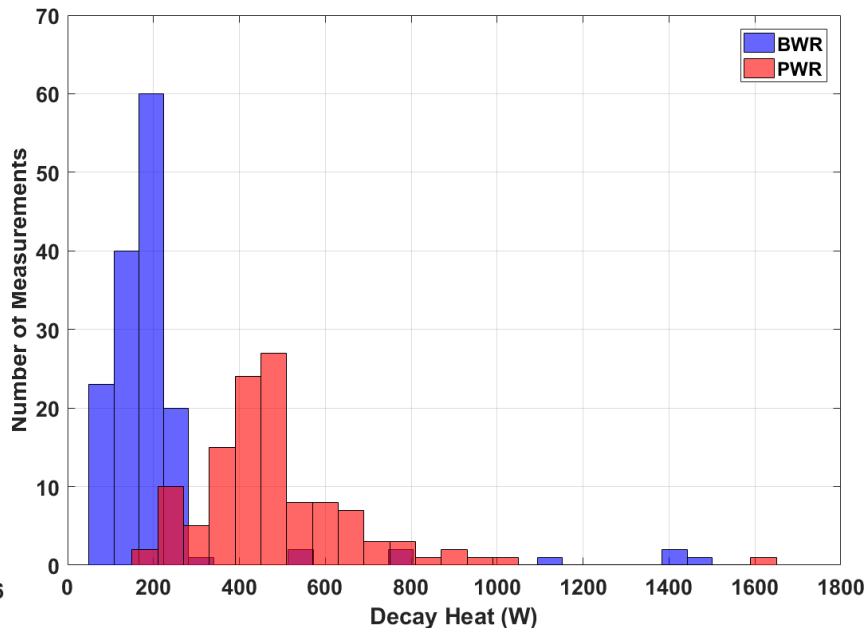
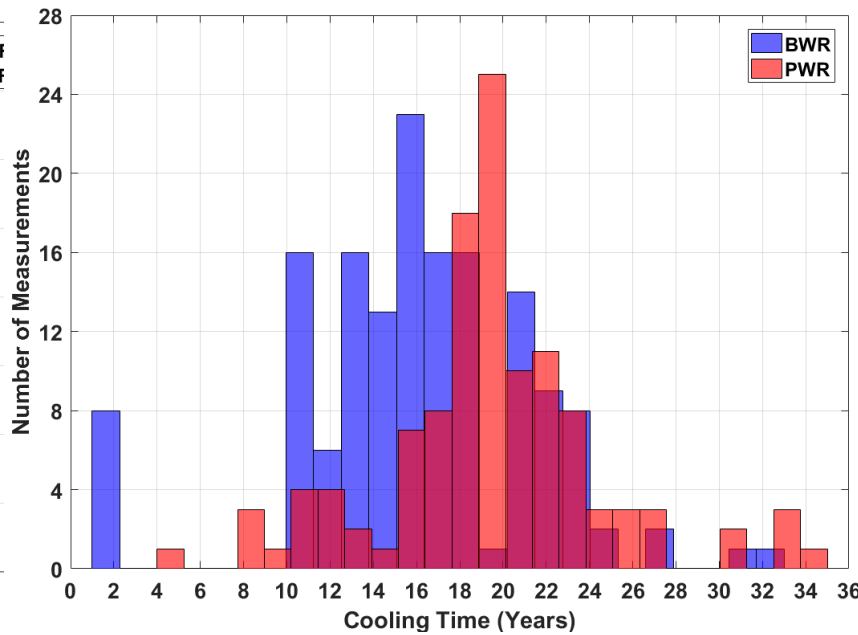
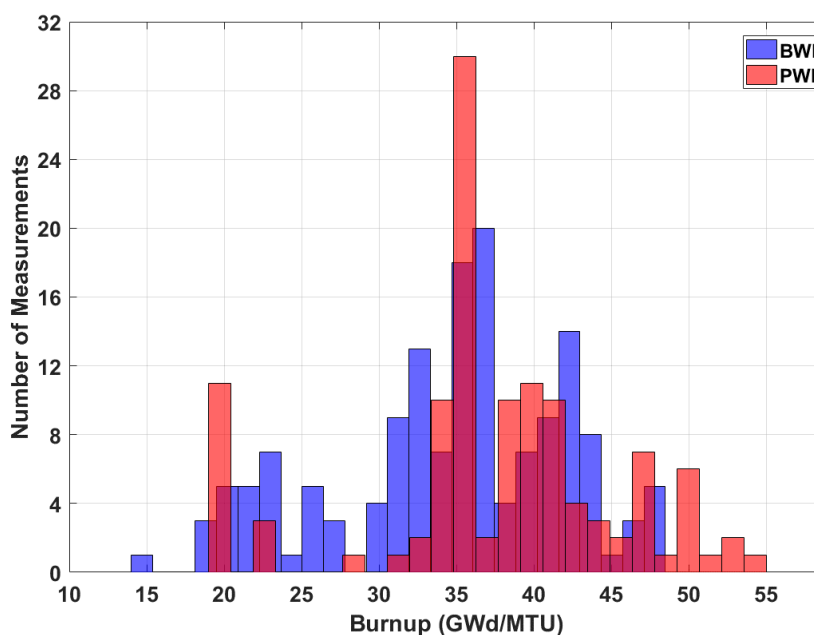
Reactor	Type	Number of Fuel Assemblies	Number of Decay Heat Measurements
Barsebäck 1	BWR	7	11
Barsebäck 2	BWR	4	6
Forsmark 1	BWR	9	11
Forsmark 2	BWR	11	20
Forsmark 3	BWR	7	13
Oskarshamn 2	BWR	11	13
Oskarshamn 3	BWR	27	30
Ringhals 1	BWR	20	48
Total	BWR	96	152
Ringhals 2	PWR	29	44
Ringhals 3	PWR	35	57
Ringhals 4	PWR	16	17
Total	PWR	80	118
Total (BWR and PWR)		176	270

BWR Fuel Assembly (FA) Types			
Fuel Vendor	Fuel Design	Array Size	Number of meas.
ASEA ATOM	AA 8x8	8x8	5
ASEA ATOM	AA 8x8-1	8x8	71
KWU	KWU8x8-2	8x8	1
ASEA ATOM	SVEA64-1	8x8	18
KWU	KWU9x9-5	9x9	3
AREVA	ATRIUM 10B	10x10	2
AREVA	ATRIUM 10XM	10x10	2
GE	GE14	10x10	3
ASEA ATOM	SVEA100	10x10	16
ABB ATOM	SVEA96	10x10	30
WESTINGHOUSE	SVEA96 Opt 3	10x10	1
Total			152

PWR Fuel Assembly (FA) Types			
Fuel Vendor	Fuel Design	Array Size	Number of meas.
FRAMATOME	15x15 AFA3GAA	15x15	2
KWU	KWU 15x15	15x15	33
WESTINGHOUSE	W15x15	15x15	9
SIEMENS	17x17 HTP	17x17	6
ABB ATOM	AA17x17	17x17	9
FRAGEMA	F17x17	17x17	16
WESTINGHOUSE	W17x17	17x17	43
Total			118

- Majority of fuel types are represented. 152 BWR (using 96 FA) and 118 PWR (using 80 FA) measurements → Total 270 measurements .
- A number of repeat measurements using the same fuel assembly

Clab Measurements as a function of Burnup, Cooling Time, and Decay Heat



- In general good sampling of burnup ranges
- No measurement beyond 55 GWd/MTU

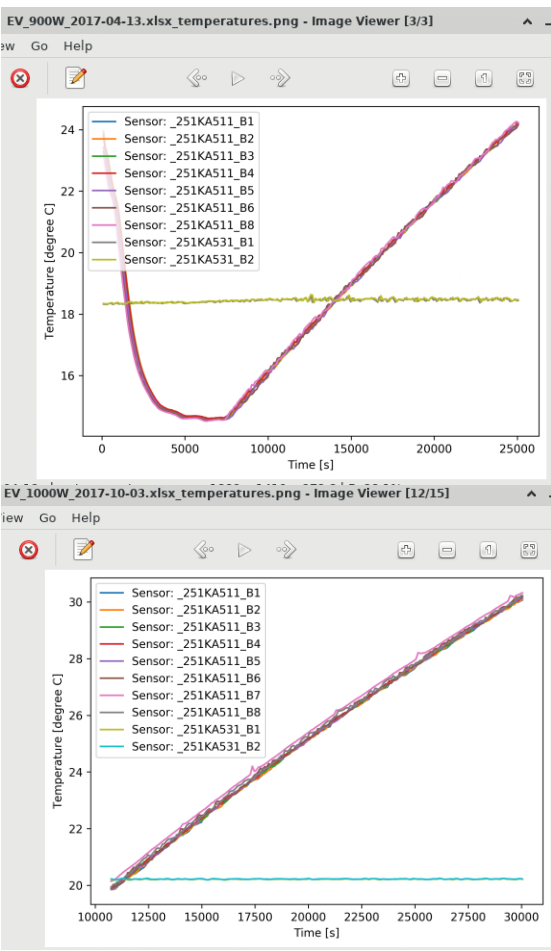
- Significant number of measurements for cooling times between 10-22 years
- Under sampling for cooling times below 10 years

- BWR measurements clustered around 200 W – over sampled
- Significant under sampling for decay heat over 900 W

Oversampling for lower decay heat (especially BWR) and under sampling for higher decay heat. Visualization of measurement this way would help with sampling of key parameters in future campaigns.

Quality of Calibration and Fuel Assembly (FA) Measurements

Bad Quality Calibration Measurements

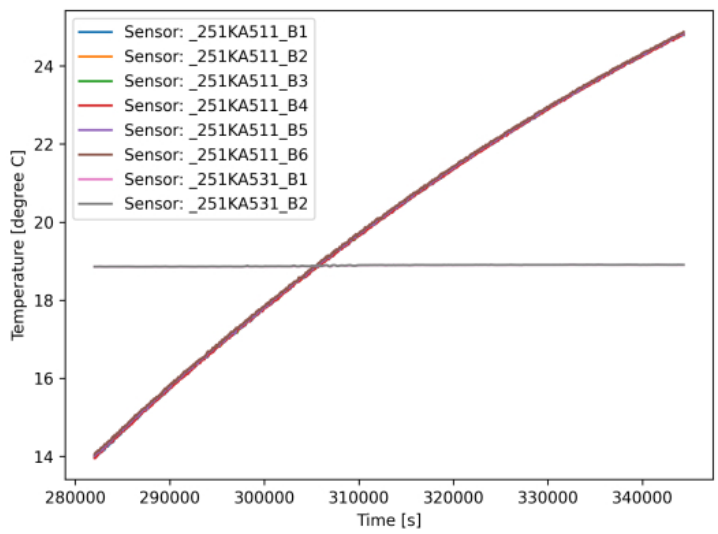


Potential issues with calibration measurements:

1. Strange behavior of sensors
2. Non-symmetric measurements
3. Noisy pool temperature

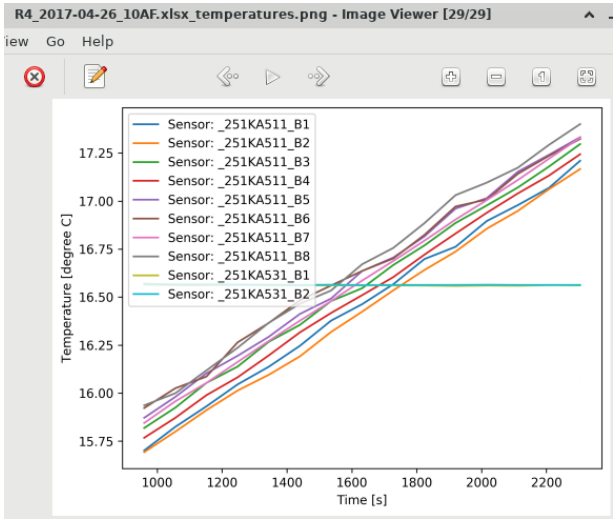
Excluded 6 calibration measurements from evaluation

Good Quality FA Measurement



1. Stable pool temperature (low noise, no anomalous behavior).
2. Symmetry (similar amount of calorimeter data above and below the pool temperature).
3. Adequate measurement time.

Bad Quality FA Measurement

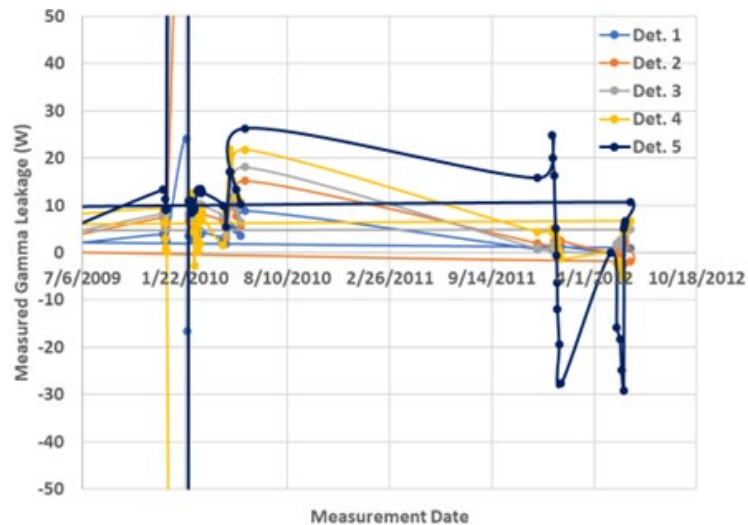
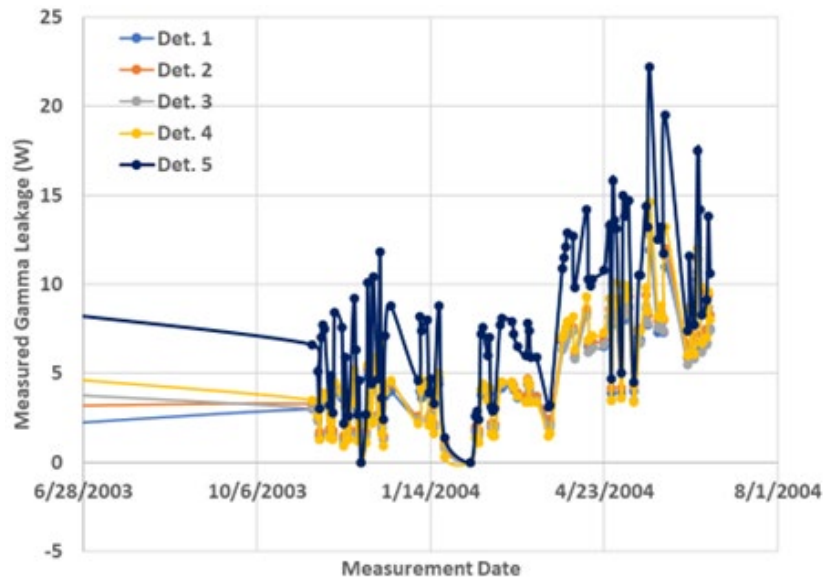


1. Very short measurement time
2. Large temperature differences between sensor data

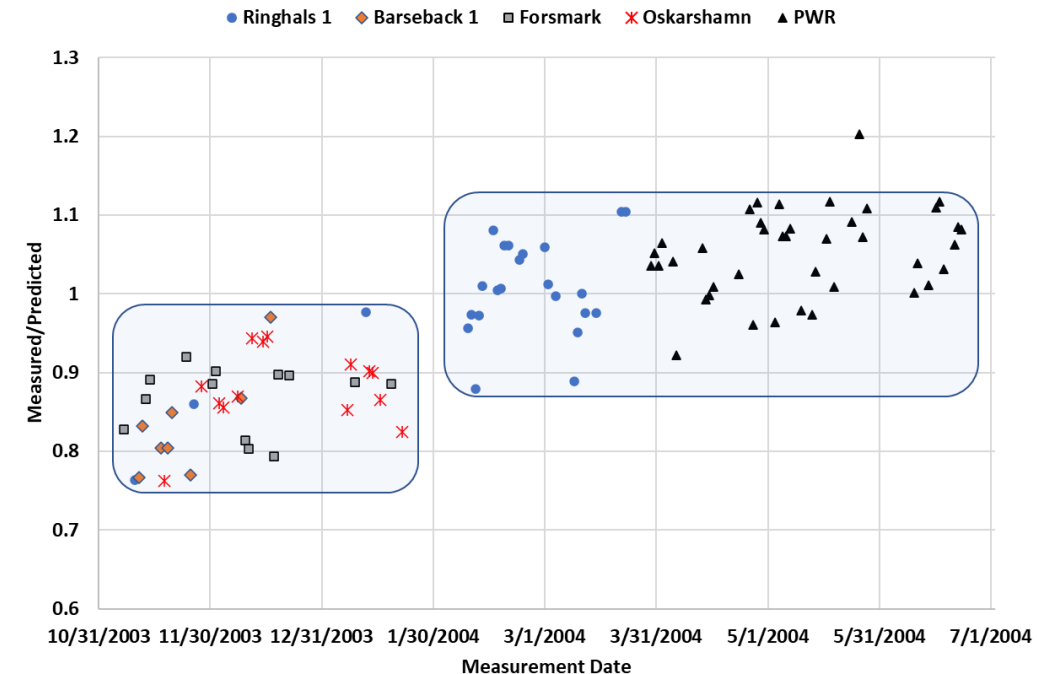
Excluded 5 FA measurements from evaluation (3 FA has other measurements)

Quality of calibration measurements, using heater assembly, and fuel assembly measurements are the key for any good measurements that can be used for benchmarking/validation. Developed screening criteria will be beneficial for future measurements as well.

Measurement Quality – Gamma Leakage



- Majority of the gamma leakage measurements were non-credible
 - Negative values
 - Very high values
 - Zero values
- Stratification of detector gamma leakage (large differences in gamma leakage fractions between detectors)



Using the best subset, MCNP model validated. Gamma leakage values are based on the validated model

Lessons Learned for Future Decay Heat Measurement Campaigns

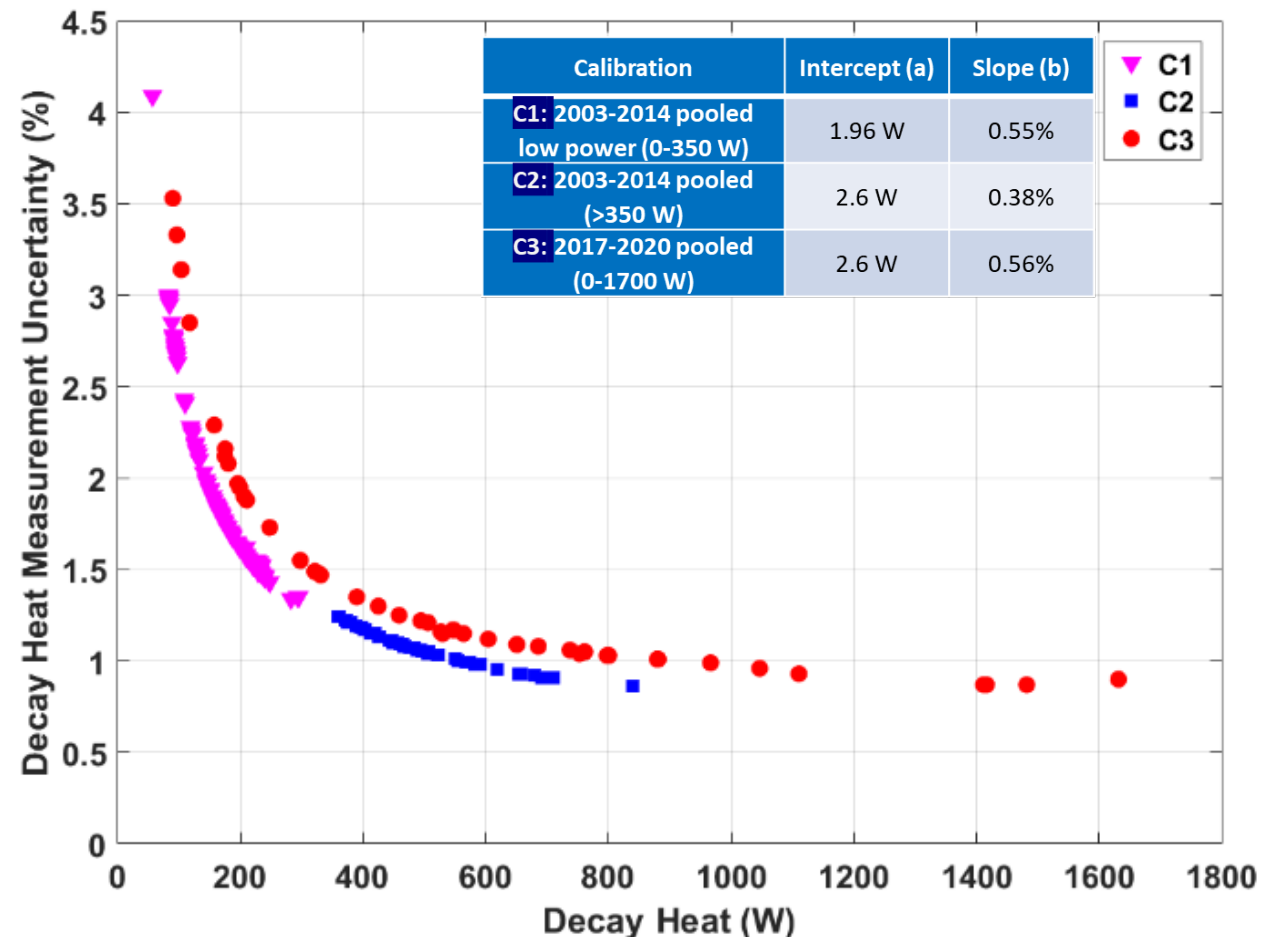
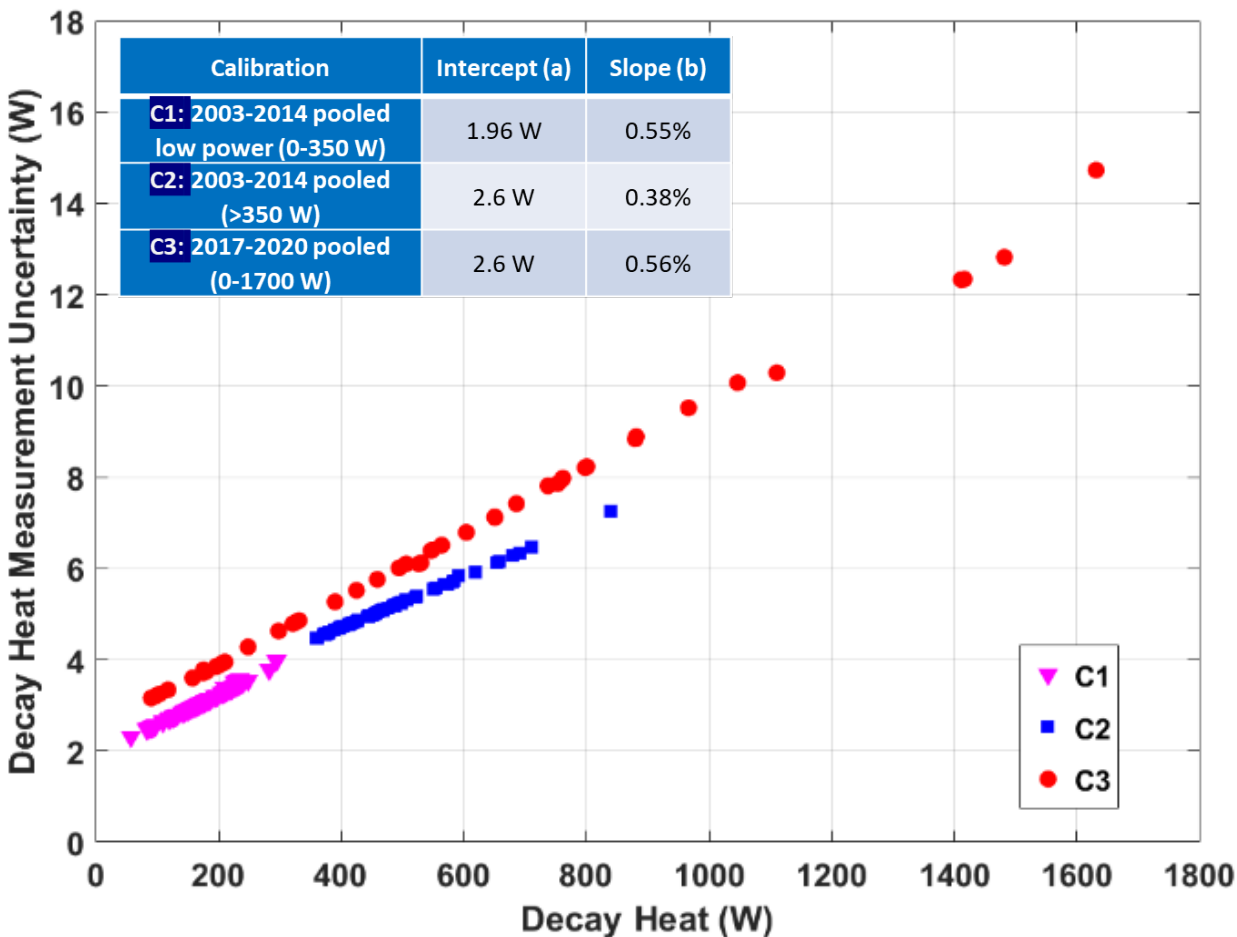
Performing decay heat measurements is **very expensive** and if there are issues with the measurements, they should be identified, issues should be resolved, and measurements should be repeated promptly before moving the fuel assembly.

Key lessons learned include:

1. The **data sampling rate for heater power, pool temperature, and calorimeter temperature should be increased as power increases** to provide a similar number of data points for all measurements.
2. Ensure **calibration data is well distributed across the range of power needed** for upcoming fuel assembly measurements.
3. **Measured data should be screened for quality following each measurement.** Quality screening includes temperature stability, noise, symmetry, and temperature vs. time fit uncertainty. **Measurements that fail quality screening can be promptly repeated.**
4. Assess **gamma detector reliability and consistency** during each campaign and/or measurement.
5. Future measurement candidate fuel assemblies can be selected to fill gaps in the population of measured data and to **extend the validation range.**
6. **Repeat measurements representing different decay heat ranges** are valuable for direct confirmation of good system performance and estimated measurement uncertainty.

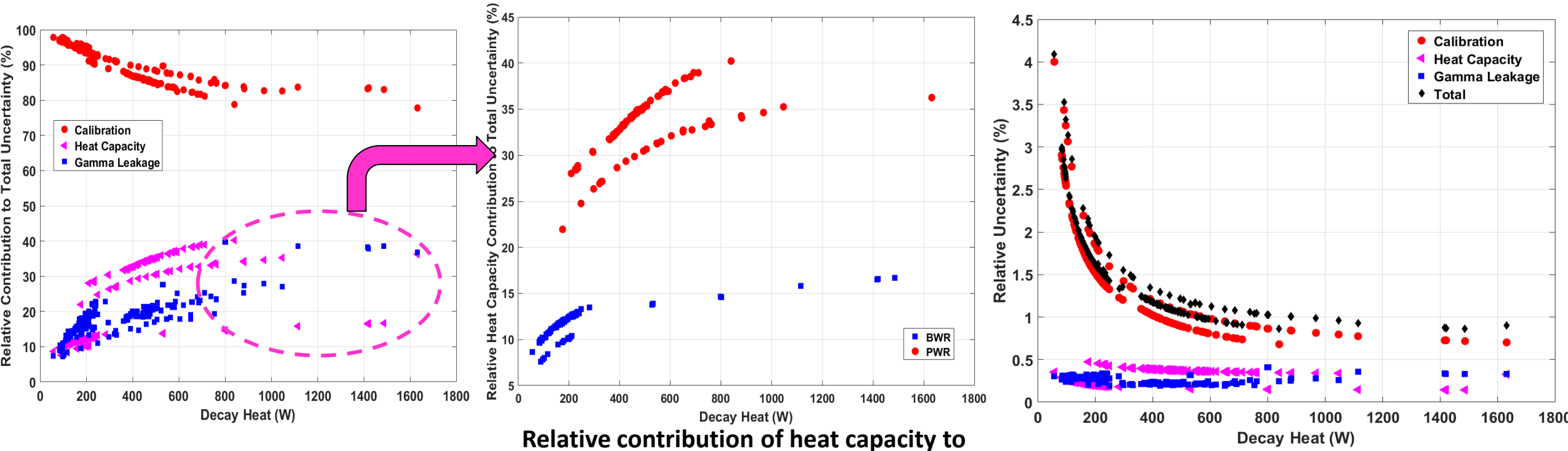
The lessons learned from the current evaluation will be the guidelines for the next measurement campaign when the calorimeter is ready for the new measurements.

Uncertainties in Measured Decay Heat



Multiple trends are due to differences in calibration curves

Uncertainty Components



Relative contribution of heat capacity to total uncertainty for BWR and PWR fuel assemblies

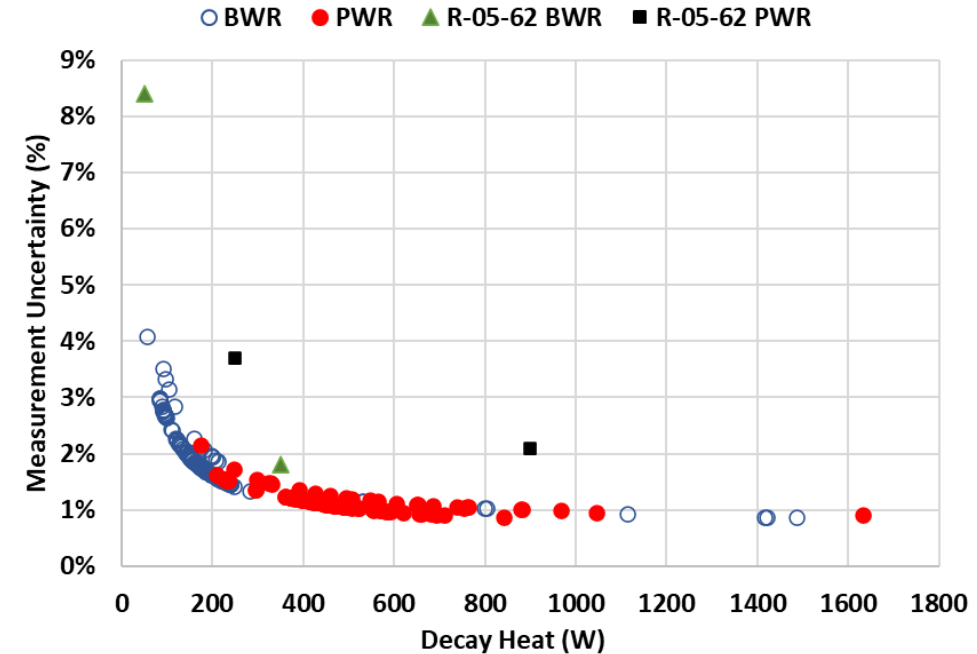
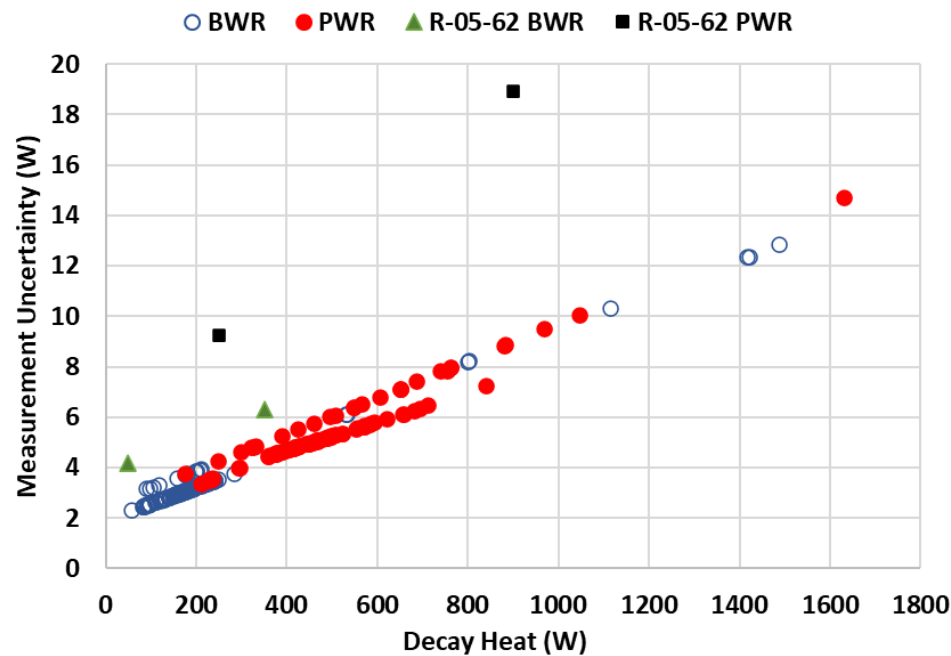
$$TU(W) = \sqrt{CU^2 + \Delta mc^2 + GLU^2} + BiU$$

$$TU(\%) = TU(W) * 100 / T DH$$

TU: Total Uncertainty; CU: Calibration Uncertainty; GLU: Gamma Leakage Uncertainty; TDH: Total Decay Heat

Primary driver is the uncertainties in calibration

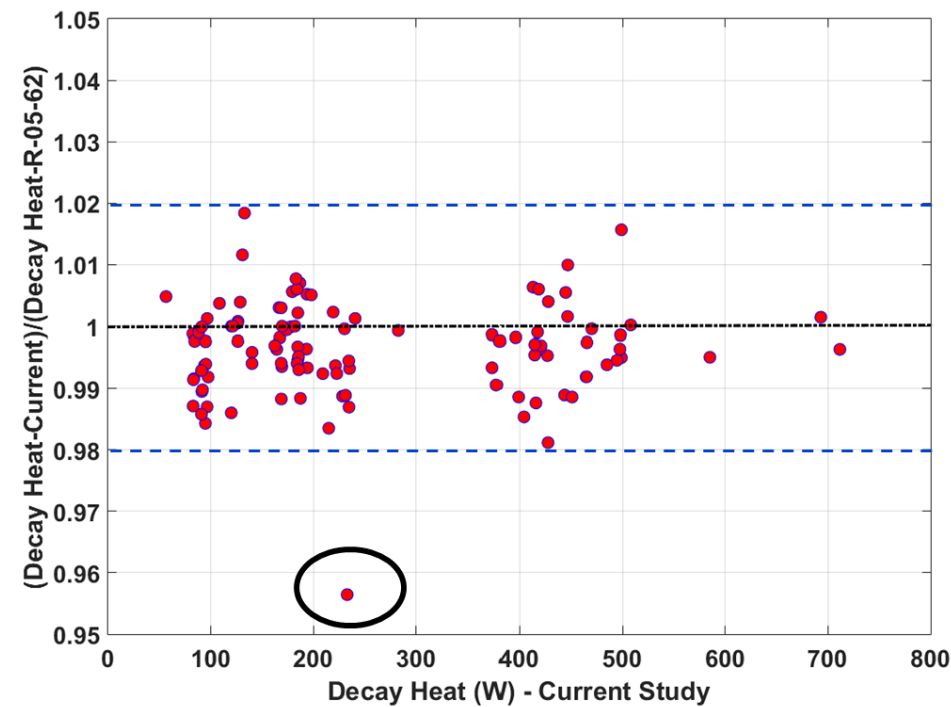
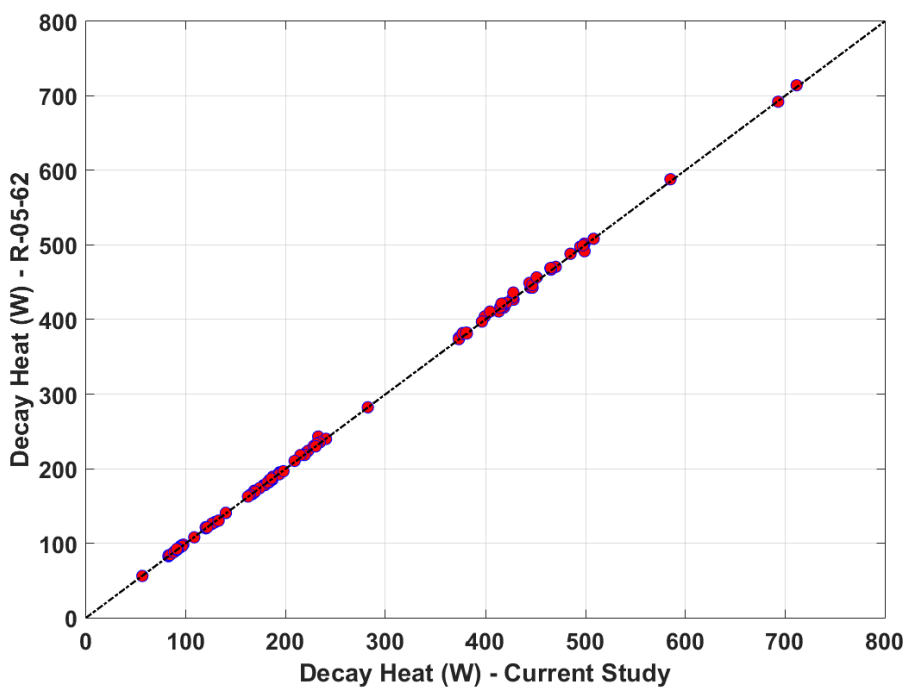
Total Uncertainty Comparison to R-05-62



Uncertainty estimates are lower than R-05-62 estimates. Why?

1. Evaluation of data quality for measurements
 - Outlier screening
 - Data pooling testing
 - Bad data rejectionleading to lower calibration uncertainty (42% to 75% of the R-05-62 calibration uncertainty)
2. R-05-62 assumes **8.3 to 10% uncertainty in fuel mass and volume** for mcp correction. This is arbitrary and unrealistic.
 - This evaluation assumes 1% uncertainty, based on OE data.
3. Gamma leakage evaluation – overall contribution of gamma uncertainty to total uncertainty is small in both evaluations.

Comparison of Decay Heat Values - Current Study versus R-05-62

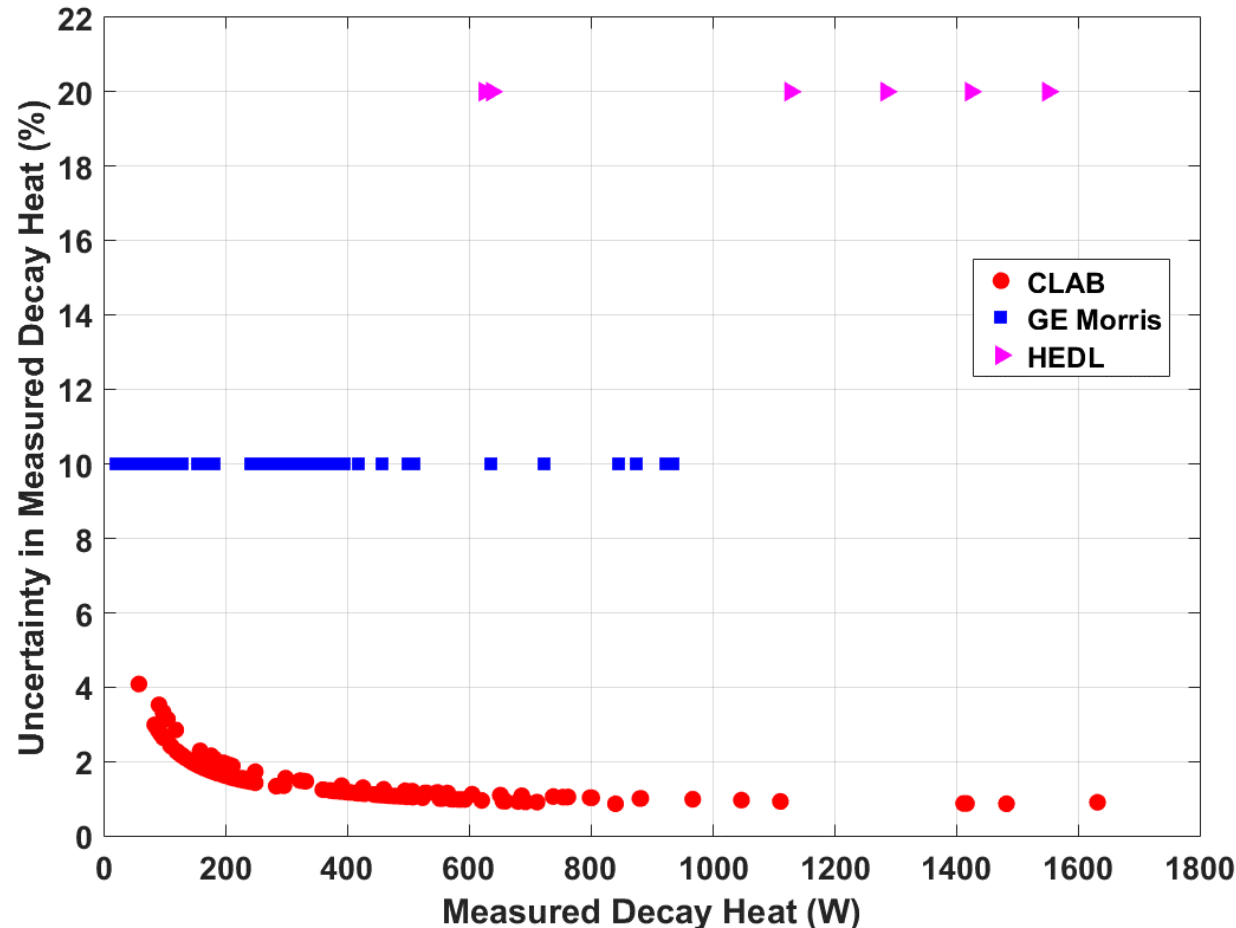


Decay heat values within $\pm 2\%$, except one measurement

Assembly ID	Measurement date	Burnup - Current Study [MWd/MTU]	Burnup R-05-62 [MWd/MTU]	Current Study Total Decay Heat [W]	R-05-62 Total Decay Heat [W]	Current/ R-05-62 Decay Heat
5A3	6/13/2003	19808	19699	234.6	237.7	0.987
5A3	6/16/2003	19808	19699	235.1	236.7	0.993
5A3	6/18/2003	19808	19699	232.8	243.4	0.956

Current evaluation is more consistent for repeat measurements

Recommended Validation Set



- Due to very large uncertainties, a limited number of points, and no documentation on uncertainty analysis, **removal of HEDL measurements from the validation set is proposed.**
- **The GE-Morris measurement set can be removed from the decay heat validation set** as the released Clab measurements now cover majority of the desired enrichment, burnup, cooling time, and decay heat range.
- **Exclusion of reconstructed fuel assembly measurements** due to availability of detailed data and/or modeling complexity.
 - List of reconstructed assemblies provided
 - Depends on the inventory for the validation

Clab measurements offer high quality measurements with low measurement uncertainty

Ongoing Validation Activities

ORIGEN

- Origen 6.2 simple
- Origen 6.2 cycles
- Origen 6.2 – axial – detailed evaluation

Polaris

- Polaris 6.3, 2D ENDF/B-VII.1
- Polaris 6.3, 2D ENDF/B-VIII
- Polaris 6.2, 3D ENDF/B-VII.1
- Polaris 6.2, 3D ENDF/B-VIII

SNF

- SNF 1.6, Casmo4/Simulate3, JEFF 2.2
- SNF 1.6, Casmo4/Simulate3, ENDF/B-VII.1
- SNF 1.8, Casmo5/Simulate5, ENDF/B-VII.1

Objective is to compare different modeling approaches (very simple to very detailed), cross section libraries, and codes.

Validation report expected to be published in late 2025 or early 2026

Summary and Forward Looking

Evaluation of Clab Decay Heat Measurements

- All measurements, from 2003-2021, evaluated for quality
- Developed screening criteria for data quality, which will be beneficial in future campaigns
- Excluded 6 calibration and 5 fuel assembly measurements
- Measurement uncertainty below 1% (2 sigma) for high decay heat
 - Significant gain in operational margins for entire back-end
- EPRI report reviewed by experts from global community and published in October 2024
- A journal article is published in Progress in Nuclear Energy

Validation of Clab Decay Heat Measurements - 2025

- Calculations using SNF, ORIGEN, Polaris
- Evaluating sensitivity to cross section libraries
- Evaluating sensitivity to cooling time
- Evaluating sensitivity to model details
- Validation report will include key lessons learned and will make recommendations
- Validation report will be published in 2026 and will be publicly available

2025 and Beyond

- Finishing calorimeter upgrades
- Performing repeat measurements
 - Using developed screening metrics for data quality
- Evaluation of repeat measurements
- Performing measurements – targeted sampling to close technical gaps
- Validation of new measurements
- Publicly available EPRI report for new measurements and validation results



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High Burnup Research Project Review

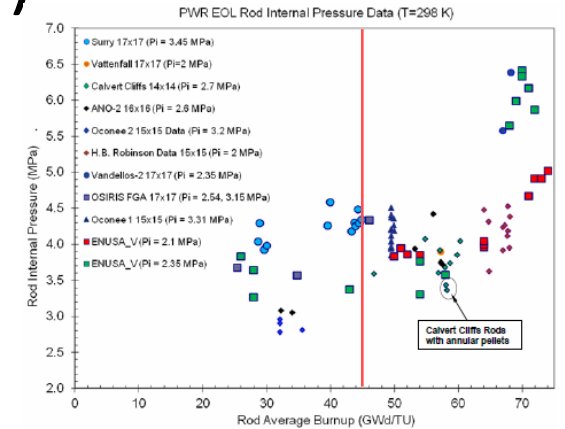


Dr. Joe Faldowski, DBA, PMP
Sr. Program Manager

China Workshop
October 13-15, 2025

Cladding Performance RFA – Background

- As fuel is burned longer in reactor (>45 GWD/MTU)
 - Hydrogen content increases
 - Internal pressure increases
 - Oxide thickness increases
- This RFA studies the effects of these changes on spent fuel cladding properties
 - Develop technically sound bases



Rod Internal Pressure vs. Burnup

Support regulatory acceptance of *practical* approaches for dry storage and transport of high burnup spent fuel

Approach

1. High-burnup Research project

- DOE-EPRI HBU Research Project currently underway at North Anna

2. Study of Cladding Properties

- Data Collection
 - Collaboration (NFIR, SCIP, EDF, ...)
 - Focus on newer claddings irradiated to high burnup
- Modeling
 - Incorporation of data into analytical models
- Knowledge Transfer
 - Interactions with industry, NRC, labs, international (conferences, meetings)
 - Seminars/workshops in support of international members

HBU Demo – Scope – High Level Plan

- Scope:
 - Load cask with High Burnup fuel
 - Determine initial condition of the fuel through sister rods
 - Collect temperature and gas composition data during storage
 - Store cask at least 10 years
 - Determine post-storage condition of the fuel
 - Ship cask to examination facility
 - Open cask without rewetting and inspect fuel
 - Option to reclose and continue storage and measurements

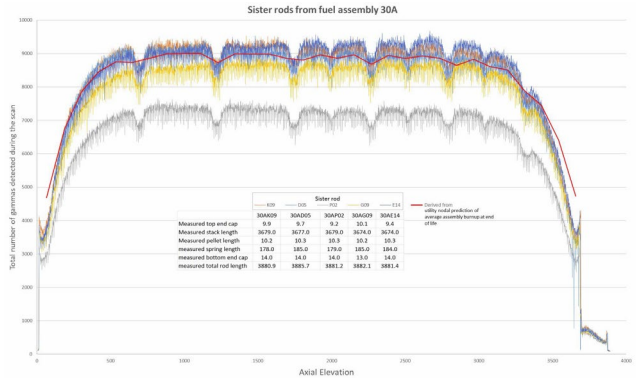


HBU Demo – Initial Contract – Phases 1 & 2

- Project began in 2013 with DOE contract to EPRI:
 - “...design and implement a high burn-up, large scale, long term, dry storage cask R&D project for SNF”
 - Project team included EPRI (w/Orano, Dominion, Framatome, Westinghouse, NAC), US DOE, NLs, NRC, IRT
- Scope:
 - Design, license, fabricate instrumented cask
 - Fuel selection
 - Identify, pull and ship sister rods
 - Load cask
 - Collect data
 - Store cask

1	6T0	2 (TC Lance)	3K7	3T6	4	6F2	
	Zirlo, 54.2 GWd 4.25% 3cy, 11yr 912.2 W	M5, 53.4 GWd 4.55% 3cy, 8yr 978.2 W	Zirlo, 54.3 GWd 4.25% 3cy, 11yr 914.4 W	Zirlo, 51.9 GWd 4.25% 3cy, 13yr 799.5 W			DRAIN PORT
5	3F6	6 (TC Lance)	30A	22B	20B	5K6	5D5
	Zirlo, 52.1 GWd 4.25% 3cy, 13yr 800.9 W	M5, 52.0 GWd 4.55% 3cy, 6yr 1008.6 W	M5, 51.2 GWd 4.55% 3cy, 5 yr 1142.4 W	M5, 50.5 GWd 4.55% 3cy, 5 yr 1121.2 W	M5, 53.3 GWd 4.55% 3cy, 8yr 975.1 W	Zirlo, 55.5 GWd 4.2% 3cy, 17yr 814.5 W	
11 Vent Port	5D9	12	28B	13	F40	57A	30B
	Zirlo, 54.6 GWd 4.2% 3cy, 17yr 802.6 W	M5, 51.0 GWd 4.55% 3cy, 5 yr 1135.0 W	Zirc-4, 50.6 GWd 3.59% 3cy, 30yr 573.8 W	M5, 52.2 GWd 4.55% 3cy, 8yr 1037.0 W	M5, 50.6 GWd 4.55% 3cy, 5 yr 1124.8 W	M5, 51.8 GWd 4.55% 3cy, 8 yr 941.3 W	
17	5K7	18	50B	19 (TC Lance)	3U9	0A4*	15B
	M5, 53.3 GWd 4.55% 3cy, 8yr 961.7 W	M5, 50.9 GWd 4.55% 3cy, 5 yr 1131.1 W	M5, 50.9 GWd 4.55% 3cy, 5 yr 1131.1 W	Zirlo, 53.1 GWd 4.45% 3cy, 10yr 920.2 W	Low-Sn Zy-4, 50 GWd 4.9% 2cy, 22yr 646.2 W	M5, 51.0 GWd 4.55% 3cy, 5 yr 1135.8 W	6K4
							M5, 51.9 GWd 4.55% 3cy, 8 yr 941.2 W
23	3T2	24 (TC Lance)	3U4	25	56B	26	54B
	Zirlo, 55.1 GWd 4.25% 3cy, 11yr 934.7 W	Zirlo, 52.9 GWd 4.45% 3cy, 10yr 914.2 W	M5, 51.0 GWd 4.55% 3cy, 5 yr 1133.7 W	M5, 51.3 GWd 4.55% 3cy, 5 yr 1136.3 W	M5, 53.5 GWd 4.4% 3cy, 8yrs 988.2 W		3U6
							Zirlo, 53.0 GWd 4.45% 3cy, 10yr 916.9 W
29	4V4	30	5K1	31 (TC Lance)	5T9	4F1	
	M5, 51.2 GWd 4.40% 3cy, 8yr 914.2 W	M5, 53.0 GWd 4.55% 3cy, 8yr 968.0 W	Zirlo, 54.9 GWd 4.25% 3cy, 11yr 927.7 W	Zirlo, 52.3 GWd 4.25% 3cy, 13yr 804.3 W			High Priority Assys

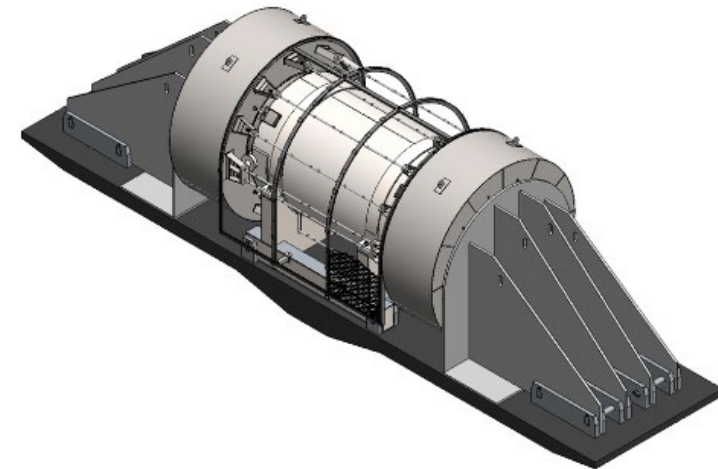
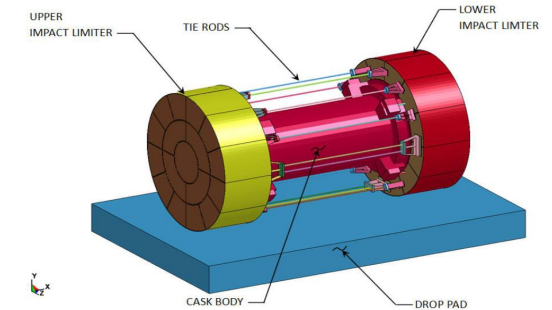
Loading Pattern



ORNL Report: SFWD-SFST-2017-000003

HBU Demo – Current Contract

- Project team
 - EPRI (w/OFS, TN, Dominion, Framatome)
 - US DOE, NLs, NRC, IRT
- Scope:
 - Continue monitoring
 - Obtain transport license
 - Transportation plan (describe approach)
 - Prep cask for shipment
 - Obtain gas sample
 - Load on conveyance

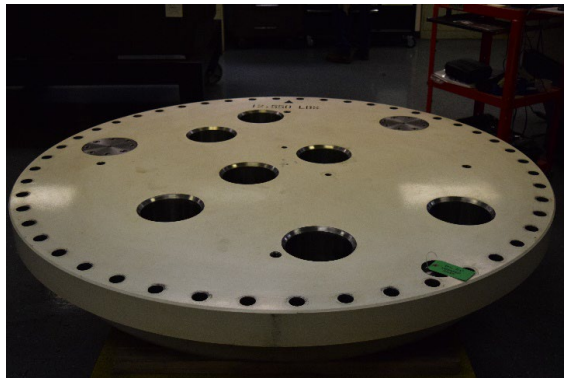


High Burnup Research Project Cask

- Used an existing TN-32 bolted metal cask
 - Originally fabricated in 2003
- Modified cask
 - Machined holes in lid for thermocouples
 - Installed impact limiter brackets
 - Used existing vent port for gas samples
- Licensed cask for storage at North Anna



Original nameplate



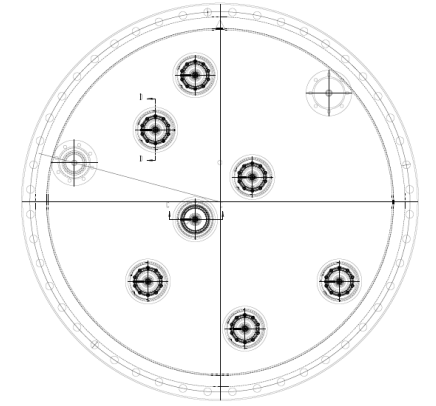
Machining holes in lid



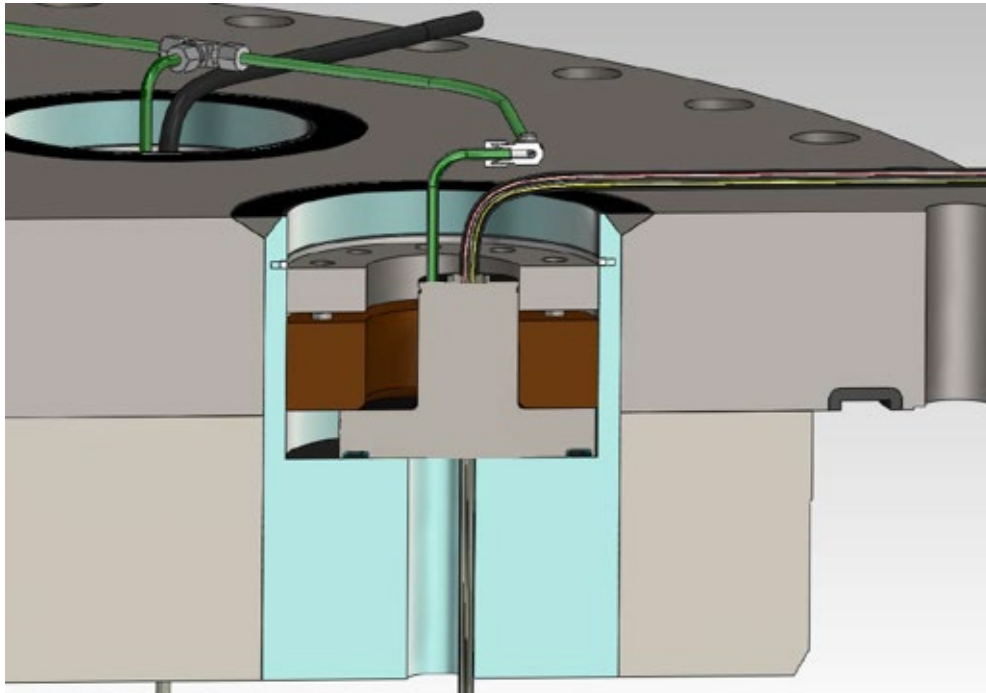
Vent port with quick-connect

Thermocouples

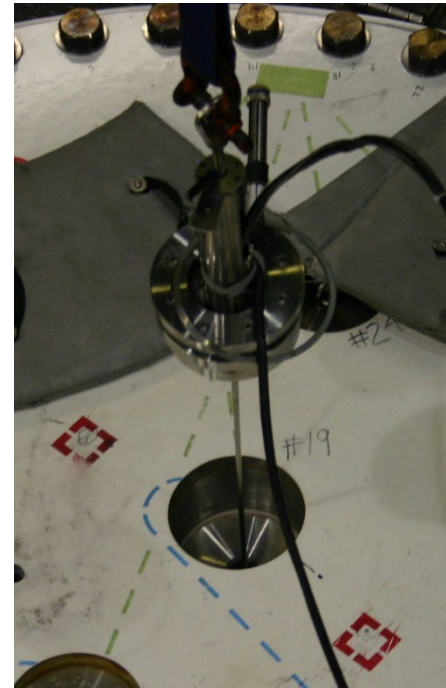
- 63 Thermocouples - 7 lances with 9 axial TCs each
- Installed into guide tube location after loading
- Jacking plate and double metallic o-ring for confinement



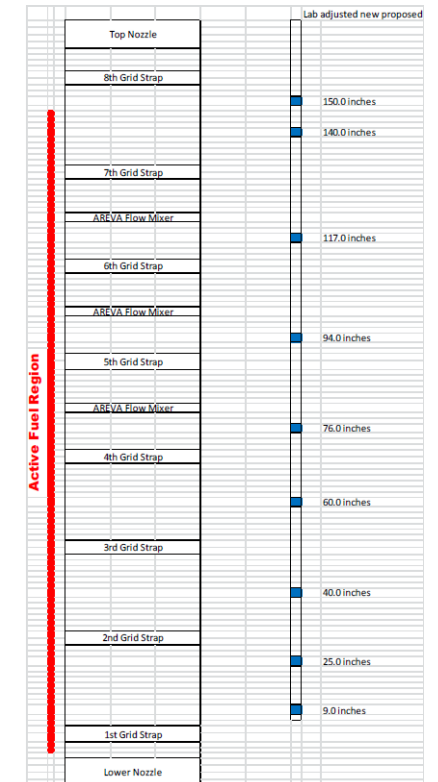
Thermocouple radial locations



Thermocouple closure assembly



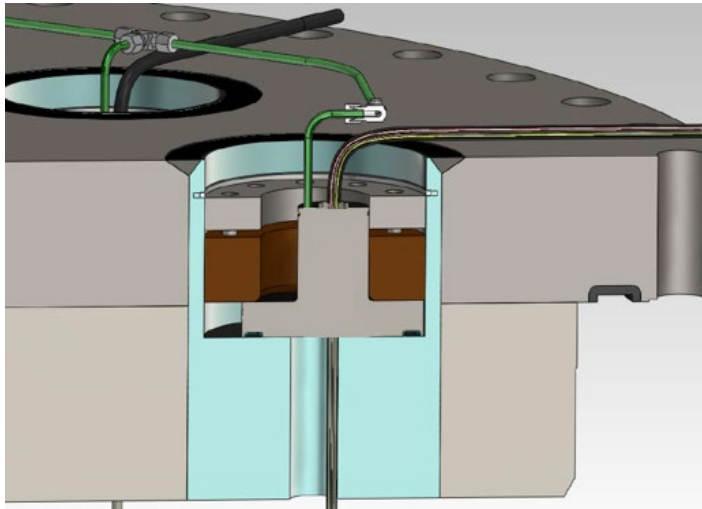
Installing thermocouple
(used with permission from Dominion Energy)



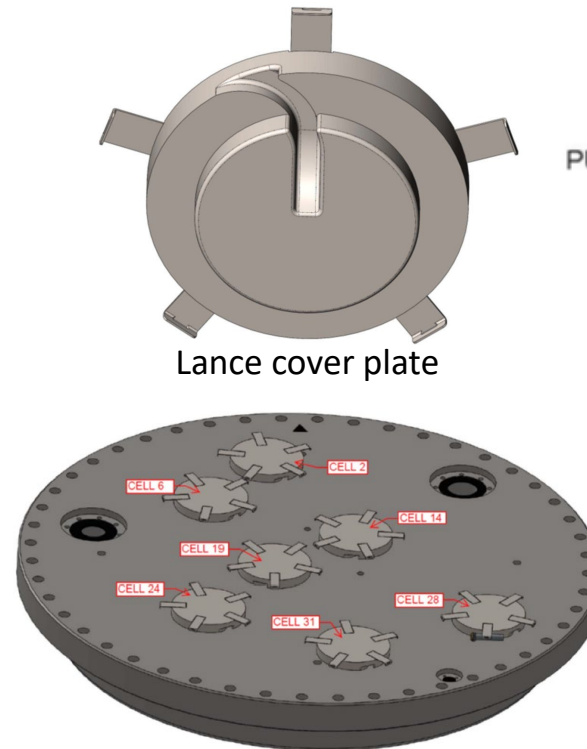
Thermocouple axial locations

Transport Configuration for Thermocouples

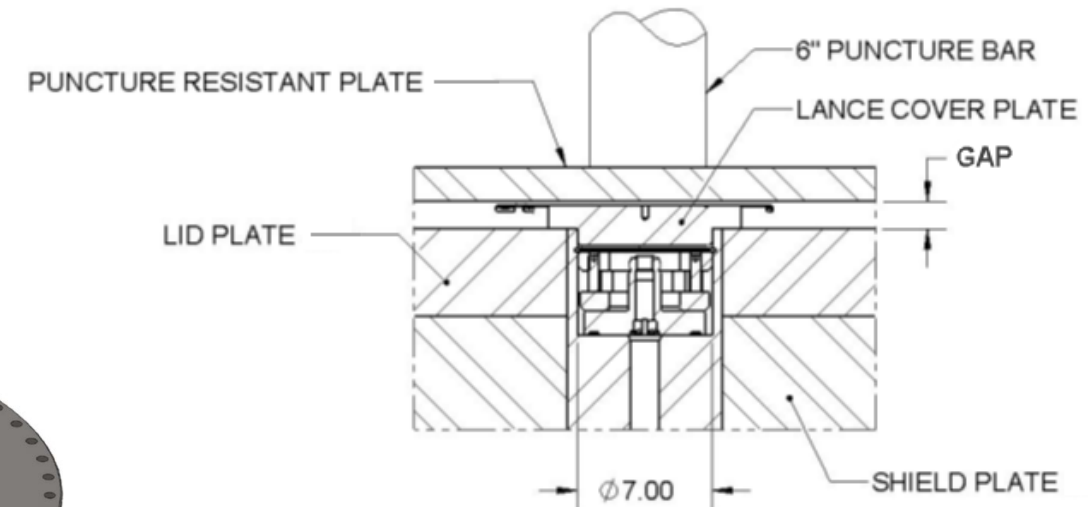
- Ship in current configuration with thermocouple as containment boundary
 - Install lance cover plate and puncture resistant plate



Thermocouple in storage configuration



Lid with lance cover plates installed



Thermocouple in transport configuration

Fuel Details - Summary

- 32 assemblies – 17x17
- Burnup: 50.0 – 55.5 GWd/MTU (52.4 average)
- Enrichment: 3.59 – 4.55 (4.40 average)
- Discharge dates: Apr 1987 to March 2012
 - Cooling time at loading: 5.7 – 30.6 years (10.6 average)
 - Cooling time 7/1/2027: 15.3 – 40.2 years (20.2 average)
- Decay heat at loading: 0.57 – 1.14 kW (0.95 average) – 30.5 kW total
- Decay heat 7/1/2027: 0.48 – 0.79 kW (0.73 average) – 23.5 kW total
- Loading 14.98 MTU total
- Components installed
 - 7 thermocouple lances
 - 6 poison rod assemblies

Clad Type	Qty	Burnup Range
Zr-4	1	50.6
low tin Zr-4	1	50
Zirlo	12	51.9 - 55.5
M5	18	50.5 - 53.5

Fuel Selection - Loading Pattern

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 912.2 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 978.2 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 914.4 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 799.5 W	
					DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 800.9 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1008.6 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1142.4 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1121.2 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 975.1 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 814.5 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 802.6 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.0 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 573.8 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1037.0 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1124.8 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 941.3 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 961.7 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1131.1 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 920.2 W	20 0A4* Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 646.2 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.8 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 941.2 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 934.7 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 914.2 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1133.7 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1136.3 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 988.2 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 916.9 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 914.2 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 968.0 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 927.7 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 804.3 W	High Priority Assys

KEY
Location (Thermocouple)
Assy ID (high priority)
Cladding , BU
Enr, #cycles, Yrs cooled
Decay Heat (loading), (transport)

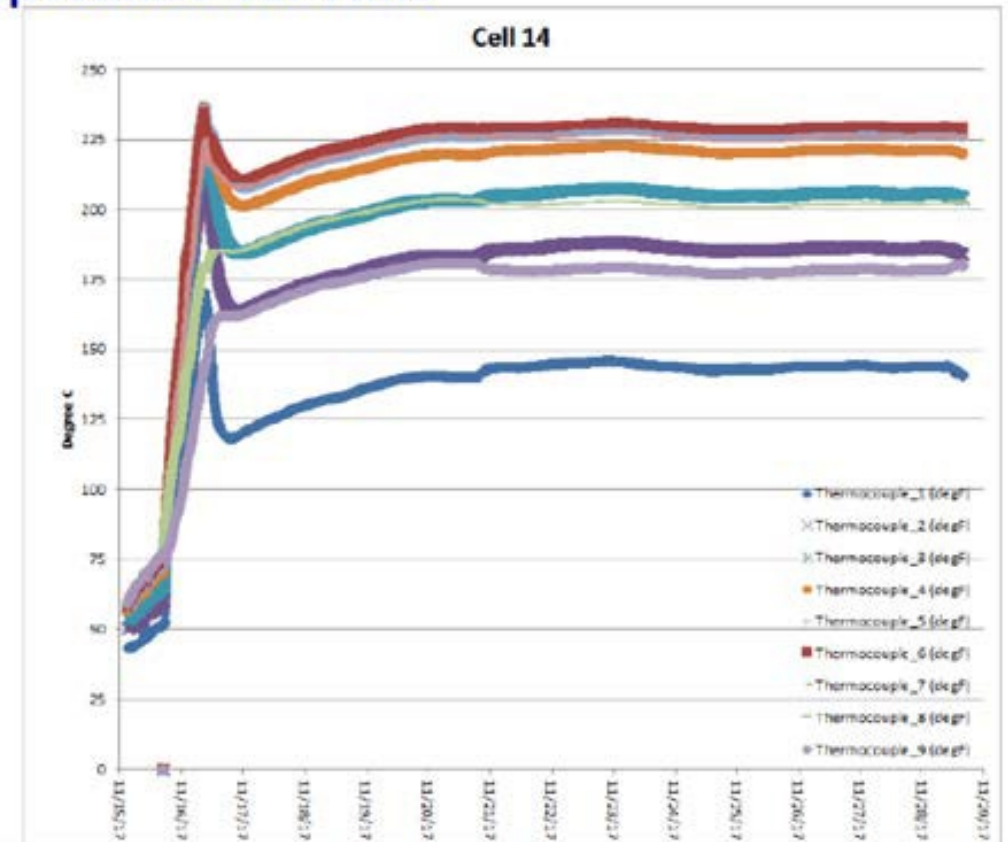
Clad Type	Qty	Burnup Range
Zr-4	1	50.6
low tin Zr-4	1	50
Zirlo	12	51.9 - 55.5
M5	18	50.5 - 53.5

High Burnup Research Project

Detailed modeling shows considerable margin between design basis loading and actual loading resulting in lower temperatures than expected



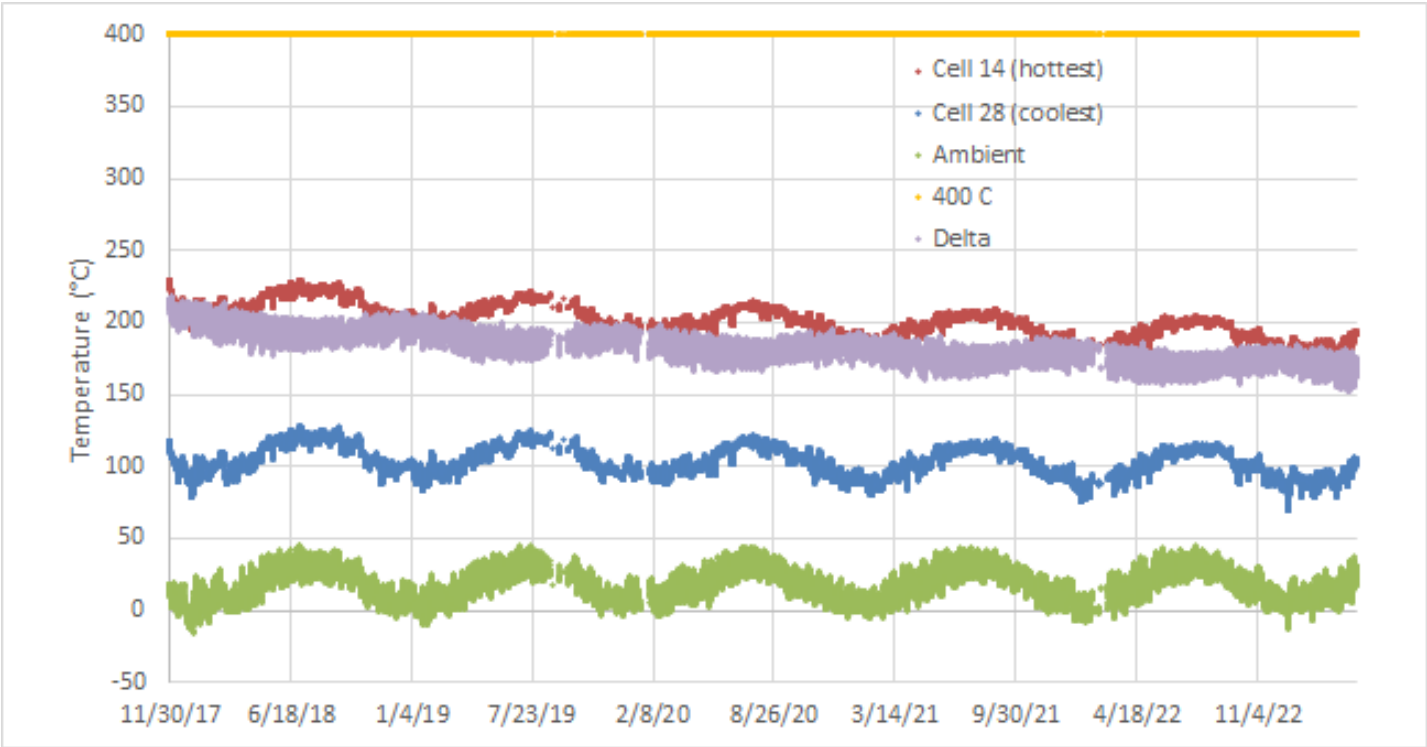
Temperature vs. Time



HBU Project – Temperature Monitoring Data

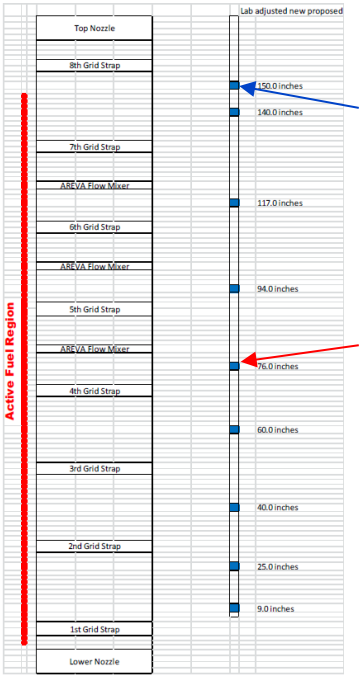
- Data continues to be collected and uploaded semi-annually

	1	2	3	4	
5	6	7	8	9	10
11	12	13	14	15	16
17	18	19	20	21	22
23	24	25	26	27	28
	29	30	31	32	



Temperature for hottest and coolest thermocouple
Nov-2017 to Apr-2023

First 5 years:
~6 ½ °C drop per year
Dependent on:
■ cooling time
■ location

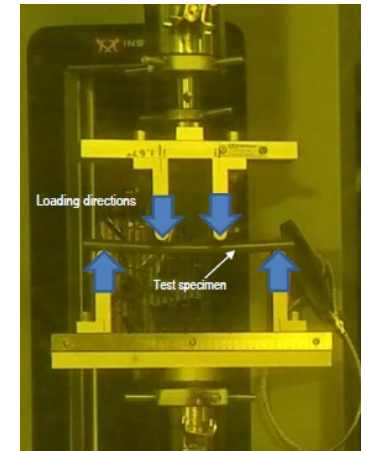


HBU Demo – Sister Rods

- Sister rods
 - 25 sister rods shipped to ORNL Jan 2016
 - Determine initial condition of the fuel
 - Perform separate effects tests for closing data gaps
 - Phase 1 of sister rod testing complete and results published
 - Nondestructive: ORNL/SPR-2017/484 Rev. 1
 - Destructive:
 - ORNL/SPR-2022/2678
 - PNNL-33781
 - Phase 2 final test plan published 9/15/23 (SAND2023-09981R)
 - Focus on creep and annealing
 - Phase 2 testing being reevaluated
 - Testing on hold for now



Courtesy NAC International

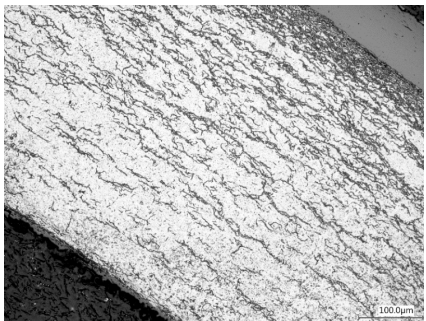


Load frame for 4-point bend test
ORNL/SPR-2022/2678

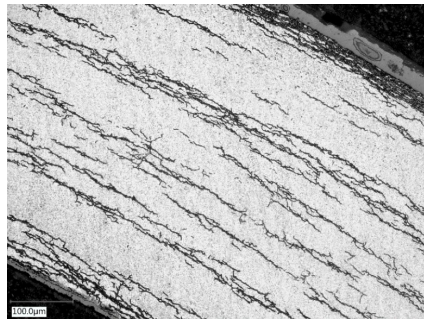
High level industry support for Phase 2 testing

HBU Sister Rod Testing Examples

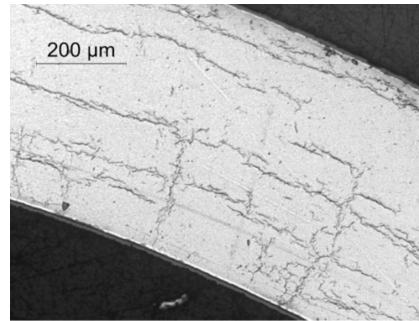
- Sister rod testing at Oak Ridge Nat'l Lab
 - Heat treated 3 rods to 400°C
 - Observed higher permeability
 - Observed lower fatigue life
 - M5 developed longer radial hydrides



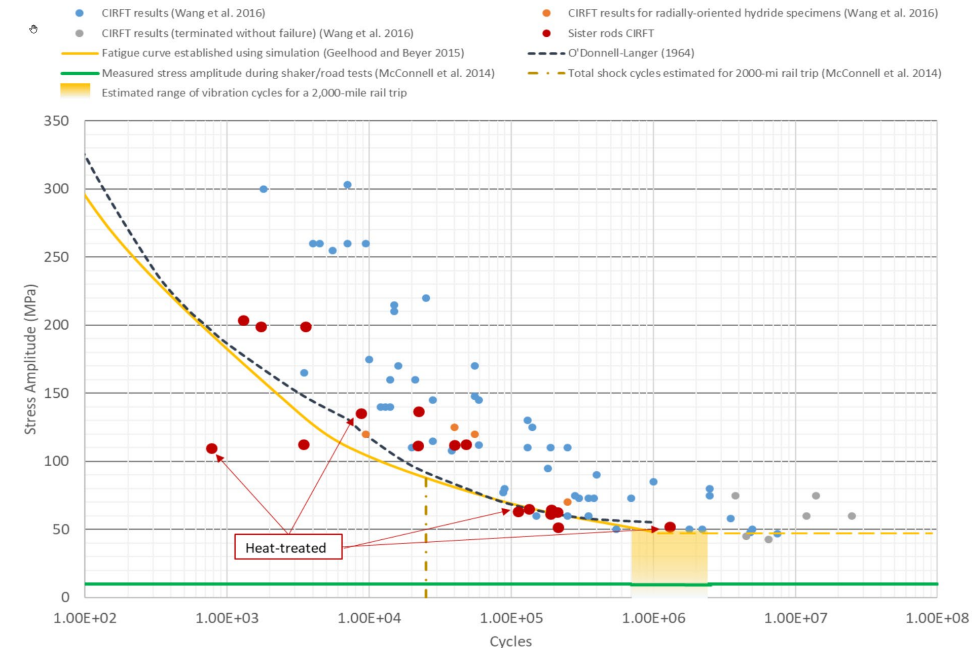
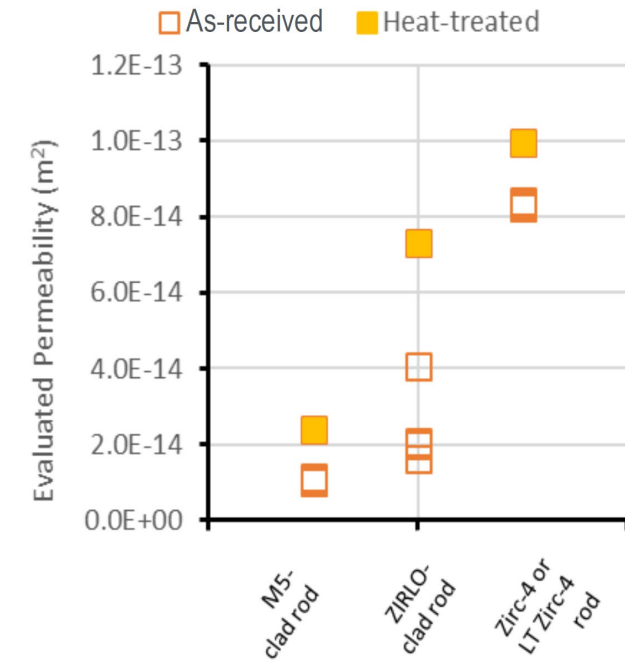
Zr-4



Zirlo

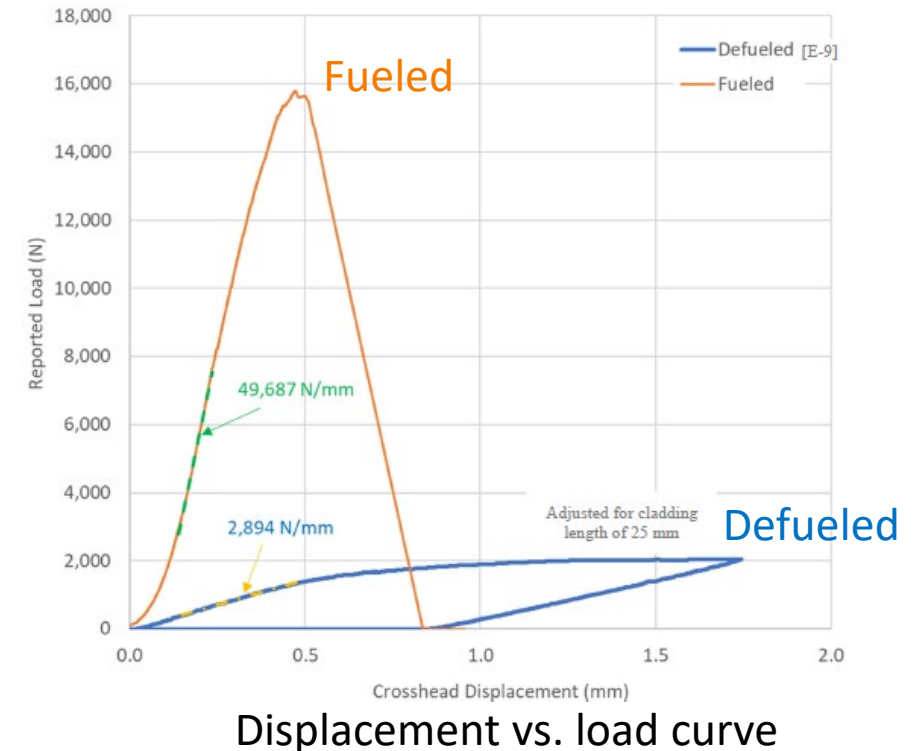


M5



HBU Sister Rod Testing Examples

- Sister rod testing at Oak Ridge Nat'l Lab
 - First ever fueled compression test
 - 8 times the load capacity vs. defueled
 - Fuel release from rod fracture (4-point bend)
 - Total < 5 mg and respirable < 0.5 mg
 - Fission gas release 1.6 - 3.6%
 - Compared to 30% assumed in NUREG-2215



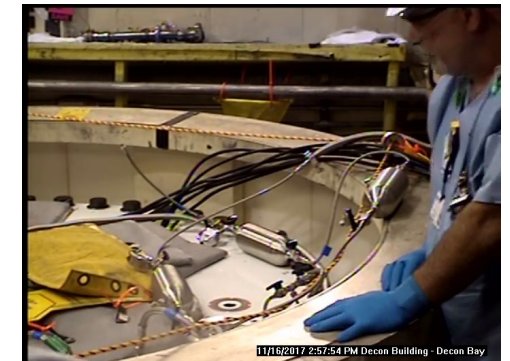
Measured data indicates significant conservatism in many analyses

HBU Project – Shipment Planning

- Completion of HBU Demo project requires shipping cask, opening dry and inspecting fuel
- Final gas sample to be collected prior to shipment
 - Gas sample to confirm no rod failures during storage period
- Shipment in 2027 is a top priority for DOE and EPRI
 - Shipment will go to Idaho National Laboratory (INL)
 - Follow up rod retrieval from the cask and testing will be conducted at INL



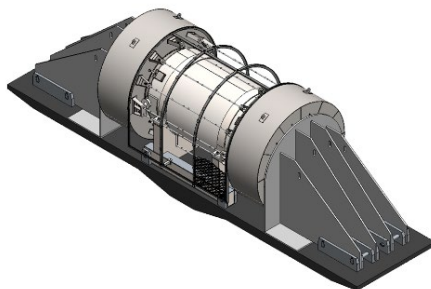
EPRI Report 1002882



Collecting gas sample during loading



Wood material for impact limiters



Shipping frame



TN-32B cask at EPRI

Available for dry run



Example transload operation



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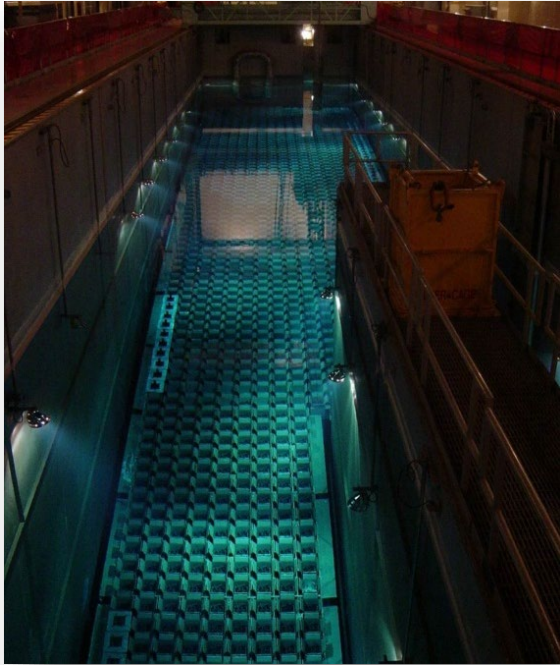
Advancements in SFP Criticality for Existing LWR Fuels and Roadmap for Advanced LWR Fuels



Hatice Akkurt, PhD
Senior Technical Executive

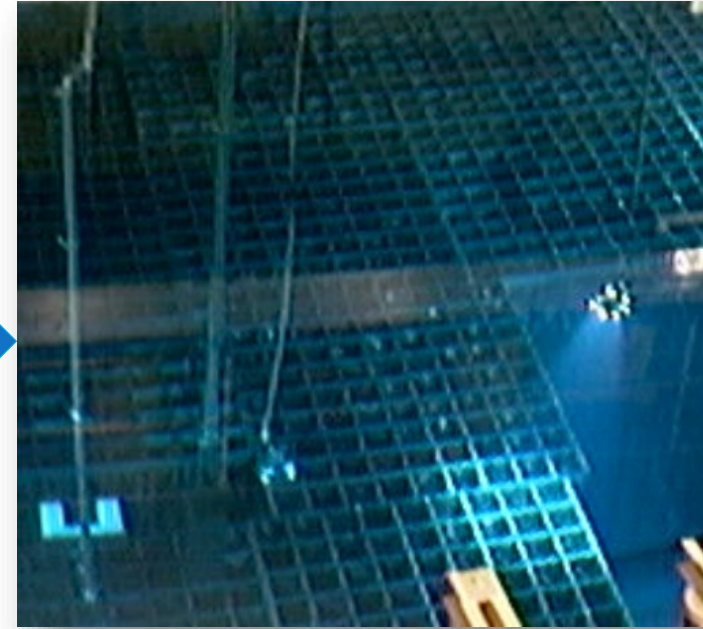
China Workshop
October 13-15, 2025

Spent Fuel Pool (SFP) Criticality



Storage Capacity:
~600 Fuel Assemblies

Increased
demand for SFP
storage space



Storage Capacity: ~1500-
2000 Fuel Assemblies

1) Burnup
credit

2) Neutron
absorber
materials
(NAMs)

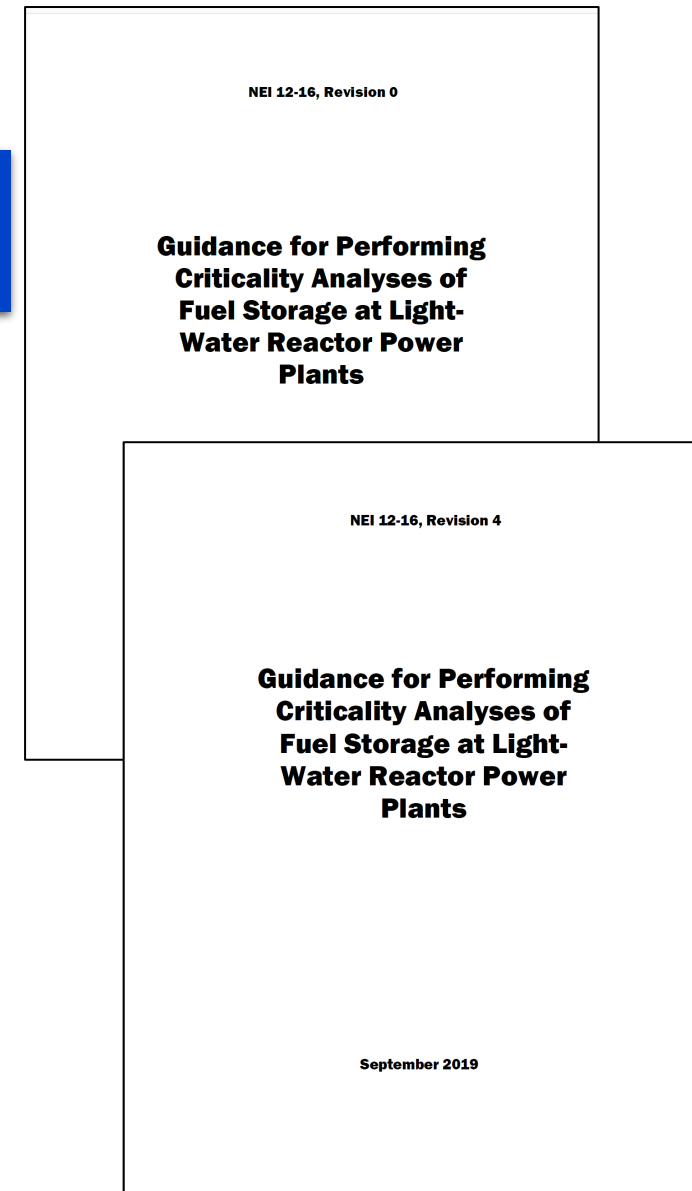
- Relying on spacing for Criticality control, **easy to analyze and justify criticality safety margins**
- As the need for more storage needed, **SFPs were re-racked, sometimes, in batches even using different NAMs**

- **As the SFP criticality became more complex, preparation of application and regulatory review time increased significantly over time**
- **Guidance and consistency was needed for the applicants and reviewers**

NEI 12-16: Criticality Guidance Document

NEI 12-16 Objective: Provide durable guidance for consistent and simplified criticality analysis for applicants and reviewers

- Historically, Spent Fuel Pool (SFP) Criticality Safety Analyses (CSA) were simple but over time they became more complex
- Increased application complexity with no comprehensive guidelines for application preparation, expectations, and the review process
 - More NRC Requests for Additional Information (RAIs)
- NEI 12-16 project inventoried, categorized, evaluated, and reached agreement on numerous issues
 - Initially, NAM monitoring was part of NEI 12-16; NRC and industry agreed that guidance on NAM monitoring should be stand alone and moved to NEI 16-03: Guidance for NAM monitoring for SFPs
- NRC, industry and EPRI put significant efforts toward the development and review of NEI 12-16 over time
 - **Many public meetings, multiple round of RAIs, and one week long audit**



NEI 12-16, Revision 0 was submitted to the NRC in March 2013, fee waiver granted in August 2013 and review cycle started in September 2013. EPRI Benchmarks were reviewed under NEI 12-16 umbrella.

NEI 12-16- Appendix C – Criticality Analysis Checklist

NEI 12-16, Revision 3
March 2018

- **Criticality analysis checklist** prepared, during one week long audit, and included as **Appendix C in NEI 12-16, Revision 2 in January 2017.**
 - Checklist is 6 pages long and follows the order of NEI 12-16 content
- **Objectives of the checklist are:**
 - Provides useful guidance to the applicant to ensure that all the applicable subject areas are addressed in the application
 - If not, provide justification for alternative approaches
 - Assist the regulator during review in identifying areas of the analysis that conform or do not conform to the guidance in NEI 12-16

APPENDIX C: CRITICALITY ANALYSIS CHECKLIST

The criticality analysis checklist is completed by the applicant prior to submittal to the NRC. It provides a useful guide to the applicant to ensure that all the applicable subject areas are addressed in the application, or to provide justification/identification of alternative approaches.

The checklist also assists the NRC reviewer in identifying areas of the analysis that conform or do not conform to the guidance in NEI 12-16. Subsequently, the NRC review can then be more efficiently focused on those areas that deviate from NEI 12-16 and the justification for those deviations.

Subject	Included	Notes / Explanation
1.0 Introduction and Overview		
Purpose of submittal	YES/NO	
Changes requested	YES/NO	
Summary of physical changes	YES/NO	
Summary of Tech Spec changes	YES/NO	
Summary of analytical scope	YES/NO	
2.0 Acceptance Criteria and Regulatory Guidance		
Summary of requirements and guidance	YES/NO	
Requirements documents referenced	YES/NO	
Guidance documents referenced	YES/NO	
Acceptance criteria described	YES/NO	
3.0 Reactor and Fuel Design Description		
Describe reactor operating parameters	YES/NO	
Describe all fuel in pool	YES/NO	
Geometric dimensions (Nominal and Tolerances)	YES/NO	
Schematic of guide tube patterns	YES/NO	
Material compositions	YES/NO	
Describe future fuel to be covered	YES/NO	
Geometric dimensions (Nominal and Tolerances)	YES/NO	
Schematic of guide tube patterns	YES/NO	
Material compositions	YES/NO	
Describe all fuel inserts	YES/NO	
Geometric Dimensions (Nominal and Tolerances)	YES/NO	
Schematic (axial/cross-section)	YES/NO	
Material compositions	YES/NO	
Describe non-standard fuel	YES/NO	
Geometric dimensions	YES/NO	

Primary objective of the checklist was to improve efficiency for the applicant and reviewer

SFP Criticality

$$k_{max} = k_{eff} + \sum_{i=0}^m Bias_i + \sqrt{\sum_{j=0}^n Uncertainty_j^2}$$

Uncertainties are statistically combined (assuming that such uncertainties are mutually independent) while biases are summed up

Uncertainties

- **Depletion Code Uncertainty**
- Criticality Code Validation Uncertainty
- Fuel Manufacturing Tolerances
- Rack Manufacturing Tolerances
- Burnup Uncertainty (BU)
- Facility Structural and Material Uncertainties
- Uncertainties for Validation Gaps
- Monte Carlo Calculational Uncertainty

Biases

- **Depletion Code Bias** (Applicant Depletion Code Bias)
- Criticality Code Validation Bias
- Moderator Temperature Bias
- Design Basis Fuel Assembly Bias
- Eccentric Positioning Bias

How to address depletion uncertainty and bias was one of the primary challenges

Depletion Uncertainty and Bias

- No critical experiments using spent fuel
- Critical experiments are very expensive
- Using fresh fuel assumption for spent fuel is overly penalizing and causes loss of SFP storage space
- How to account for uncertainty and bias for spent fuel?

1998 Kopp Memo:

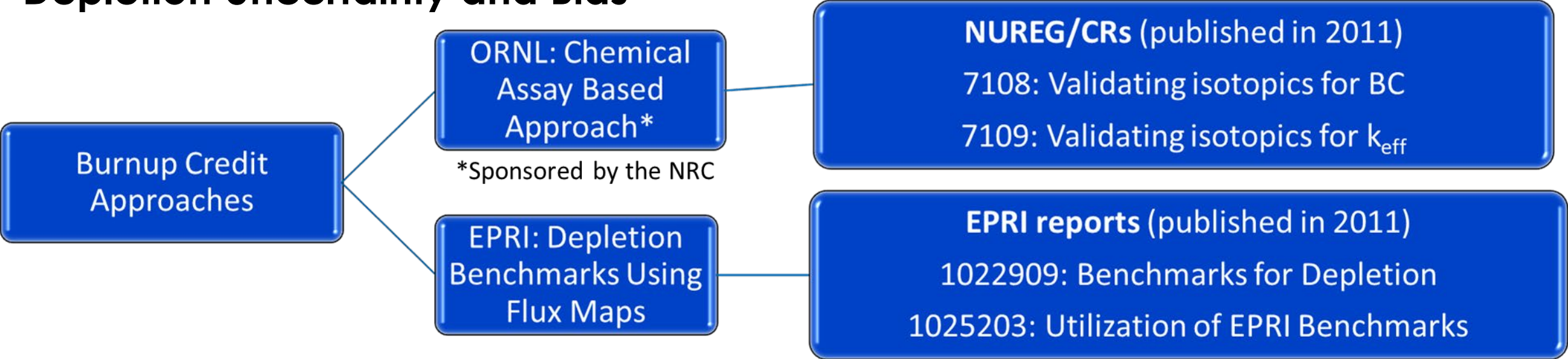
“In the absence of any other determination of the depletion uncertainty, an uncertainty equal to 5 percent of the reactivity decrement to the burnup of interest is an acceptable assumption.”

1998-2009

Easy to use, implement, justify; subsequently, used by many utilities

NRC: What is the technical justification or where is the documentation for 5% decrement?

Depletion Uncertainty and Bias



Chemical Assay Based Approach

- Limited data with large experimental errors
- Consequently, large operational penalties
- Loss of storage space

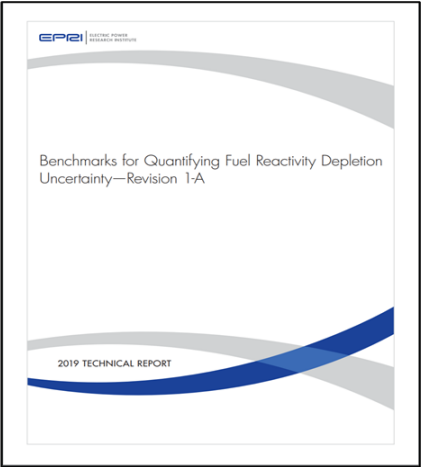
Flux Maps Based Approach

- Flux maps provide **high precision (<1% statistical error)** measurements
- Based on operational data from 4 PWR units and 44 cycles
- Development of benchmarks from measured data required significant analysis

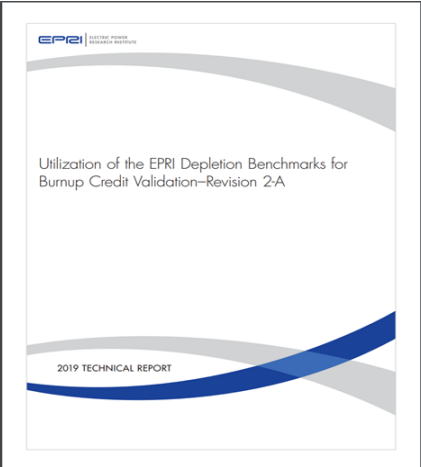
Loss of storage space in SFPs is a major concern for utilities

EPRI Benchmarks: Final SER and –A Reports

Received final SER on July 26, 2019



3002016035, *Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty-Revision 1-A*, published **September 18, 2019**



3002017254, *Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation - Revision 2-A*, published **September 18, 2019**

Burnup (GWD/MTU)	EPRI Uncertainty (%)	Additional NRC Bias (%)
10	3.05	0.0
20	2.66	0.0
30	2.33	0.0
40	2.12	0.15
50	1.95	0.35
60	1.81	0.54

- Revision-A reports include:
 - Final Safety Evaluation report (SER), as received from the NRC
 - Draft SER
 - Comments on draft SER, provided by EPRI and the industry, and comment resolution tables, generated by the NRC
 - Earlier versions of the EPRI reports
 - All RAIs (multiple round)
 - All RAI responses
- Revision-A reports were published and submitted to the NRC in September 2019.
- EPRI reports and Revision-A reports are publicly available for download from epri.com



EPRI benchmarks showed that Kopp memo (5%) is conservative and provided technical justification for additional margins

EPRI Benchmarks for Depletion Uncertainty and Bias

Regulatory Approval (US)



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

January 6, 2020

Mr. Nima Ashkebaoussi
Director, Fuel Cycle Programs
Nuclear Energy Institute
1201 F Street, NW, Suite 1100
Washington, DC 20004

SUBJECT: VERIFICATION LETTER OF THE APPROVAL VERSION OF ELECTRIC POWER RESEARCH INSTITUTE (EPRI) TECHNICAL REPORT "BENCHMARKS FOR QUANTIFYING FUEL REACTIVITY DEPLETION UNCERTAINTY - REVISION 1-A" AND "UTILIZATION OF THE EPRI DEPLETION BENCHMARKS FOR BURNUP CREDIT VALIDATION - REVISION 2-A"

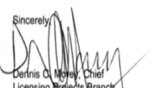
Dear Mr. McCullum:

By letter dated September 26, 2019 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML19269ED56), the Nuclear Energy Institute (NEI) and Electric Power Research Institute (EPRI) submitted an approval ("A") version of EPRI technical reports "Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty - Revision 1-A" and "Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation - Revision 2-A" to the U.S. Nuclear Regulatory Commission (NRC) staff. NEI and EPRI have done so in accordance with our request to publish approval proprietary and non-proprietary versions of these technical reports, as detailed in the transmittal letter dated July 19, 2019 (ADAMS Accession No. ML19186A112), of the NRC staff's final safety evaluations for the original technical reports.

The NRC staff has completed its review of the approval version of the technical reports. The NRC staff verified that NEI and EPRI have met the requirements and determined that the submitted "-A" versions are acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the accepted versions of the technical reports.

The technical reports are now approved for use in future licensing actions.

Please contact Jonathan G. Rowley of my staff at (301) 415-4053 if you have on questions on this subject.

Sincerely,

Dennis G. Meyer, Chief
Licensing Projects Branch
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation

Docket No. 99902028

The NRC staff has completed its review of the approval version of the technical reports. The NRC staff verified that NEI and EPRI have met the requirements and determined that the submitted "-A" versions are acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the accepted versions of the technical reports.

The technical reports are now approved for use in future licensing actions.

Received final approval letter from the NRC on January 6, 2020

OECD/NEA International Reactor Physics Benchmark Handbook

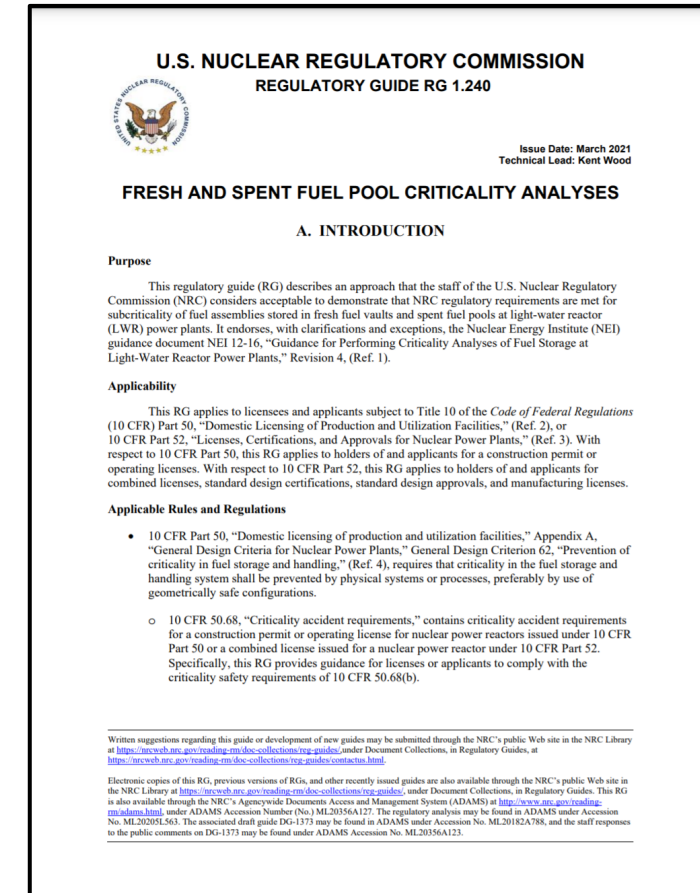
EPRI benchmarks were also reviewed by OECD/NEA International Reactor Physics handbook for Benchmark Evaluation (IRPhBE) Working group and approved for inclusion in the IRPhBE Handbook

Can be requested and downloaded from OECD/NEA website



NEI 12-16 Rev. 4 Endorsement via Regulatory Guide (RG) 1.240

- After the approval of the EPRI Benchmarks, section on depletion uncertainty and bias in NEI 12-16 was revised. Recommended two options:
 1. Use of 5% for reactivity decrement
 2. Use of EPRI benchmarks, if additional margin is desired
 - Use of EPRI benchmarks require additional analysis
- Draft Regulatory Guide (DG 1. 240) was issued in August 2020
 - Despite long review cycle, 15 exceptions and clarifications were included in draft RG
 - Comments were provided to the NRC
 - Several public meetings were conducted
 - ACRS meeting March 2021 was conducted
- Final RG 1.240 was issued in March 2021 after ACRS meeting



RG 1.240: ML20356A127

Regulatory Guide (RG) 1.240 – Area of applicability is limited for fuel up to 5% enrichment and 62 GWd/MTU

SFP Criticality for Existing LWR Fuels – Conclusions

- **Review cycle was very long**
- **EPRI benchmarks** provided technical bases for 5% reactivity decrement
 - Demonstrated additional margins exist and can be used by performing additional analysis
- **NEI 12-16 provides great framework**
 - Using checklist is very helpful and it is a tool that is being used for pre-application meetings
- **Recent experience with applications** showed that
 - Number of RAIs decreased substantially (0-3 RAIs compared to 60-80 RAIs and multiple round of RAIs in some cases)
 - Regulatory review is completed in 12-18 months

Despite very long review cycle, end products are being used by the utilities and seem to achieve its main objectives so far

Implementation by Utilities and Outcomes

- Regulatory review time:
 - 42 months → 15 months
- Number of RAIs:
 - Over 80 → 0 for 2 recent applications for Dominion
- Similar outcomes for Constellation and Callaway



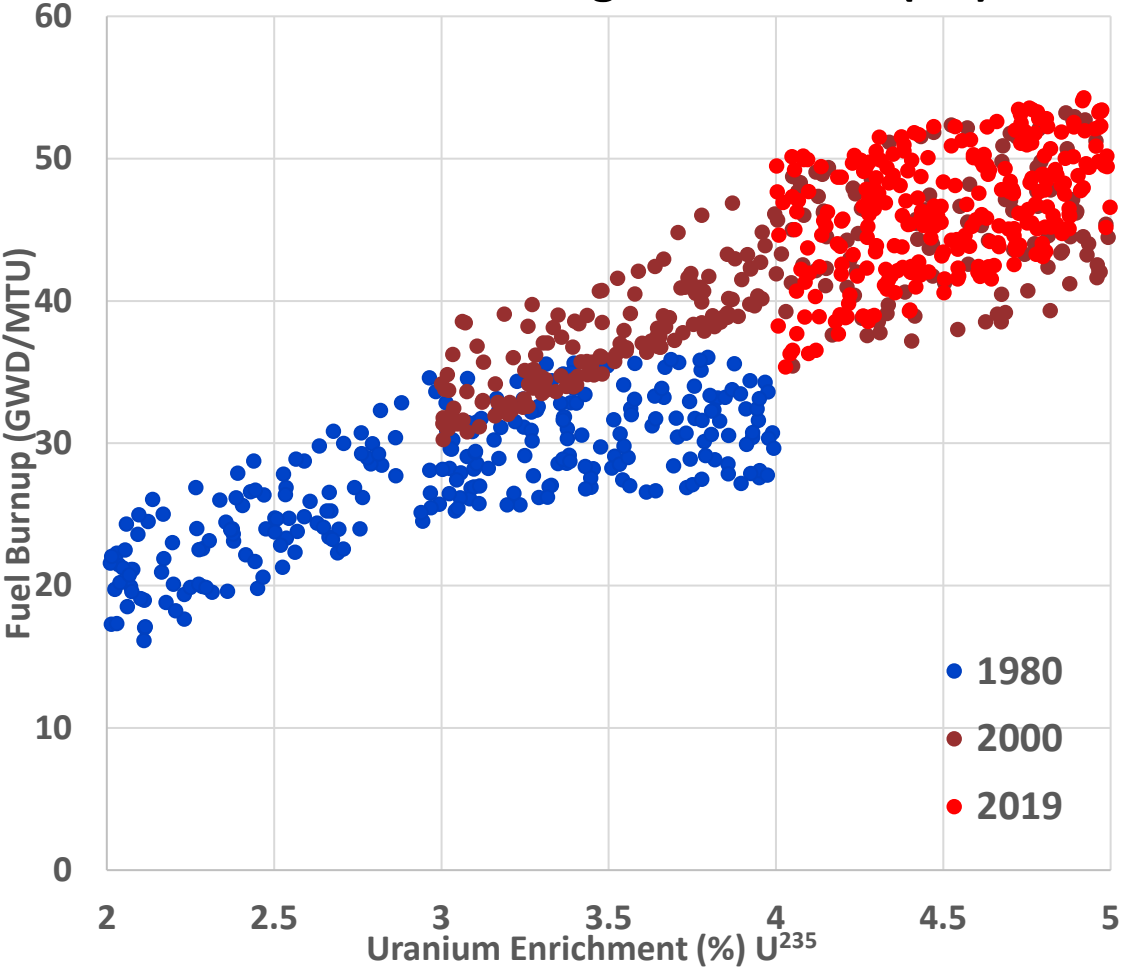
Congratulations to Dominion, Constellation, and Callaway for being first implementers and being one of the winners of the EPRI Tech Transfer Award in 2023



SFP Criticality for Advanced LWR Fuels (ATF/LEU+/HBU)

Spent Fuel Pool (SFP) Criticality for Advanced Fuels

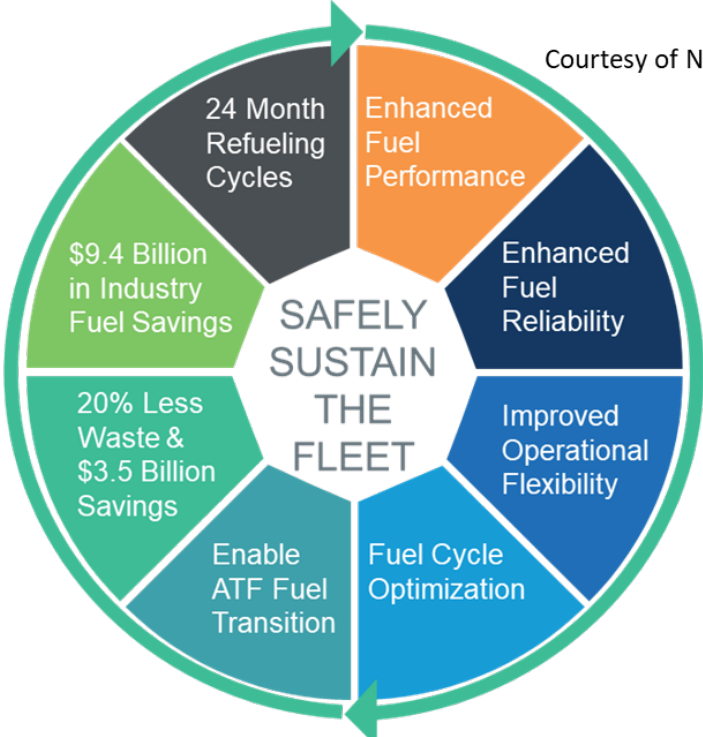
Evolution of Fuel Design Over Time (US)



Advanced Fuels refer to

1. Accident Tolerant Fuel (ATF) concepts
2. High Enrichment (HE) Fuel
3. High Burnup (HB) Fuel

Advanced Fuel Benefits



Advanced Fuels (ATF, HB, HE) requires new analysis for SFP and New Fuel Vault

EPRI ATF/LEU+/HBU Workshop - Review of Technical Readiness for Fresh and Spent Fuel Storage & Transportation

Objectives:

- To evaluate the technical readiness for near term implementation of ATF/LEU+/HB
 - Review of the significant amount of work already completed by numerous organizations, including EPRI, NRC, vendors, and utilities
 - Identify any remaining issues and develop a path forward

Desired Outcome:

- To identify a clear and timely path forward for NRC review and implementation of ATF/LEU+/HBU fuel by industry

ATF/LEU+/HBU Workshop

Focus Areas:

1. Overview of fuel types and specifications
 - Fuel changes and potential impact on criticality
2. Code system capabilities and validation of the codes
3. Depletion uncertainty
4. Use of RG 1.240 for new and used fuel storage (based on NEI 12-16 Criticality guidance)
5. Dry storage & Neutronic issues

Workshop Participation

- **Total number of registered attendees: 106 (37 in-person)**
- Representatives from 10 countries
 - Brazil, Czech, Canada, France, S. Korea, Spain, Sweden, Switzerland, UK, USA
- Representatives from
 - NRC
 - Utilities (US and non-US),
 - ORNL, INL, DOE
 - Fuel vendors (Westinghouse, GNF, Framatome)
 - Studsvik
 - NEI

ATF/HE/HBU Workshop – Review of Technical Readiness for Fresh and Spent Fuel Storage (Wet and Dry) & Transportation Structure

Day 1

- **General overview** – Industry perspectives and Fuel overviews
- **NRC Updates**; SCALE Updates; Criticality code validation

Day 2

- **Depletion uncertainty** (EPRI; ORNL; Comparison of results)
- **Code Validation** (Polaris and Parcs; Casm5 and Simulate5; Paragon2 and ANC)
- **Comparison of results from different codes** (Casm5 versus Triton/Newt versus Polaris)
- **Dry Storage and Transportation** – NRC Technical Readiness

Day 3

- **24 months versus 18 months** – Absorber and burnup profiles (Industry presentations)
- **Significance of ATF/HE/HBU: Fuel changes** (fuel vendor presentations)
- **Discussions** – to determine consensus on certain items, technical gaps, if any, and path forward

Aiming to develop an EPRI report on workshop to summarize key points and agreements

1. Fuel Features

1. ATF – Coatings

- Ongoing demonstrations of performance
- **Impact on reactivity slightly negative**

2. Dopants

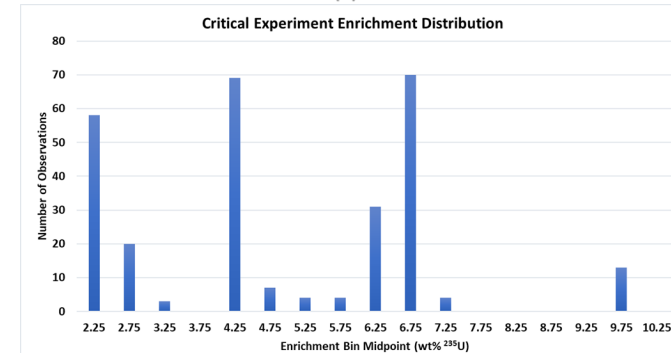
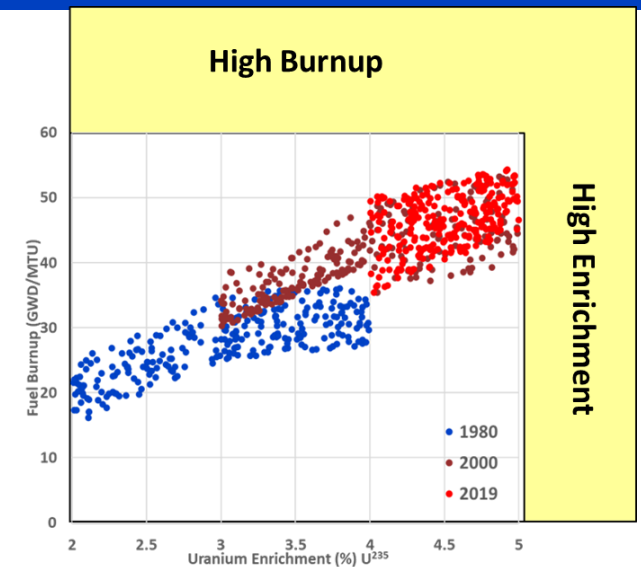
- Significant history in BWRs and ready for use
- Increased fuel density, similar trends with depletion (compared to undoped pellets), and lower fission gas release (considered in updated RG 1.183 Rev. 1)
- **Impact on reactivity: Small positive to small negative depending on the product**

3. LEU+

- Enrichments: $5\% < E < 8\%$, likely close to 6.5% for existing plants
- **Several transportation packages already approved**
- **Sufficient critical experiments for validation**

4. HBU

- $62 < BU < 80$, likely interim limit ~ 68 followed by goal of reaching to ~ 75
- **Newer materials show smaller physical changes during depletion, supporting HBU** (see graphs from vendor presentations for grid growth, clad oxidation, etc.)
- **Improved validation basis in 7303 – with the addition of more data and removal of high uncertainty data**



Significant number of experiments in the 5-8% range

Incremental improvements consistent with industry's history – no major changes for neutronics; gains for corrosion resistance

2. Readiness of Codes

1. Criticality codes

- Consensus: Scale/MCNP – no challenges
- Code validation: Enough critical experiments for LEU+ code validation

2. Depletion codes

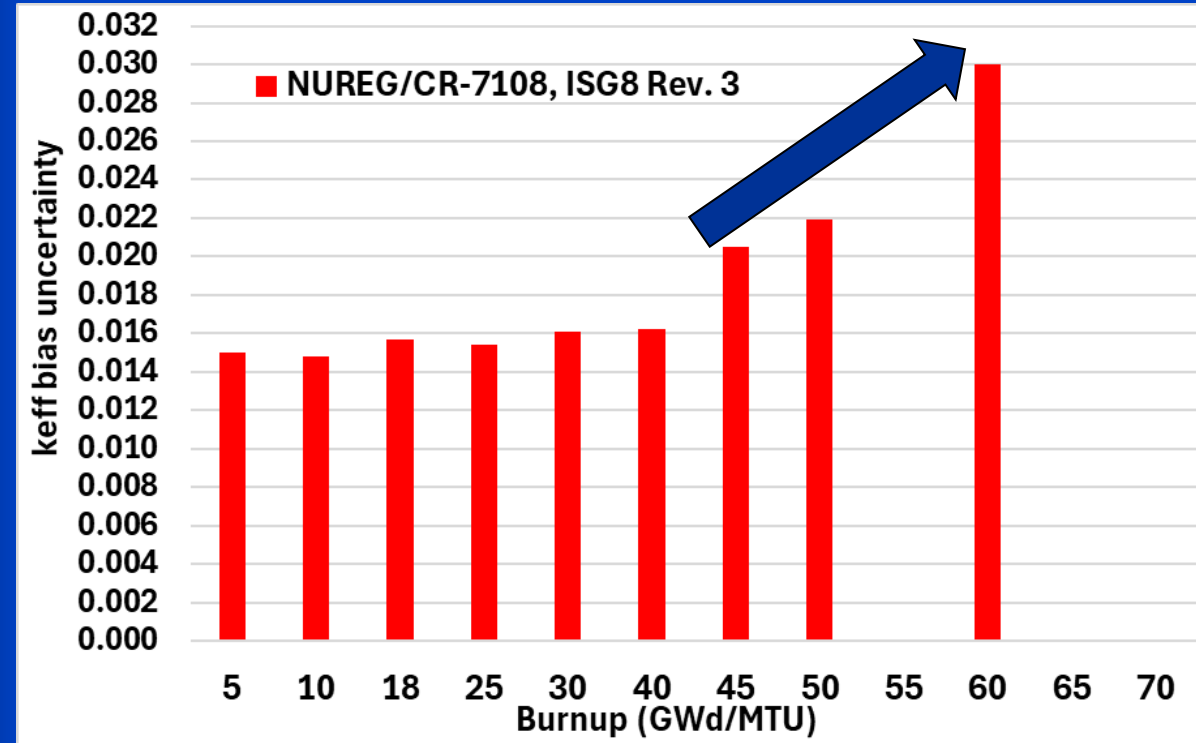
- Approved (PARAGON2, LANCR, etc.) or submitted for approval (CMS5)
- Confirmatory analysis by comparison to other codes (Polaris and/or Triton) – vetted/validated via NUREG/CRs

Codes and nuclear data does not show any cliff edge effects:

1. None of the codes required any modifications for ATF/LEU+/HBU
2. **Codes are in good agreement with each other as part of confirmatory analysis**

3. Depletion Uncertainty (DU) – NUREG/CR-7108

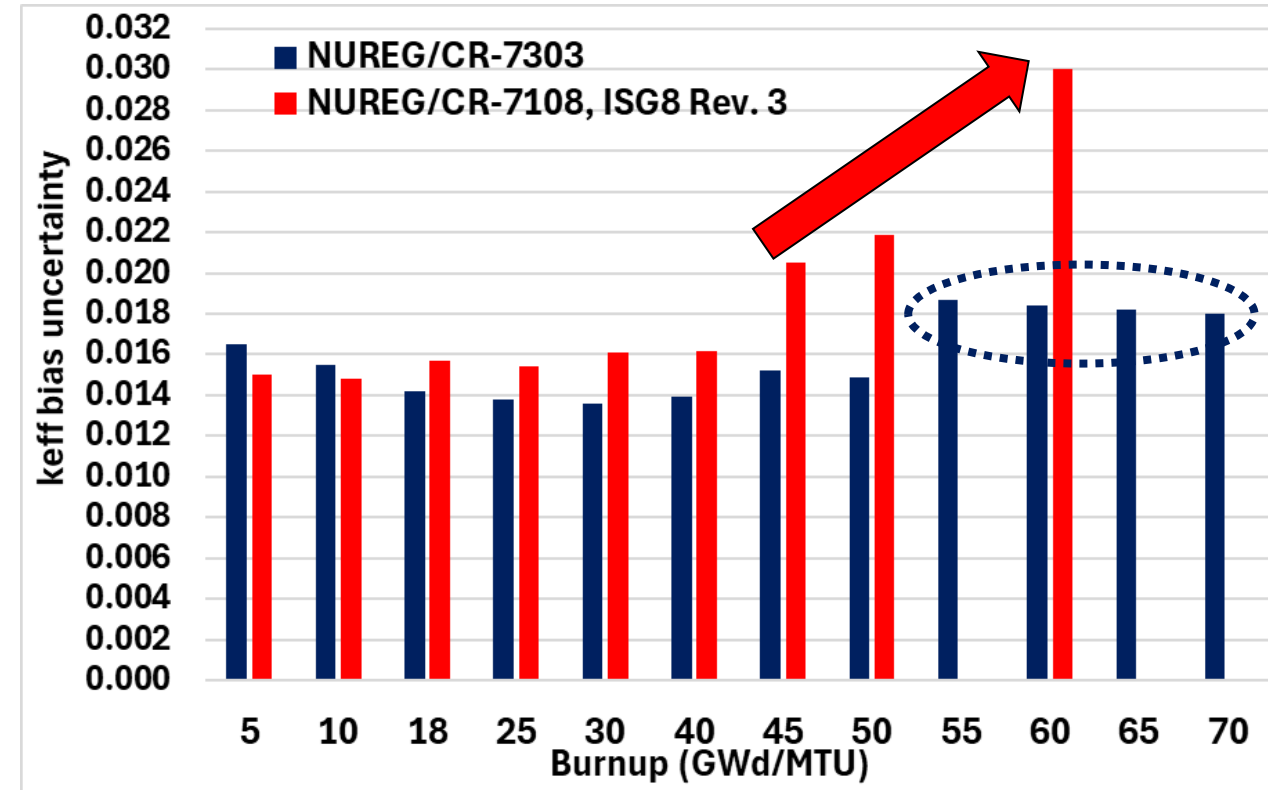
- NUREG/CR-7108 was published in 2012
- Based on chemical assay measurement → Large measurement uncertainty
- **Showed increase in uncertainty with increasing burnup**
 - NRC was concerned about cliff-edge effect beyond 60 GWD/MTU
- Showed **Kopp memo** (5% uncertainty in reactivity decrement) **is not conservative**
 - Caused significant challenges during EPRI Benchmark regulatory review
- **NUREG/CR-7108 was implemented via ISG-8, Rev. 3 (used for dry storage)**



Increase in depletion uncertainty with increasing burnup

3. Depletion Uncertainty (DU) – NUREG/CR-7108 versus 7303

- **NUREG/CR-7303 published in September 2023**
 - Added improved quality measurements
 - Excluded some low-quality measurements
- **NUREG/CR 7303 versus 7108**
 - 7303 shows significant reduction in depletion uncertainty compared to 7108
 - Increased enrichment and burnup does not increase depletion uncertainty
 - Results are still conservative due to lack of covariance and presence of RCA measurement uncertainty



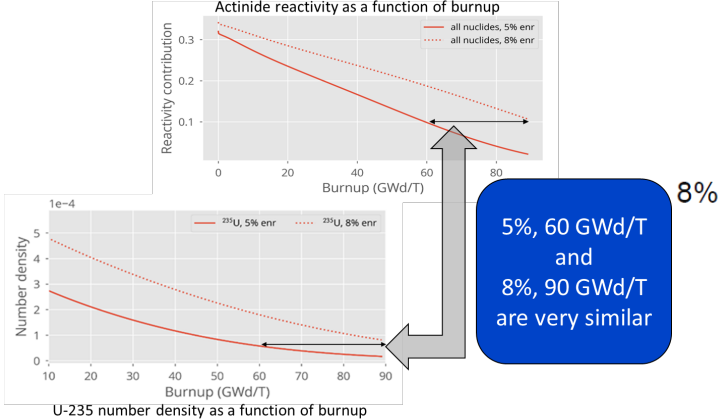
Key conclusion from 7303: Depletion uncertainty does not increase with increasing burnup – almost flat with slight decrease trend

3. Depletion Uncertainty (DU) – EPRI Benchmarks and Extension of EPRI Benchmarks

Regulator approved EPRI Benchmarks showed Kopp memo is conservative

Burnup (GWd/MTU)	Uncertainty (%)	Bias (%)
10	3.05	0.0
20	2.66	0.0
30	2.33	0.0
40	2.12	0.15
50	1.95	0.35
60	1.81	0.54

Valid up to 5% enrichment and 60 GWd/MTU Burnup



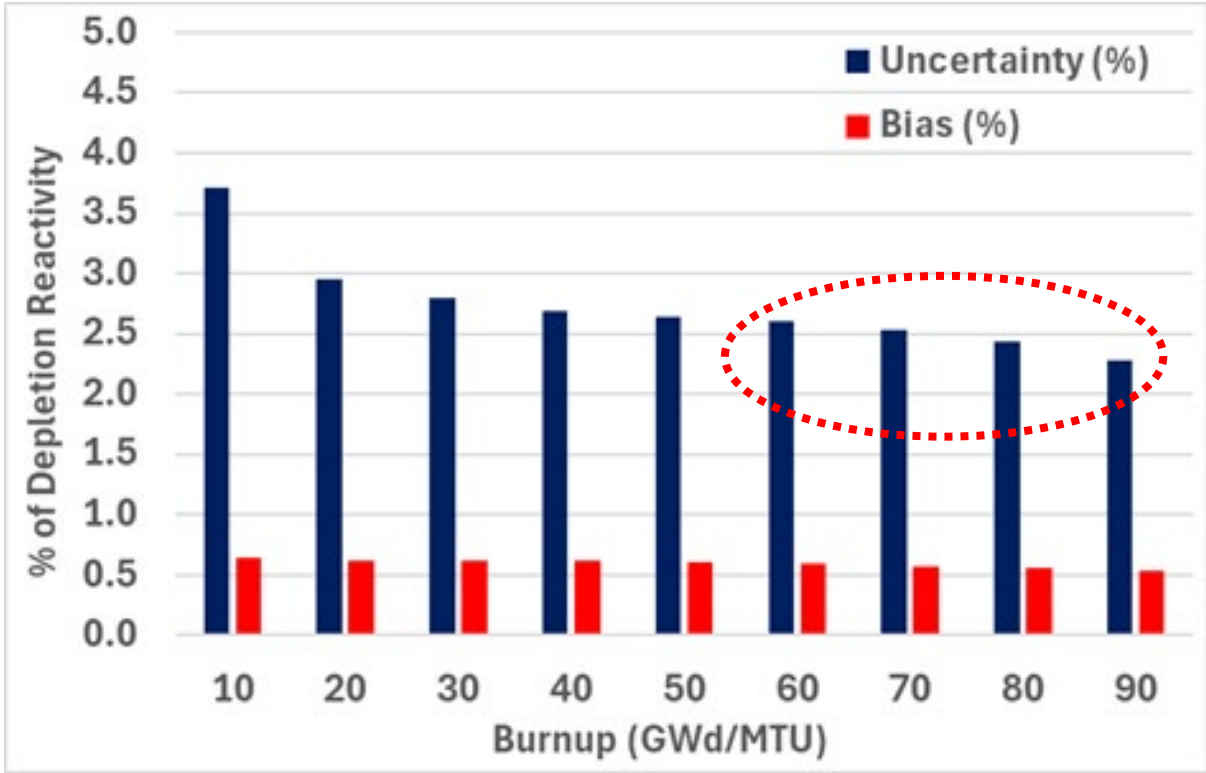
5%											
Bu	0	0.5	10	20	30	40	50	60	70	80	90
0	0.99	0.99	0.95	0.87	0.77	0.66	0.54	0.45	0.36	0.3	0.25
0.5	0.99	0.99	0.95	0.87	0.78	0.67	0.56	0.46	0.37	0.31	0.26
10	0.98	0.98	0.98	0.94	0.86	0.76	0.66	0.57	0.49	0.42	0.37
20	0.95	0.96	0.99	0.97	0.92	0.84	0.75	0.67	0.59	0.53	0.48
30	0.91	0.92	0.98	0.99	0.96	0.9	0.83	0.75	0.68	0.62	0.58
40	0.85	0.86	0.95	0.99	0.98	0.95	0.9	0.83	0.77	0.72	0.67
50	0.78	0.79	0.9	0.97	0.99	0.98	0.94	0.89	0.84	0.8	0.76
60	0.71	0.72	0.85	0.93	0.98	0.99	0.97	0.94	0.9	0.86	0.83
70	0.62	0.64	0.78	0.89	0.95	0.98	0.99	0.97	0.94	0.91	0.88
80	0.54	0.56	0.71	0.83	0.92	0.97	0.99	0.99	0.97	0.95	0.93
90	0.47	0.48	0.64	0.77	0.87	0.94	0.98	0.99	0.98	0.97	0.96

Extension of EPRI Benchmarks to LEU+/HBU - EPRI report, 3002026550

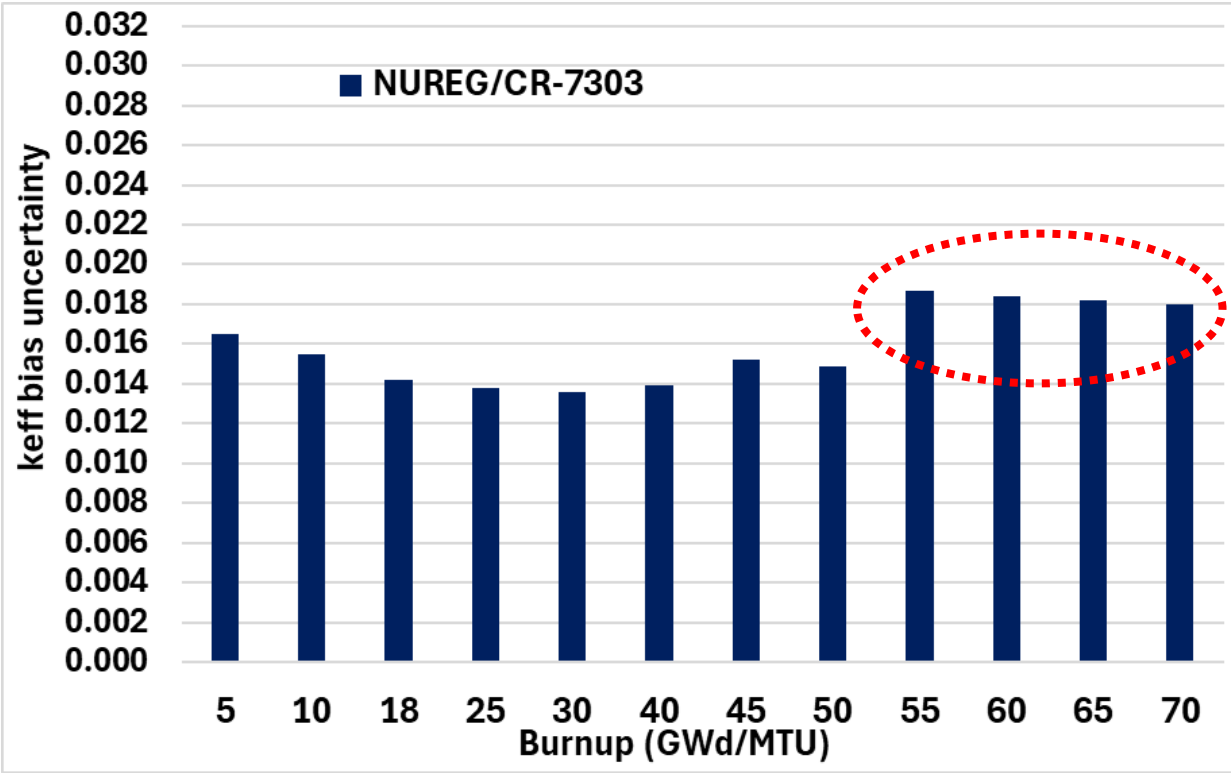
Burnup (GWd/MTU)	10	20	30	40	50	60	70	80	90
Bias (% of depletion reactivity)	0.64	0.62	0.62	0.62	0.61	0.59	0.57	0.56	0.54
Uncertainty (% of depletion reactivity)	3.7	3.0	2.8	2.7	2.6	2.6	2.5	2.4	2.3

Physics, similarity index does not show significant change for ATF/LEU+/HBU; hence, depletion uncertainty for LEU+/HBU << 5% Kopp memo

3. Depletion Uncertainty (DU) – EPRI Benchmark Extension versus NUREG/CR 7303



EPRI Benchmark Extension



Multiple results (7303, EPRI Benchmarks) show similar trends (no increase in depletion uncertainty with increasing burnup) and support continued use of 5% depletion uncertainty (Kopp memo) for ATF/LEU+/HBU

4. RG 1.240 Applicability for ATF/LEU+/HBU

- **Criticality code validation**
 - Can continue to use **NUREG/CR 6698** methodology – **Guidance still applies**
- **Depletion codes**
 - Licensing approach depends on if there is an approved TR (LEU+/HBU) – **Guidance still applies**
- **Depletion uncertainty (5% Kopp memo use)**
 - Multiple results (7303, EPRI Benchmarks) support continued use of 5% depletion uncertainty (Kopp memo) for ATF/LEU+/HBU – **Guidance still applies**
- **Unvalidated nuclides**
 - Conclusions in **NUREG/CR 7109** applies to LEU+/HBU – **Guidance still applies**
- **Fuel Assembly physical changes**
 - Values and trend may change - **Guidance still applies**
- **Axial Burnup Distributions**
 - Generic burnup shapes need to be confirmed for 24-month cycles – **Guidance still applies**
- **Eccentric positioning**
 - **Guidance continues to apply**
- **Multiple misloads**
 - **Guidance continues to apply**
- **Volatile fission products**
 - RG 1.183 Rev.1 covers doped pellets - **Guidance still applies**

There was consensus that guidance in RG 1.240 is applicable for ATF/LEU+/HBU despite the listed exception that states RG 1.240 is limited to 5% enrichment and 62 GWd/MTU



Upcoming EPRI & Industry Activities

Pre-submittal meetings – Key Items

- Dominion pre-submittal meeting was on July 17, 2025 and Duke pre-submittal meeting was on August 11, 2025
- Dominion used RG 1.240 along with the checklist
- Indicated will use 5% depletion uncertainty (Kopp memo)
- No major challenges on the use of RG 1.240 or Kopp memo expressed by the NRC
- Dominion timeline (based on pre-submittal meeting)
 - June 2026, submission of LAR
 - December 2027, expecting final approval from the NRC
 - Start date: May, 2028
 - Since fuel order is done ~9 months in advance, NRC agreed to provide status update in advance – especially if there are any major issues

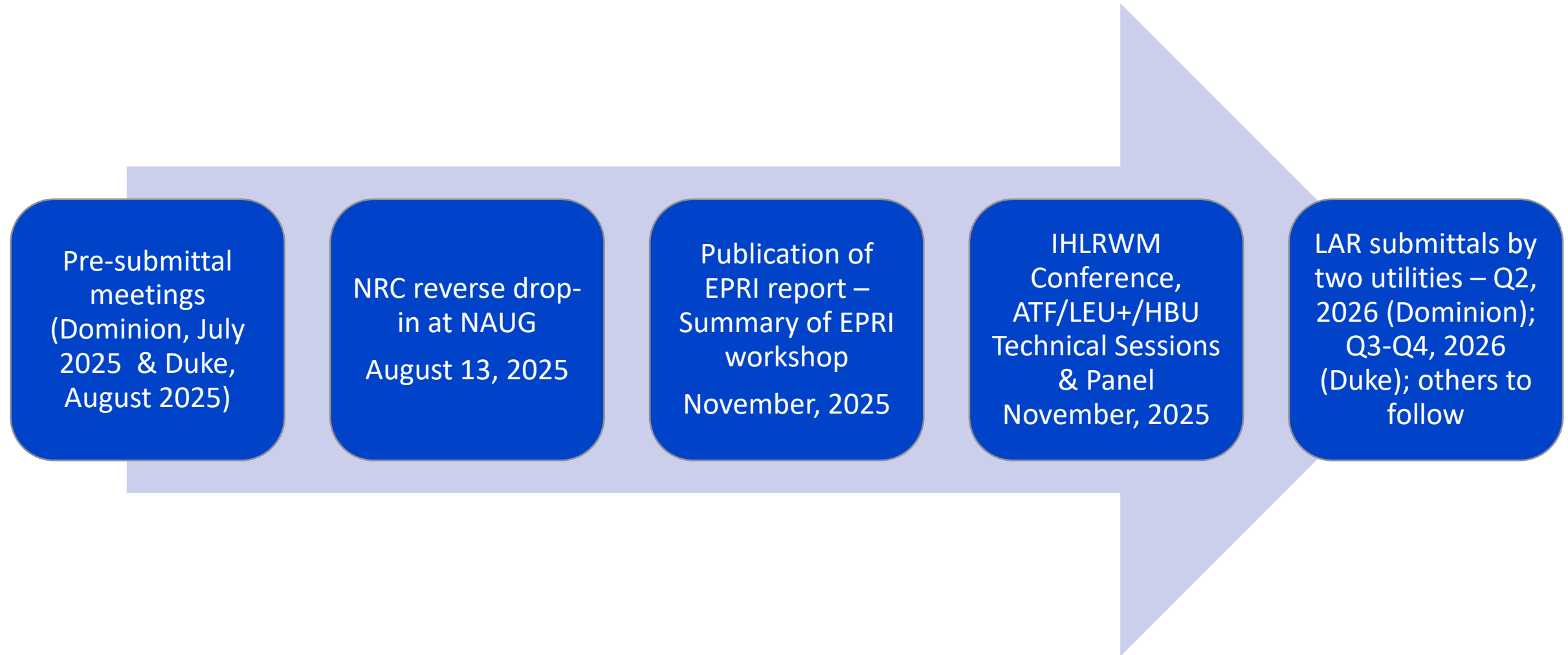
Dominion and Duke pre-submittal meetings went very well.

IHLRWM Sessions on ATF/LEU+/HBU

Paper Title	Authors
Evaluation of Technical Readiness for Fresh and Spent Fuel Wet and Dry Storage and Transportation of ATF/LEU+/HBU	Hatice Akkurt (EPRI)
Fuel Assembly Changes Impact on Spent Fuel Pool Criticality Analyses for LEU+ Applications	Michael Wenner (Westinghouse)
PWR 24-Month Cycle Characteristics for SFP Criticality Analyses	Kasey Kennett (Dominion) and David Orr (Duke)
CASMO5 Analysis of Select HTC Critical Experiments Simulating Burned Fuel	James William Carnal (UTK), Joshua Hykes and Rodolfo Ferrer (Studsvik)
Considerations for KENO Benchmark for Spent Fuel Pool Criticality Safety Analyses	David Orr and Robert Hall (Duke)
Application of Sampler to the LEU+ Burnup Credit Uncertainty Question	Robert Hall and David Orr (Duke)
Comparison of LEU+ Reactivity Decrements for SFP Burnup Credit	David Orr and Robert Hall (Duke)
Adequacy of 5% Depletion Uncertainty for LEU+/HBU SFP Burnup Credit	Hatice Akkurt (EPRI) and Robert Hall (EPRI Consultant)

In addition to technical sessions, organizing a panel session that includes NRC representative(s)

Next Steps for ATF/LEU+/HBU Implementation



EPRI workshop was instrumental in making progress for the regulatory review path



TOGETHER...SHAPING THE FUTURE OF ENERGY®

Spent Nuclear Fuel Dry Storage – Cask/Canister Integrity

Aging Management Program and Inspection guidance



Dr. Joe Faldowski, DBA, PMP
Sr. Program Manager

China Workshop
October 13-15, 2025

CISCC in DFSS

Research intensified by 2012 NRC Information Notice 2012-20

- Several incidents of CISCC observed in “in austenitic stainless steel components that were exposed to atmospheric conditions **near salt-water bodies.**” – Songs, St. Lucie, Turkey Point, and Koeberg
- Letter states “**no immediate safety concern** has been identified with currently approved licenses”
- Also, “the relationship between the proximity of the ISFSI to a salt-water body or other sources of chlorides, such as salted roads or condensed cooling tower water, and chloride-induced SCC initiation has not been defined”

In 2015 EPRI issued Technical Report 3002005371 – Susceptibility Assessment Criteria for CISCC of Welded Stainless Steel Canisters for Dry Cask Storage Systems

Multiple organizations continue to evaluate CISCC in DFSS experimentally, analytically, and operationally (inspections of systems in operation at ISFSIs)

- To date, no inspections have resulted in additional actions beyond trending

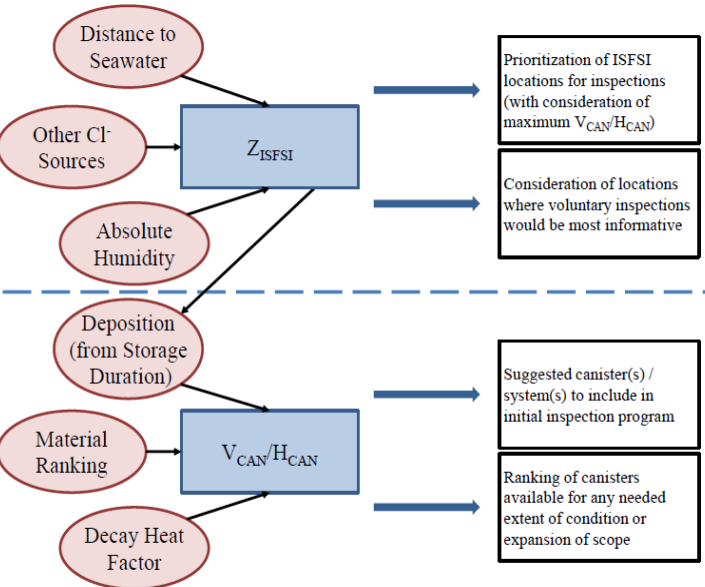
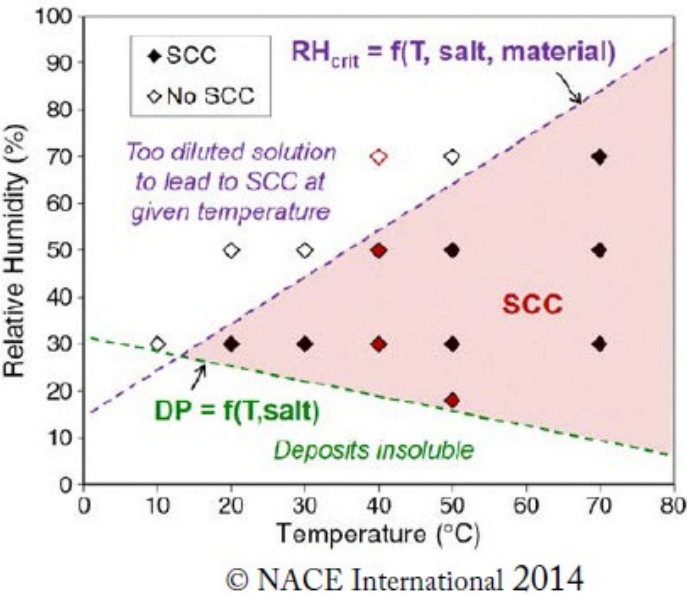
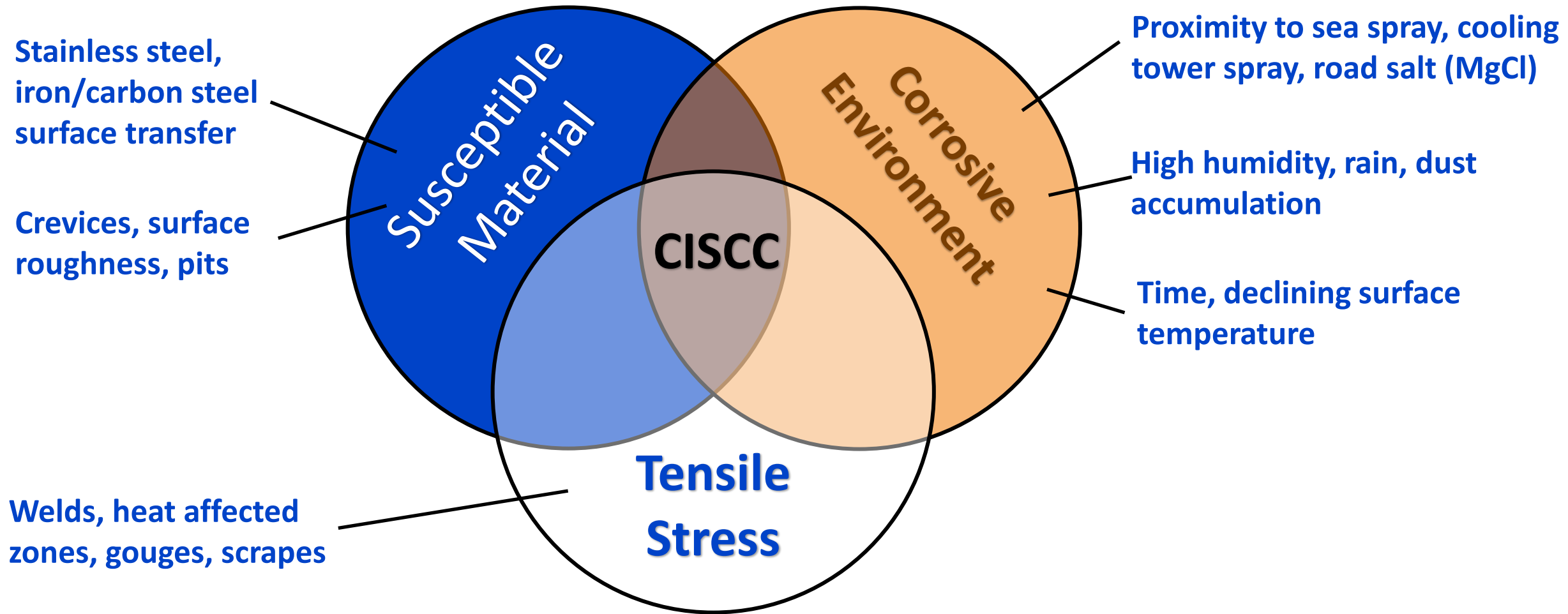


Figure 6-1
Summary of Susceptibility Assessment Criteria

The Central Aging Issue for SS Canisters: CISCC*



* Chloride Induced Stress Corrosion Cracking

CISCC is the first question to be answered in PRA:

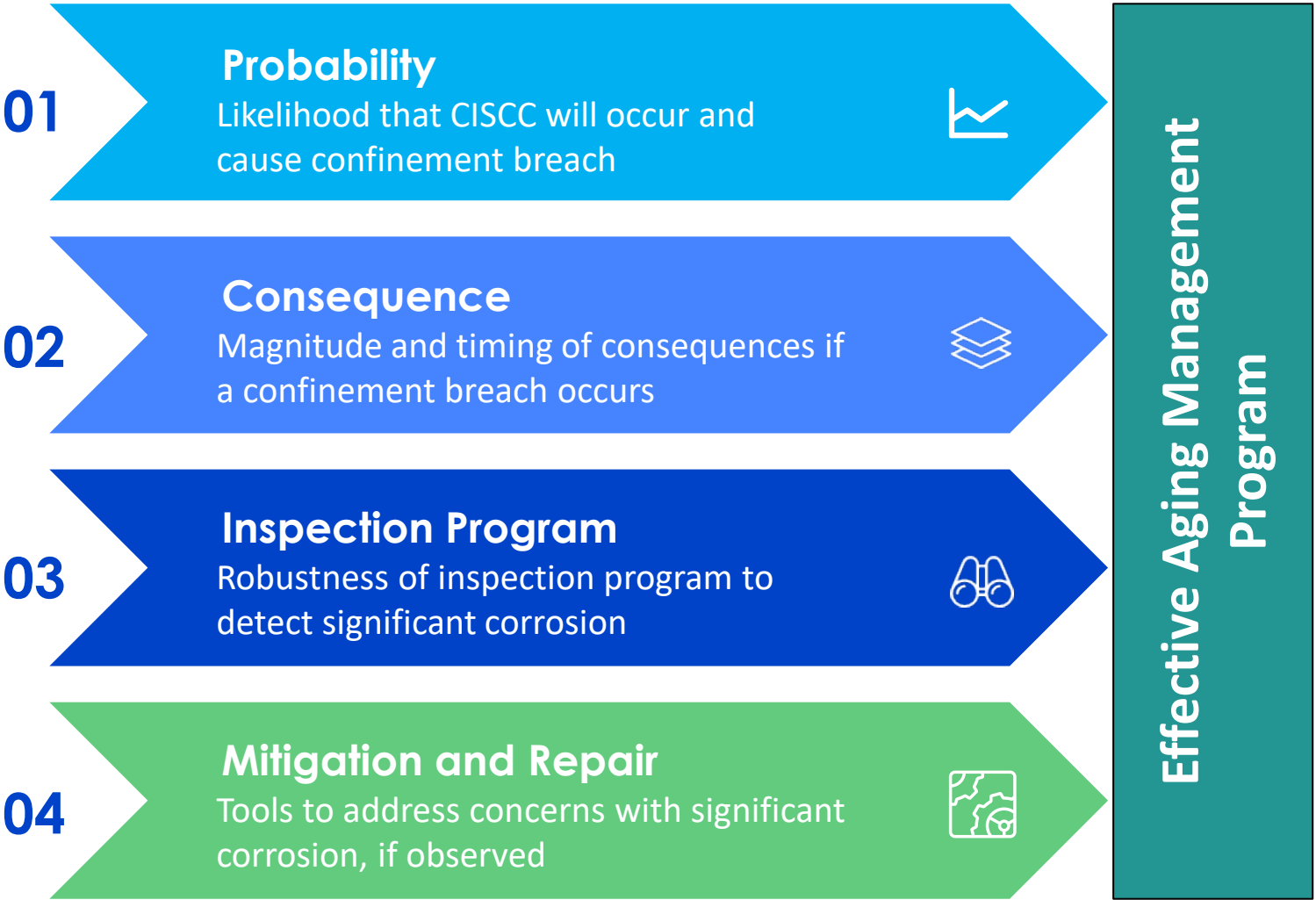
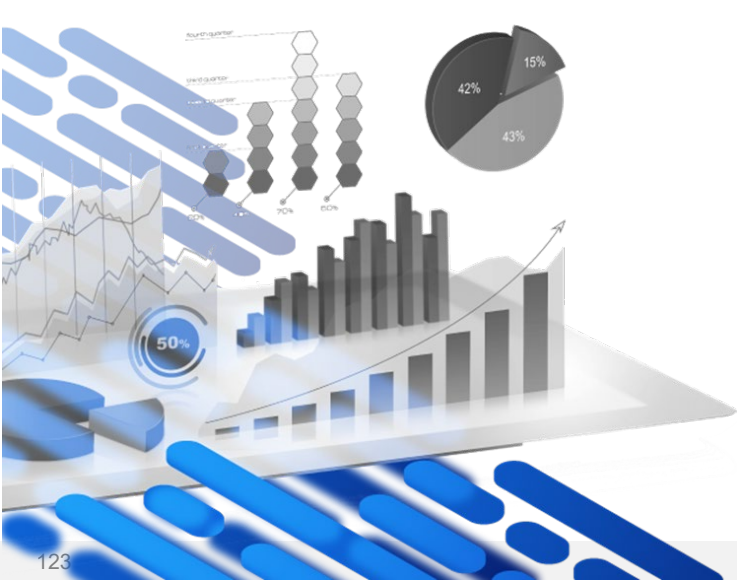
1. What can go wrong

Technical Letter Report TLR-RES/DE/CIB-2018-01

Research Framework

Criteria that allow for ranking of CISCC management effectiveness

A guide to coordinated, collaborative research leading to an end-point



Probability

Partially addressed by site susceptibility rankings in EPRI TR 3002005371

Recent empirical work at NL's focused on accelerated conditions due to long timeframes for corrosion under representative conditions

- MgCl found to be only relevant corrosive species
- Nitrates are a significant inhibitor to CISC

HAZ ~ 2.2% of canister surface => conditions must exist in this area or other susceptible area (e.g. scratches, gouges where stress exists)

Uncertainty remains

- Initiation mechanisms and timing under representative conditions
- Crack growth rates – deterministic vs. probabilistic fracture mechanics models

Probability is the second step question to be answered in PRA:

1. What can go wrong
2. How likely is it

Technical Letter Report TLR-RES/DE/CIB-2018-01

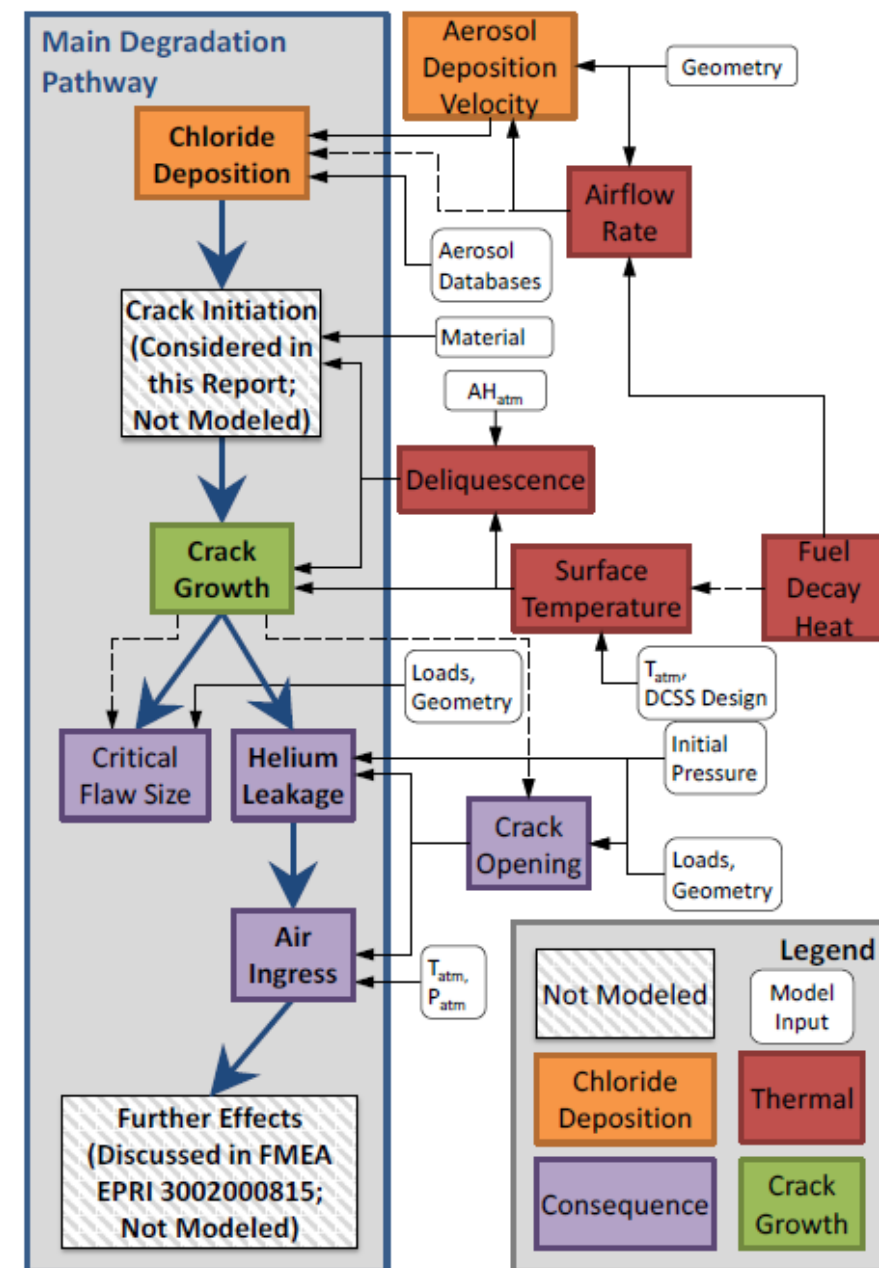


Figure A-1
Flowchart of the Degradation Process as Modeled

Consequence

Consensus is developing that consequence is generally low, especially during storage

- Timing
- Material available to escape confinement and disperse
- Likelihood of event simultaneity

Analytical work with GOTHIC and MELCOR models

- Dose found to decrease by 6 OOM in minutes

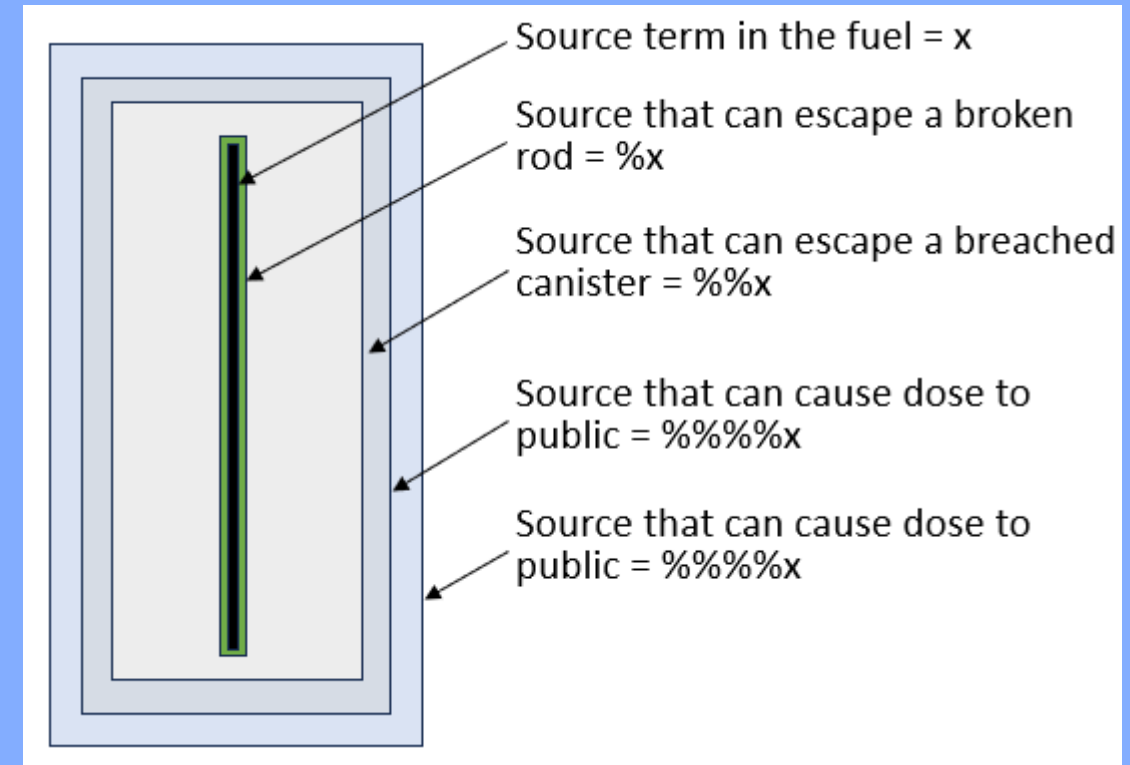
Uncertainty remains

- Availability of benchmark data to validate codes
- Best-estimate release fractions

Consequence is the third question to be answered in PRA:

1. What can go wrong
2. How likely is it
3. What are the consequences?

Technical Letter Report TLR-RES/DE/CIB-2018-01



Inspection Program

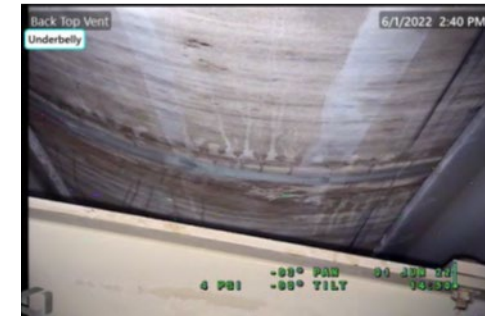
Most mature of the four framework areas

Programs are in place with inspections ongoing

- Visual inspection tools developed and in use
- No identified need for enhanced inspections to date
- Inspection data being collected and stored in AMID

Development remains

- No comprehensive effort to analyze and make sense of data available from numerous inspections
- EPRI working on deployable tools for enhanced inspection techniques, should they be needed in the future



Sandia Ring at Sonospection
12/2023

Avoiding unnecessary inspections when data supports is ALARA

Mitigation

EPRI research focused on cleaning and mitigation in situ, if/when needed

- Effective techniques
- Deployable systems

DOE research also being conducted in these areas

No emergency need to deploy mitigation, thanks to ongoing inspections, slow crack growth kinetics, and low consequence

Repair Technique	Vendor	Test Results					
		Leak	Salt Fog	SSRT	Electro-chem	Adhesion	Atmos. Exposure
Cold Spray	VRC	1	1	1	2	1	0
Arc Welding (52M)	EPRI	—	—	—	1	—	—
Arc Welding (308L)	EPRI	1	1	—	1	—	0
Inorganic Coating	Luna	3	2	1	1	2	0
Inorganic Coating	Restochem	1	2	1	1	2	0
Liquid Metal	Rawwater	3	—	—	3	—	—
Geopolymer	Riderplast	3	3	1	1	2	0
Reference / Unrepaired	—	—	—	1	1	—	0

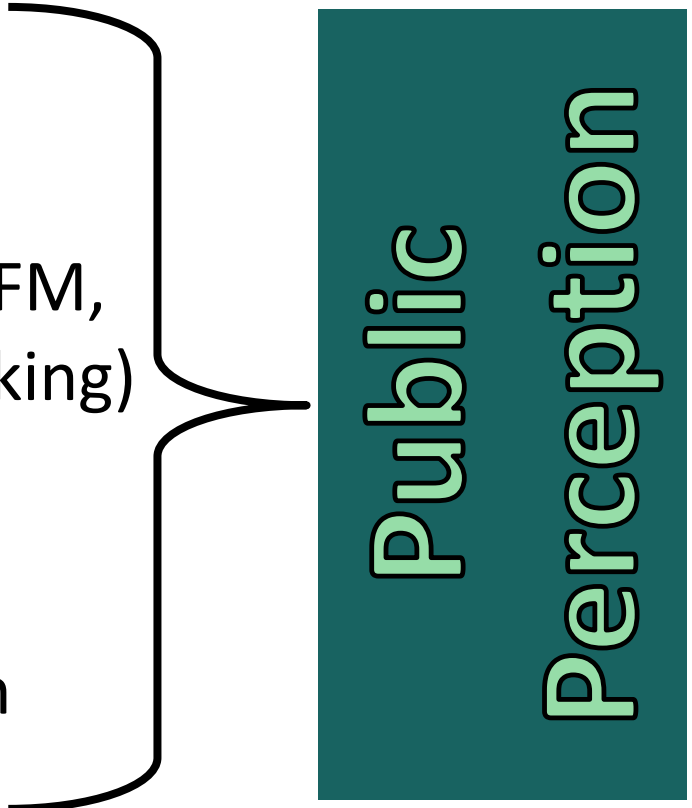
1	Test completed; no concerns identified
2	Test completed; some additional study recommended
3	Test completed; results not acceptable
0	Test results pending
—	Not tested



Next Steps toward a refocused CISCC Program

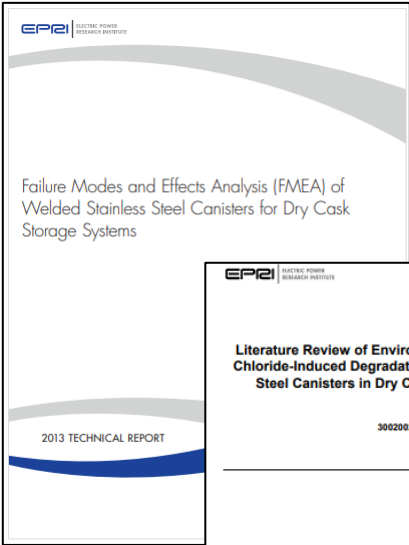
A step-wise, coordinated, and collaborative approach to achieving an end-point

1. What we know today (data and theory)
 - Inform the next steps in regulatory space
 - Low hanging fruit, short-term actions (e.g., PFM, inspections, consequence, tool develop., ranking)
2. What can still be improved upon
 - Data gaps to close within the CISCC Research Framework (e.g., GOTHIC/MELCOR validation with data)
3. Long-term actions (i.e., future renewals or after fuel leaves the ISFSI)

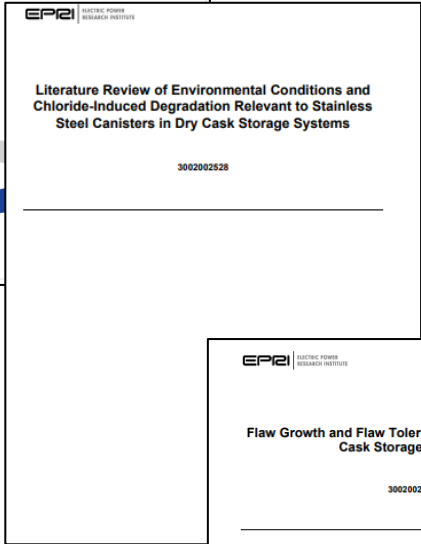


Public
Perception

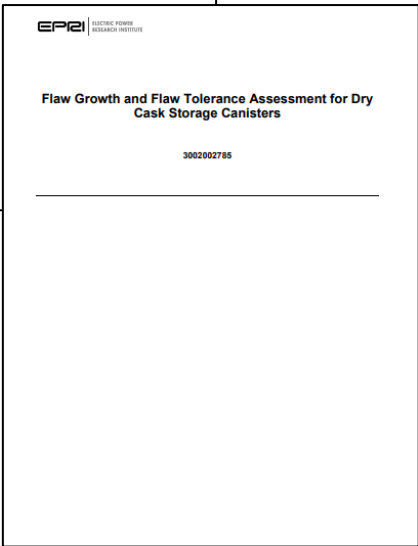
EPRI Aging Management Guidance



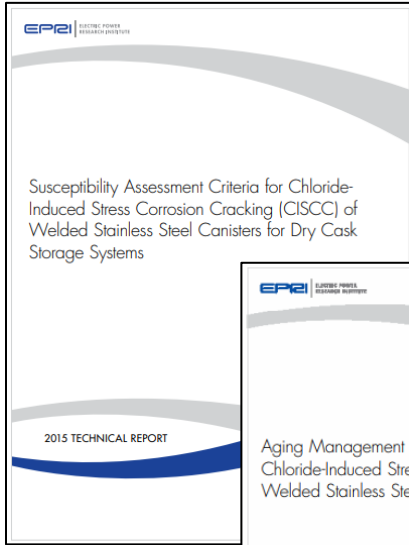
Failure Modes and Effect Analysis (3002000815, 2013)



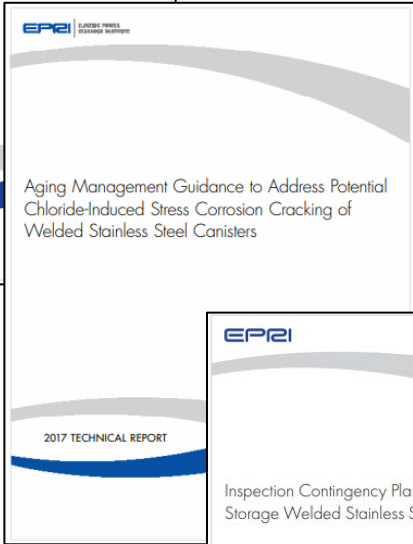
Literature Review on Cl-Induced Degradation (3002002528, 2014)



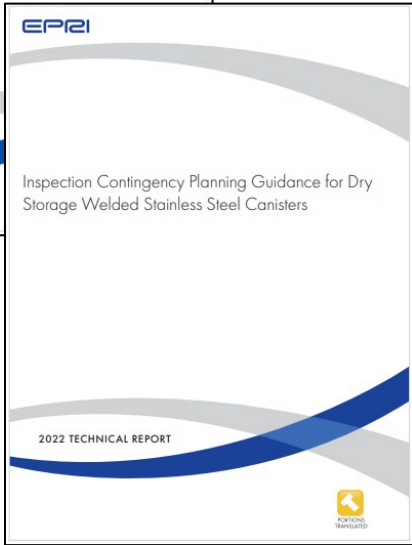
Flaw Growth and Flaw Tolerance Assessment (3002002785, 2014)



Susceptibility Assessment Criteria (3002005371, 2015)



Aging Management Guidance (3002008193, 2017)



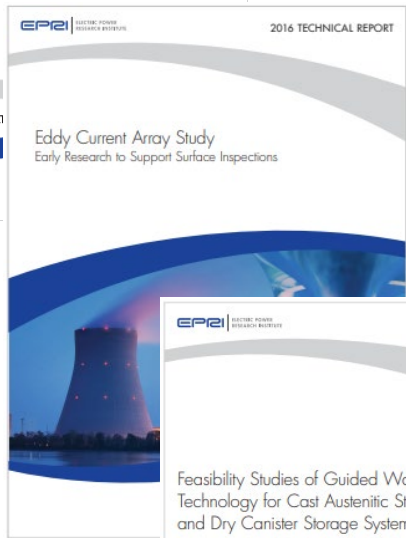
Inspection Contingency Planning (3002023424, 2022)

Due to learning since publishing, updates may be needed

EPRI Inspection Research



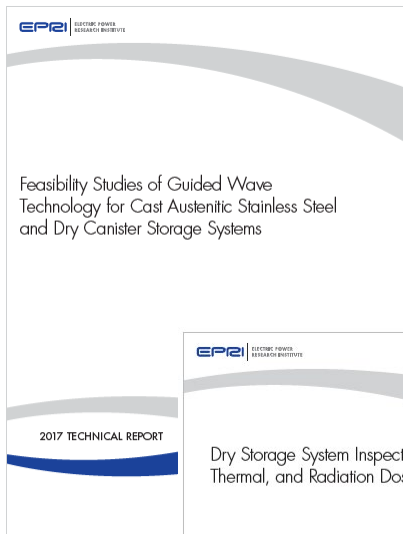
Nondestructive Evaluation: Investigation of Acoustic Emission Technologies for Monitoring Inaccessible Regions of Dry Fuel Storage Systems (3002007816, 2016)



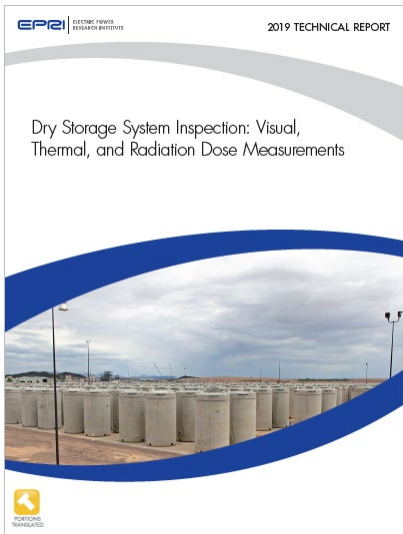
Eddy Current Array Study (3002007801, 2016)



Feasibility Studies of Guided Wave Technology for Cast Austenitic Stainless Steel and Dry Canister Storage Systems (3002010447, 2017)



Feasibility Studies of Guided Wave Technology for Cast Austenitic Stainless Steel and Dry Canister Storage Systems (3002010447, 2017)

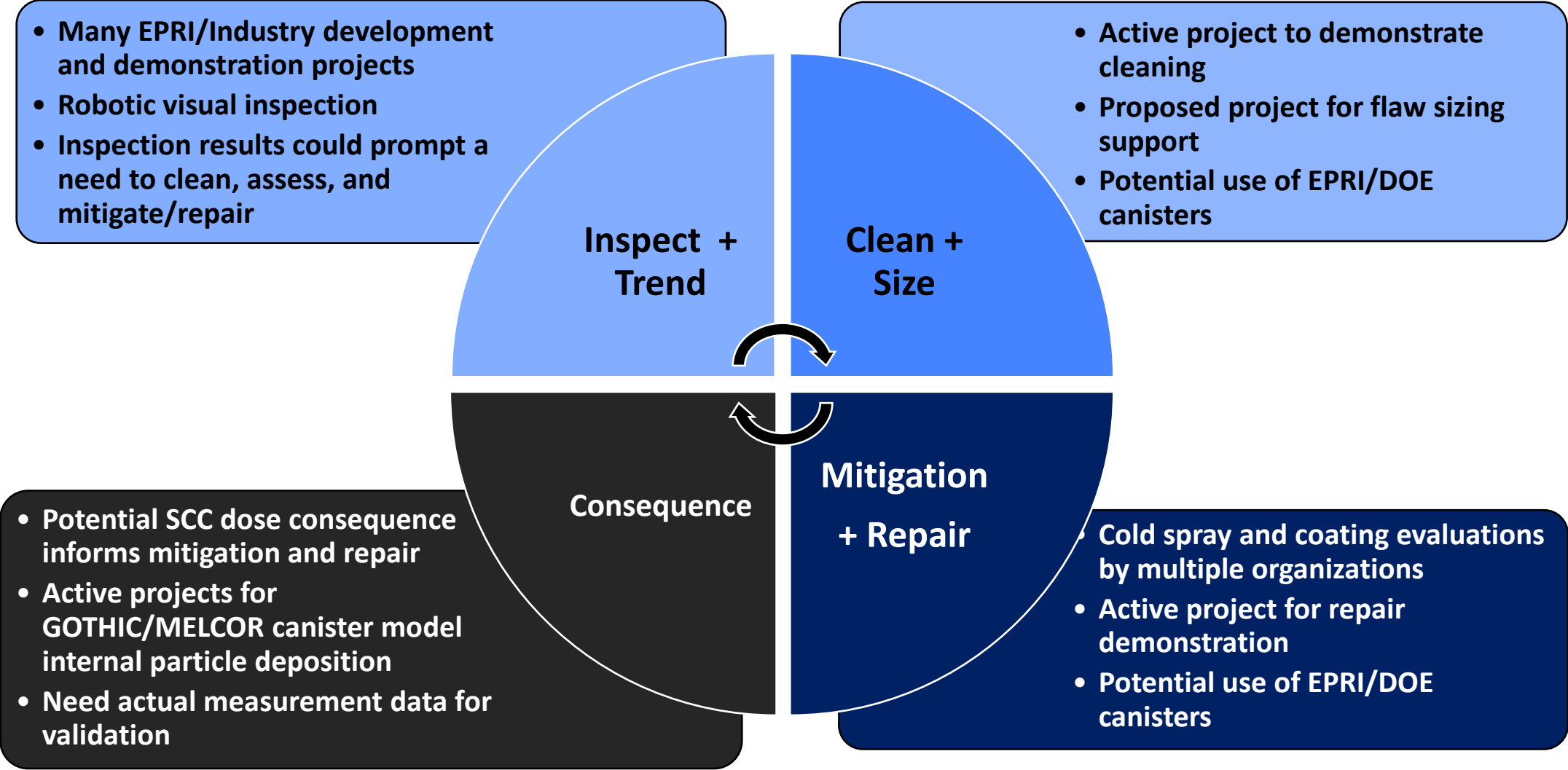


Dry Storage System Inspection: Visual, Thermal, and Radiation Dose Measurements (3002016034, 2019)

A pair of hands is shown holding a glowing, translucent globe. The background is a deep blue with a subtle pattern of stars and a nebula-like glow. The text is centered over the image.

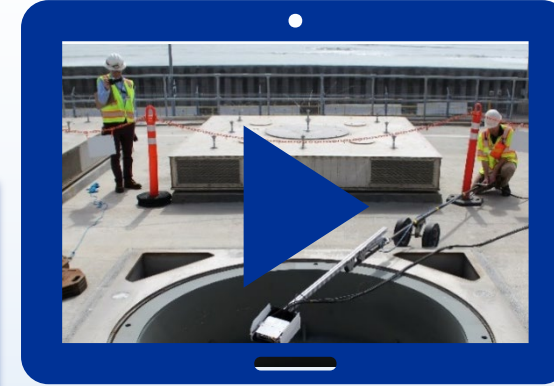
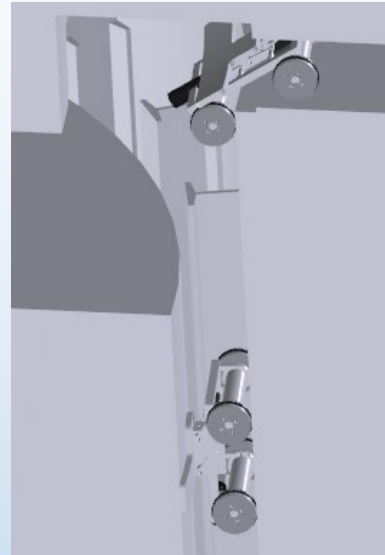
ESCP Aging Management and Canister Integrity

Canister Aging Management Research Activities

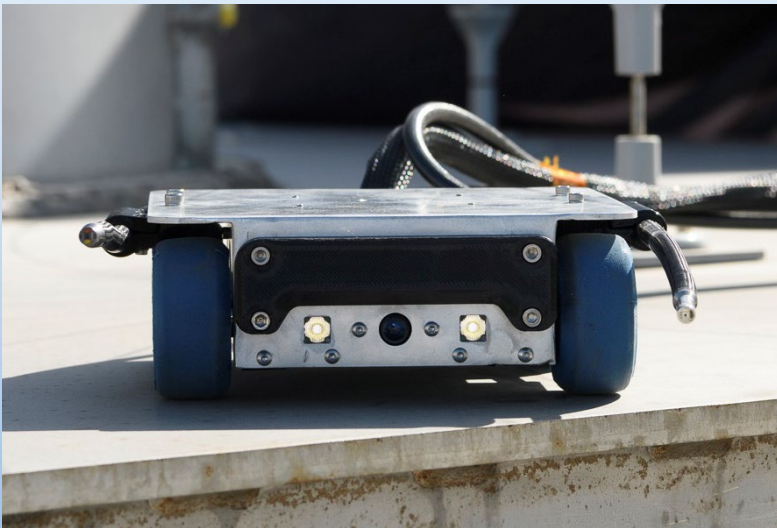


Many collaborative research activities to address current and potential future needs

Aging Management, Inspection, Repair, & Mitigation R&D



[EPRI Robotic Inspection System video on YouTube](#)



ASME Code Case N-860 for inspections approved

- Now focus is on Mitigation & Repair and Consequence Evaluation
- Many collaborative opportunities exist
- 15 total canisters received by SNL, ORNL, PNNL, EPRI for demonstration projects

ESCP Aging Management Working Group Meeting

Objectives:

1. **Evaluation of the current status of the aging management research** - what has been done to date and what can be concluded from the results.
2. **Development of a roadmap for the next 2 years** to conclude key items.

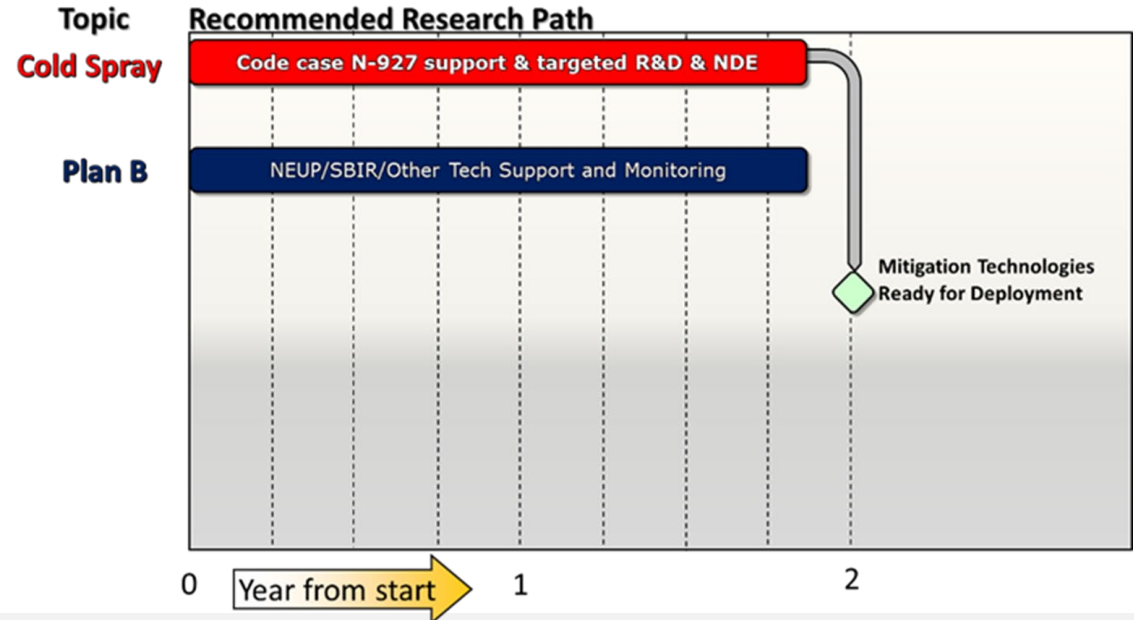
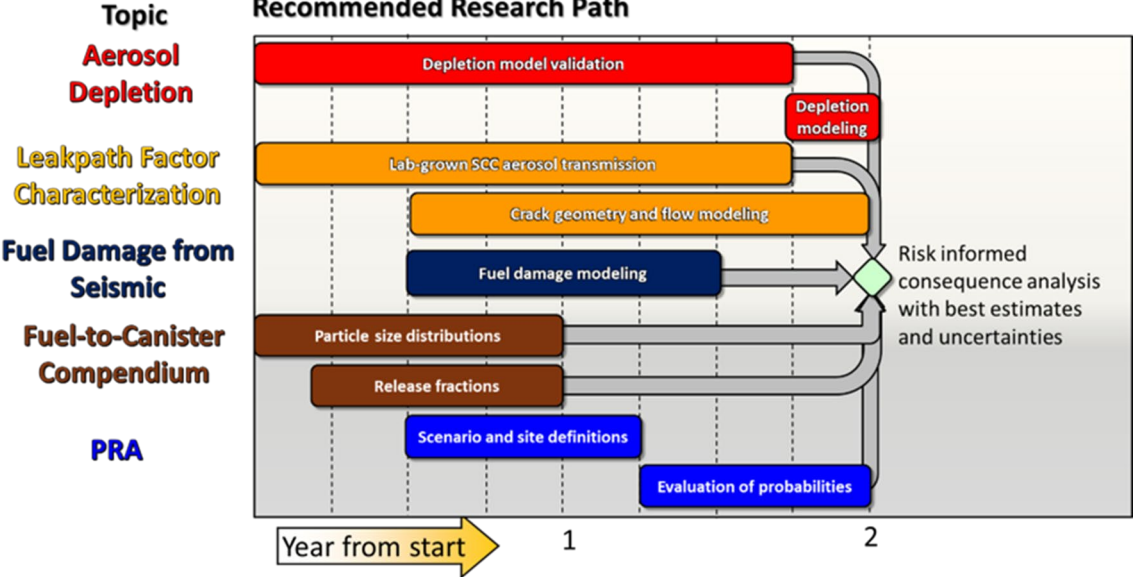
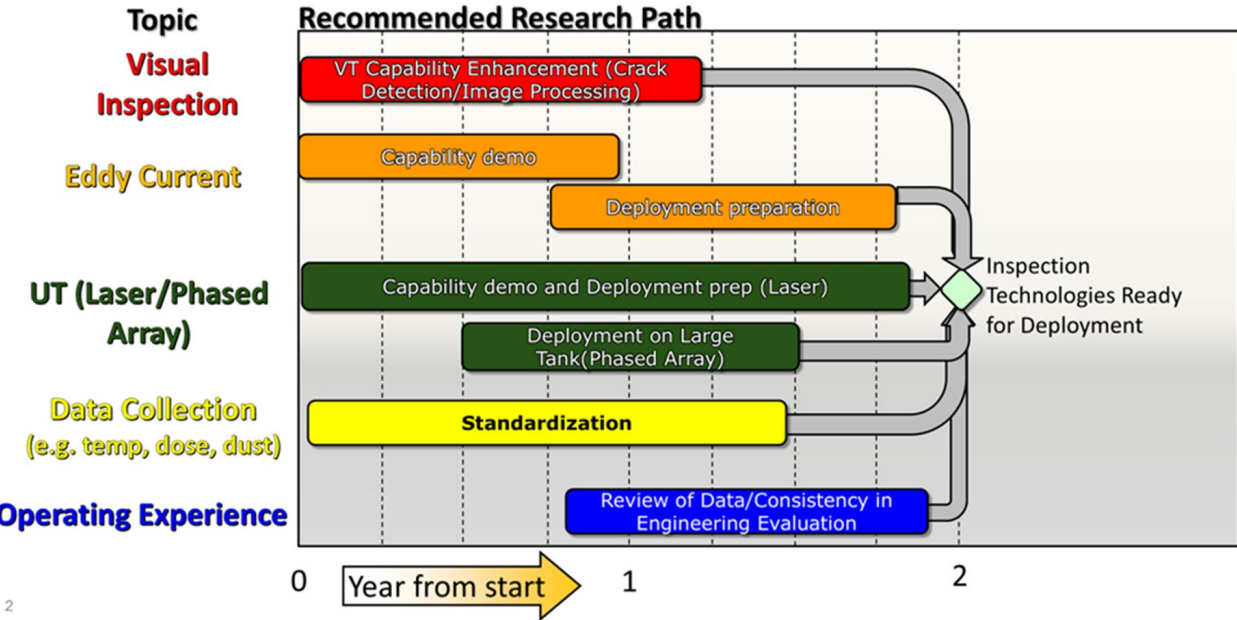
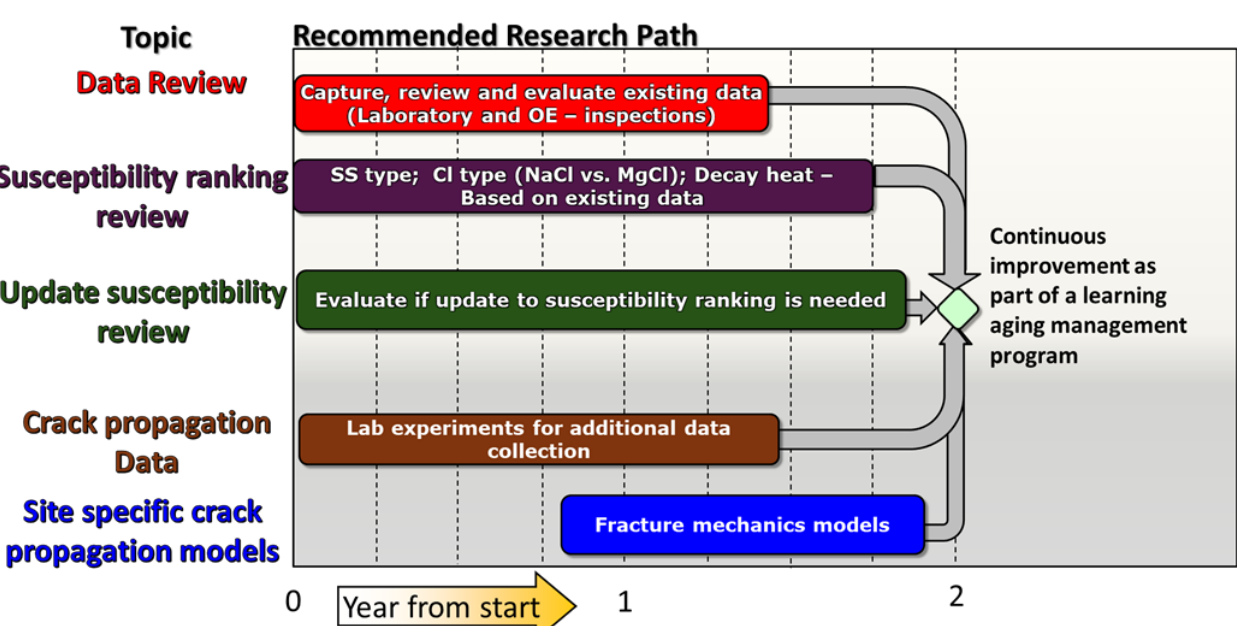
Working Group Meeting:

1. Participation by invitation only. List of invited guests developed with input from Subcommittee and Task group leads. Number of registered attendees: 35
2. Attendees include participants from utilities, vendors, regulator, DOE, National laboratories, NEI, university.
3. Developed questionnaire and distributed prior to the meeting.
4. Parallel sessions and joint sessions were scheduled.



Documentation of what has been done in the past >10 years and development of roadmap for closure of key items within the next 2 years were the key objectives

Aging Management Workshop & Recommended Roadmaps



Key Recommendations & Lead Performers

Key Recommendation	Lead Organization*
Evaluation of all the laboratory data, related to aging mechanisms and consequence, to date	EPRI/ESCP Task Groups**
Evaluation of inspection data to date with the aim of improvements	EPRI
Collection of temperature/dose data during inspections and analysis/database	Utilities during scheduled inspections
Collection of surface deposit samples during inspection	Utilities during scheduled inspections – EPRI/Labs
Standardization of sample collection and analysis, including independent analysis at multiple labs	EPRI
Collection of crack growth data for enhancements for the model used in ASME N-860 and xLPR type prediction tools	NRC/DOE/NL
Evaluation of surface and volumetric inspection tools and determination of path forward based on demonstration	EPRI (ongoing activity)
Development of Plan B for mitigation, besides cold spray	DOE/NEUP & SBIR
Collection of particle release fractions and sizes	EPRI/ESCP
Generating validation data for GOTHIC/MELCOR for consequence studies	Joint collaborative effort

*Tentative list/lead organization for SC discussions

**Provided access to the data is granted

Many of the key recommendations support multiple pillars. Recommendations will require collaboration between different stakeholders



EPRI Tool Development

Tool Development

▪ NDE TOOLS

- Robotic crawler and initial visual inspection demonstrations
- Flaw Specimen Procurement
- Capability Study

▪ MITIGATION TOOLS

- Guidance for Application and Acceptance
- Cleaning Demonstration
- Cold Spray Demonstration
- Coating Investigations

▪ REPAIR TOOLS

- Bolted Cask Seal Leakage Response Roadmap
- Dry Transfer System Technology Readiness Assessment

▪ EVALUATION TOOLS

- Aging Management Guidance with Probabilistic Confinement Integrity Assessment
- Modeled backfill flow through postulated CISCC
- GOTHIC modeling of canister backfill behavior
- Remote contamination sampling and gas leak detection

Nondestructive Evaluation (Inspection Tool Development)

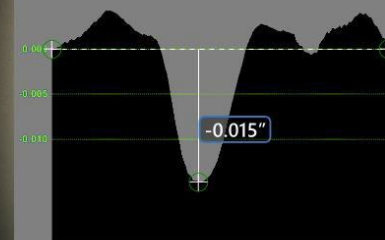
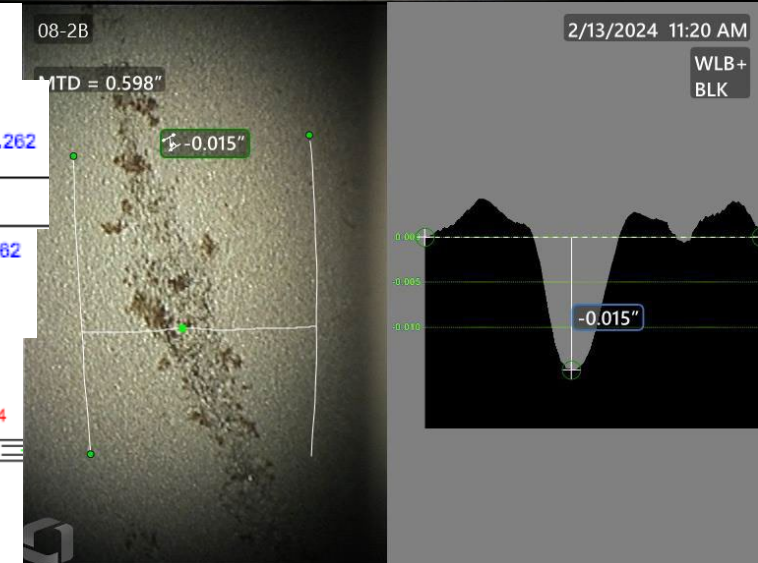
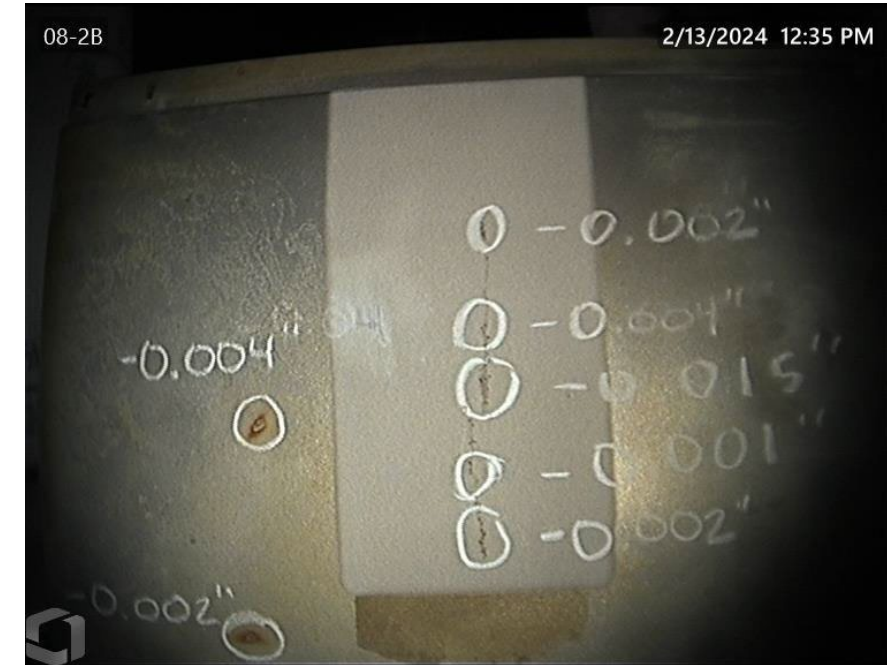
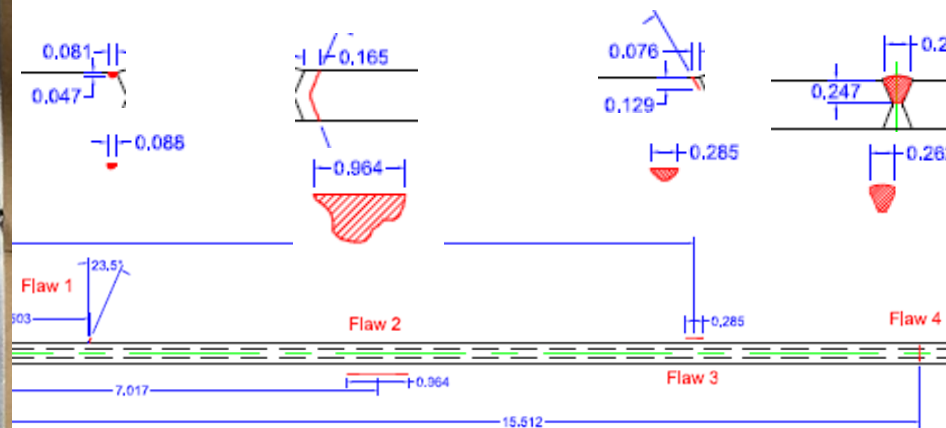
- **Project Goal** = Demonstrate surface and volumetric inspection technologies for in-situ application to stainless steel dry storage canisters
- Technologies Being Evaluated
 - Visual and Mentor Visual IQ (MViQ) System (Borescope)
 - Eddy Current Testing
 - Ultrasonic Testing (considering laser UT and alternate couplants for UT)
- Testing completed in October 2024
 - Visual capability study confirmed
 - Surface and volumetric inspection capability study vendor(s)

Planned EPRI Research Deliverables

- Capability Study Results (2025)
- Specimens available for demonstrations (2024 and beyond)
- Guidance for collection and analysis of surface deposits from in-service canisters

Mentor Visual IQ (MViQ) System (Borescope) Inspection Capability Testing

- EPRI test plates inspected at vendor facility
 - Test conducted on EPRI EC/UT sample
- Most significant indications of one sample plate were measured with varied operational parameters

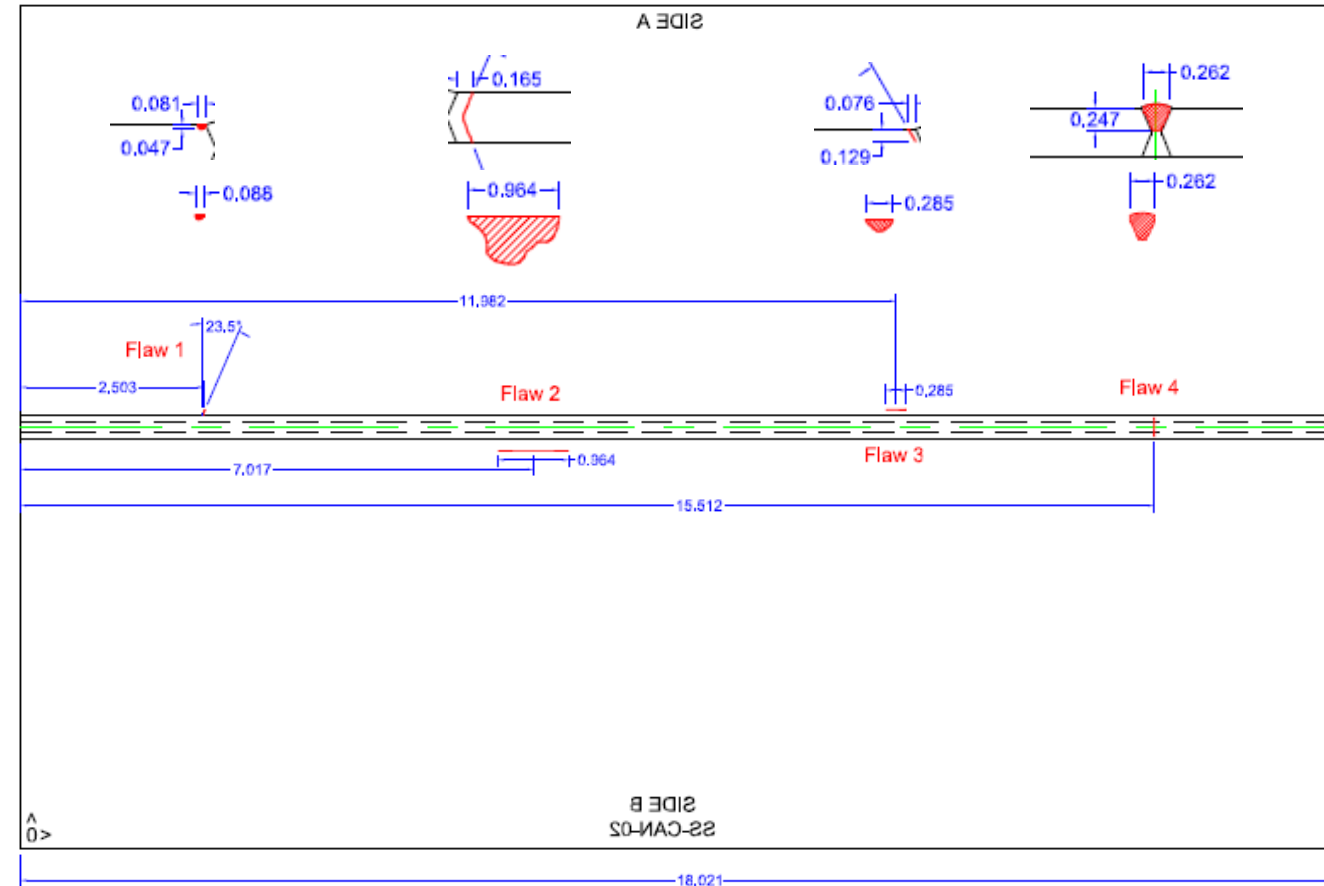


MViQ System (Borescope) Inspection Capability Testing (2/2)



- Welded plate indications
 - Measured depth (#1) was 0.15 mm (0.006 inch); design depth (Flaw 2) was 13 mm (0.510 inch)
 - Measured depth (#2) was 0.5 mm (0.02 inch); design depth (Flaw 4) was 6.3 mm (0.247 inch)

- Welded plate (EC/UT specimen) design (scale in inches)



Limited detection capability for tight flaws near weld on EC/UT specimen. Additional planned testing will focus on visual inspection capability using specimens intended for visual demonstration.

Surface and Volumetric Inspection Capability Study

- Drafted guidance for UT demonstrations to meet “Intermediate Rigor” per ASME Code Case N-860
 - Including technical basis for design of UT specimens
- Procured blind flaw specimens based on mock-up canister section
 - Canister section cut circumferentially
 - Welded back together and cut into 4 specimens
 - Applied common processes to impart flaws
- Capability Study
 - Vendors have completed capability testing at EPRI facilities
 - Targeting report issuance in Fall of 2025

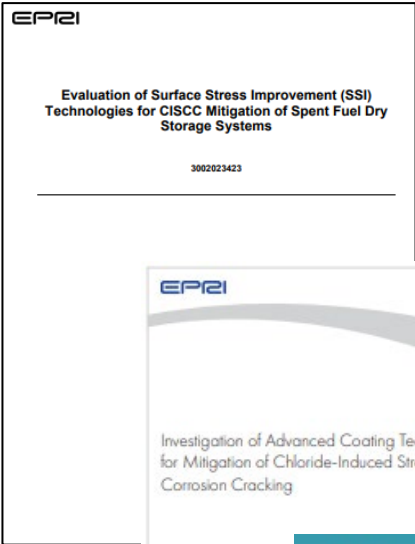


Specimen fabrication in process

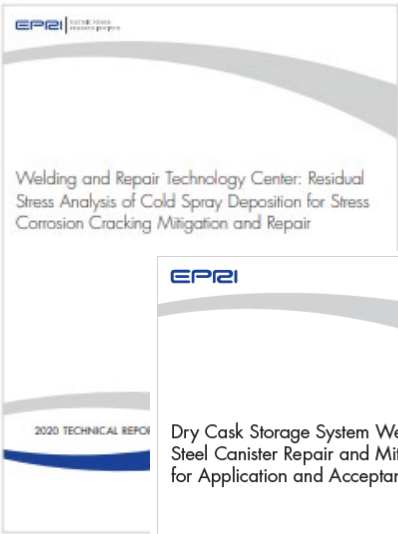
Completed EPRI Cleaning and Mitigation Research



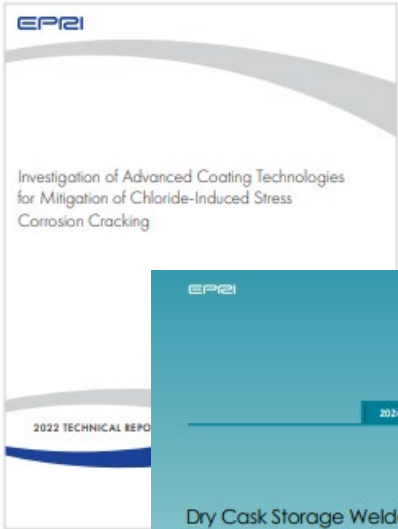
ESCP Industry Progress Report (3002013130, 2018)



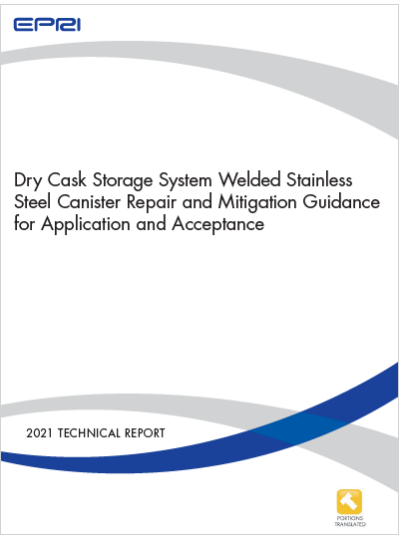
Evaluation of Surface Stress Improvement Technologies for CISC Mitigation of Canisters (3002023423, 2022)



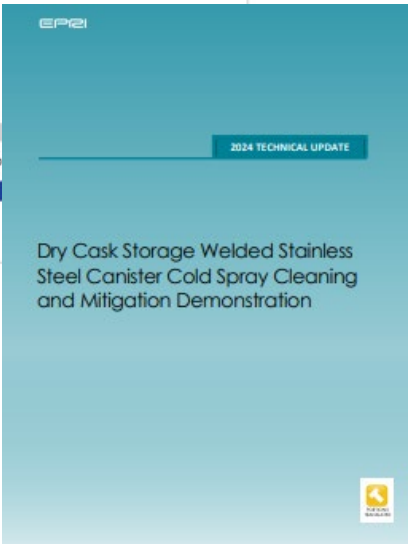
Cold Spray Residual Stress Analysis (3002018449, 2020)



Canister Coatings Evaluation (3002023825, 2022)



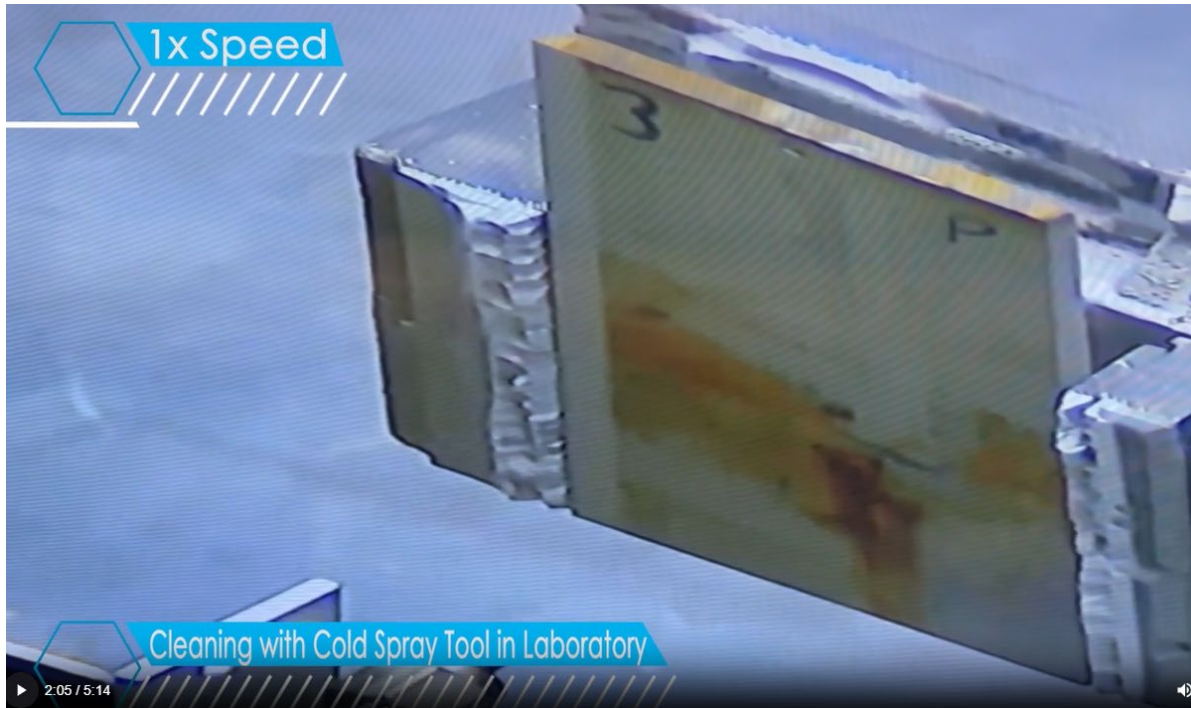
Canister Mitigation and Repair: Guidance for Application and Acceptance (3002020975, 2021)



Canister Cleaning and Cold Spray Demonstration (3002026547, 2024)

Completing research to optimize tools and demonstrate effectiveness

Canister Cleaning and Cold Spray Demonstration Key Findings



Demonstration video available on EPRI program home page:

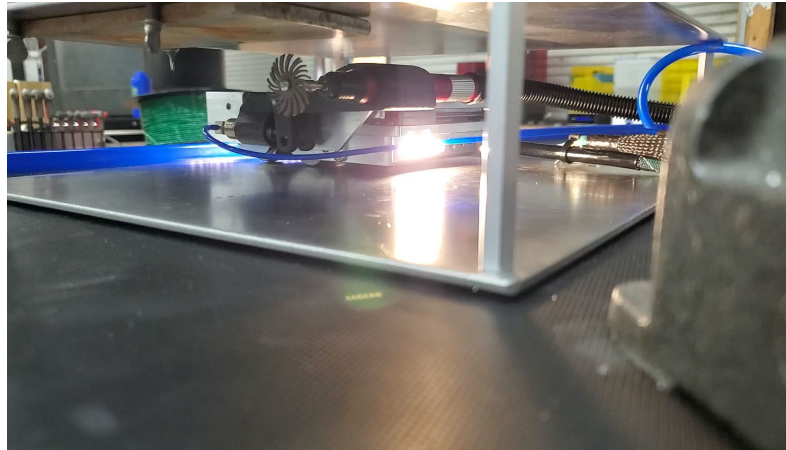
<https://www.epri.com/research/programs/061149>

ASME Cold Spray Code Case N-927 under development with EPRI support

- **Cleaning procedure removed corrosion product**
 - Surface roughness measured $\sim 3 \mu\text{m}$ (same as underlying 304H stainless steel)
 - Preferential degradation of the cleaned area after 1,158 hours of cyclic corrosion testing (CCT)
- **Cold spray coating procedure resulted in a dense coating**
 - Thickness $\sim 0.5 \text{ mm}$
 - Covered crack $\sim 40 \mu\text{m}$ wide
 - Porosity = $1.29 \pm 0.24\%$. (measured per ASTM E2109)
 - Surface roughness measured $\sim 13 \mu\text{m}$
 - Hardness depth profile = 370 HV0.3 (compared to 169 HV0.3 for underlying stainless steel)
- **Cold spray coated sample remained adherent;** no spallation after 1,158 hours of CCT
- Primary corrosion responses experienced in the cold spray coated sample
 - Iron oxide growth from the stainless steel in the uncoated area
 - Nickel oxide growth at the substrate/coating boundary and general coated area
 - Growth of the nickel oxide at the boundary accelerated by galvanic corrosion and edge effects

Dry Cask Storage System Canister Cleaning

- Evaluated Options
 - Grit Blasting (with cold spray equipment)
 - Chrome Carbide Powder
 - Ceramic Powder
 - Air Blasting
 - Scotch-Brite
 - Mini Pencil Grinder
- Evaluated and eliminated
 - Dry Ice Blasting
 - Sanding Disk



Sanding Disk not recommended based on surface roughness, potential for damage

Cleaning enables unobscured visual inspection and prepares surface for coating application

Grit Blasting (Using Cold Spray Equipment)

- Cleaning optimization varying powder feed rate, powder size, powder hardness, and spray angle
- Findings:
 - Increasing powder feed rate has significant influence on enhancing surface cleaning response
 - Surface cleaning response improved at smaller powder sizes
 - Increasing powder hardness is most influential to increasing surface cleaning quality
 - Spray angle was inconsequential to surface cleaning quality



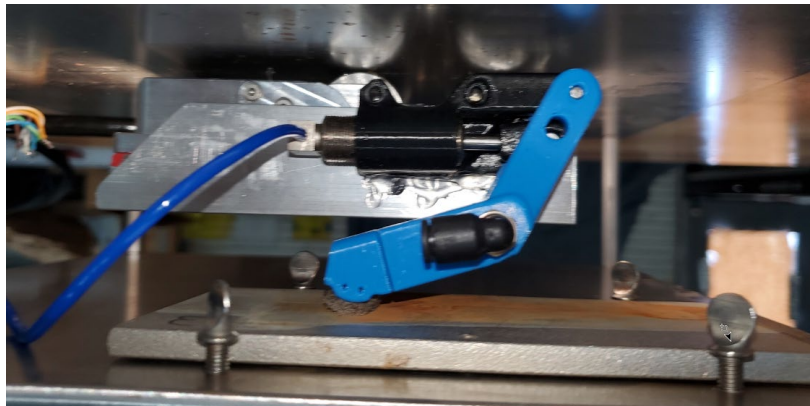
Ceramic Zirshot performed best in initial testing (4 RPM, 50 um, 0°)

Canister Cleaning with Scotch-Brite®

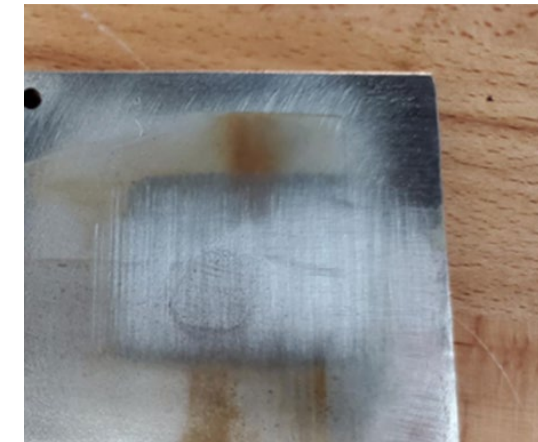
- Significant experience using Scotch-Brite® to collect dust samples from canisters in the field
- Available in different finishes
 - More coarse grit is more aggressive, better removal



Scotch-Brite® pad mounted on crawler



Before (above) and after (below) cleaning with Scotch-Brite® pad



Scotch-Brite® is a registered trademark product of 3M

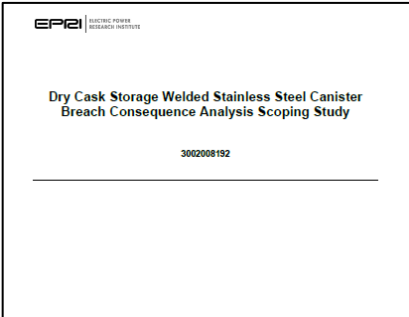
Dry Cask Storage System Canister Cleaning and Mitigation Summary

- Demonstrating mechanical cleaning technologies
- Optimizing cold spray for crack-sealing performance
- On-going efforts:
 - Refinement and validation of surface sample collection attachment to collect samples to characterize the canister environment for in-service canisters

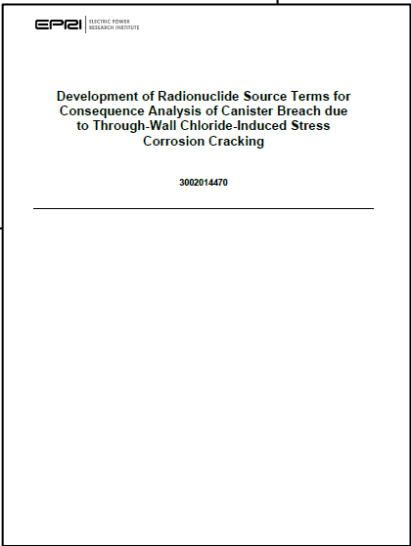
EPRI Research Deliverables

- ESCP Canister Mitigation Industry Progress Report Update (2024)
- Cleaning, Contamination Sampling, and Gas Detection Demonstration (2024)
- Welding Research and Repair Technology Center Report on Ceramic Powder Cleaning and Cold Spray Crack Sealing (2025)

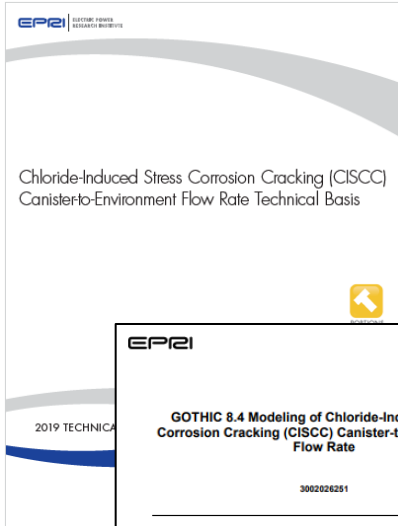
Completed EPRI Research for Understanding Dose Consequences



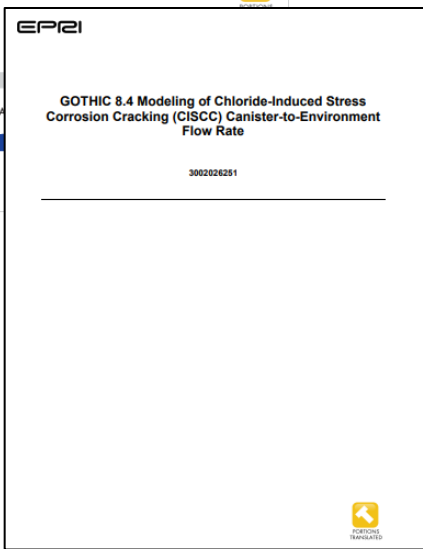
Dry Cask Storage Welded Stainless Steel Canister Breach Consequence Analysis Scoping Study (3002008192, 2017)



Development of Radionuclide Source Terms for Consequence Analysis of Canister Breach due to Through-Wall Chloride-Induced Stress Corrosion Cracking (3002014470, 2018)



Chloride-Induced Stress Corrosion Cracking (CISCC) Canister-to-Environment Flow Rate (3002015062, 2019)



GOTHIC 8.4 Modeling of Chloride-Induced Stress Corrosion Cracking (CISCC) Canister-to-Environment Flow Rate (3002026251, 2023)

Evaluating options for future research

Dose Consequences (Particle Deposition Behaviour)

- **Project Goal** = Investigate Gothic modeling of particulate behavior
- **Recent Developments** = NRC and DOE independently developing dose consequence assessments
- **Future Planning**
 - Benchmarking of GOTHIC for canister application
 - Timelines, sequences, and scenarios for evaluation
 - Gather best input recommendations for key parameters (failed fuel fraction, crud spallation fraction, release fractions)
- **Ultimate Goal** = *EPRI Guidance for Performing Dose Consequence Assessments for Welded Stainless Steel Canister Dry Cask Storage Systems*

EPRI Research Deliverables

- GOTHIC Model Development for Welded Canister Dry Cask Storage Systems (Spring 2024)
- *GOTHIC Model Refinement and Results for Welded Stainless Steel Canister Dry Cask Storage Systems (TBD)*

Developing a better understanding of the consequences of a through-wall crack

Completed EPRI Research for Addressing Bolted Cask Seal Leak Indications

1. Industry Spent Fuel Storage Handbook: Revision 1 (EPRI 3002020701, 2021)

- Discusses aging management programs as they relate to renewal of ISFSI licenses
- Provides cask system descriptions for TN metal casks and CASTOR V/21, CASTOR X systems
- Describes Dry storage system operations, maintenance, and inspection
- Includes historical spent fuel storage experience and methods for retrieval from dry storage

2. Strategies to Address Seal Leakage in Bolted Cask Dry Storage Systems (3002023425, 2022)

- Provides description of systems in use and applicable regulations in Germany, Japan, Spain and the USA, identifies methods that may address an instance of degradation in the closure of a bolted at a site that does not have an operable on-site spent fuel pool or a hot cell

3. Bolted Cask Leakage Monitoring Alarm Response Roadmap (3002028997, 2024)

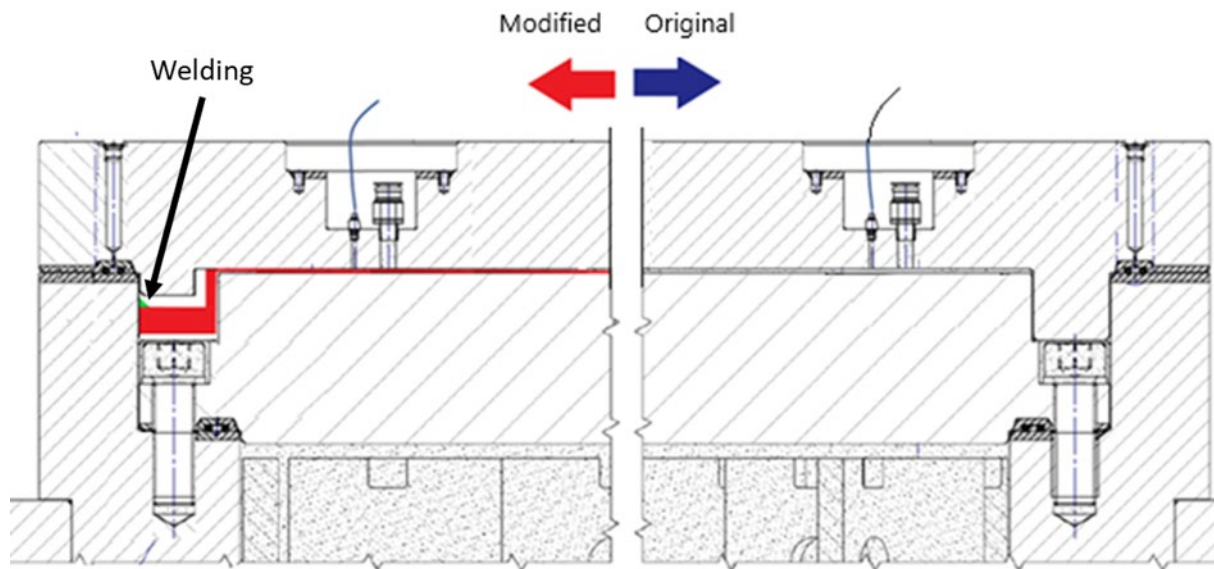
- Provides a sequence of operations to undertake in case of a pressure alarm on ENUN and Castor design bolted cask systems
- Describes designs of dry transfer systems completed in the past

Research for bolted cask aging management is complete and published

Bolted Cask Seal Leak Indication Response Roadmap

KEY RESEARCH QUESTION

- How could a site with an ISFSI and no spent fuel pool respond to a seal leakage alarm on a bolted cask



Original and modified configuration of ENUN cask closure system

KEY FINDINGS

- This report provides step by step guidance for addressing seal leakage alarms. Based on operating experience, this guidance includes process recommendations to rule out causes such as a failure of a pressure sensor or a leak through the pressure monitoring sensor.
- In case of a barrier leak, the following response options are considered in the report:
 - Retorque or Replace Bolts
 - Secondary Seal Qualification as Confinement Barrier
 - Use of an Interlid Welded Cover (shown)
 - Lid/Seal Change Inert Cabin
 - Transportation off-site for repair or replacement

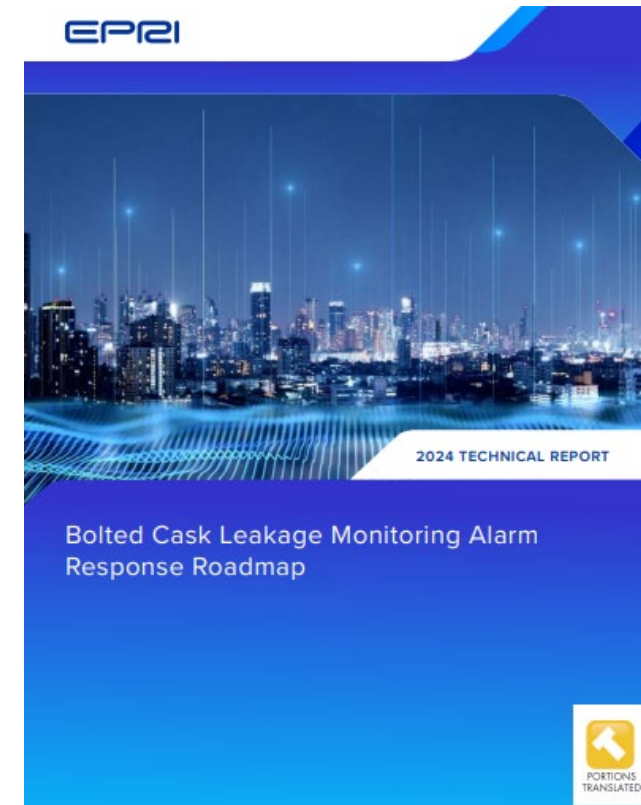
Report is complete and published (3002028997, 2024)

Bolted Cask Leakage Monitoring Alarm Response Roadmap

REPORT CONTENTS:

- Introduction
- Alarm Scenarios and Cause Analysis
- Leak Response Roadmap
- NAC Concept Facility for Seal Replacement
- Overpack Option
- Conclusions and References
- Facilities and Equipment List (appendix)
- Dry Transfer System Technology Readiness Assessment (appendix)

Bolted Cask Leakage Monitoring Alarm Response Roadmap (3002028997, 2024)



Assets under development by EPRI in Charlotte, NC



Platforms for seal testing, transportation readiness development, inspection tool validation, etc.



TOGETHER...SHAPING THE FUTURE OF ENERGY®

Cask Opening Experience



Dr. Joe Faldowski, DBA, PMP
Sr. Program Manager

China Workshop
October 2025

Spent Fuel Dry Storage Cask Opening: Operational Experiences

- Spent fuel and storage system canister degradation mechanisms have been extensively researched for >15 years
 - 1st ESCP meeting held in 2009
- Outstanding question: Do research results reflect reality?
 - Operational data provide evidence to support research findings
- A recent EPRI report (3002029312) addresses the question:
 - How has dry storage affected the condition of spent fuel?

Public confidence depends on knowing reality

Cask Opening Experience

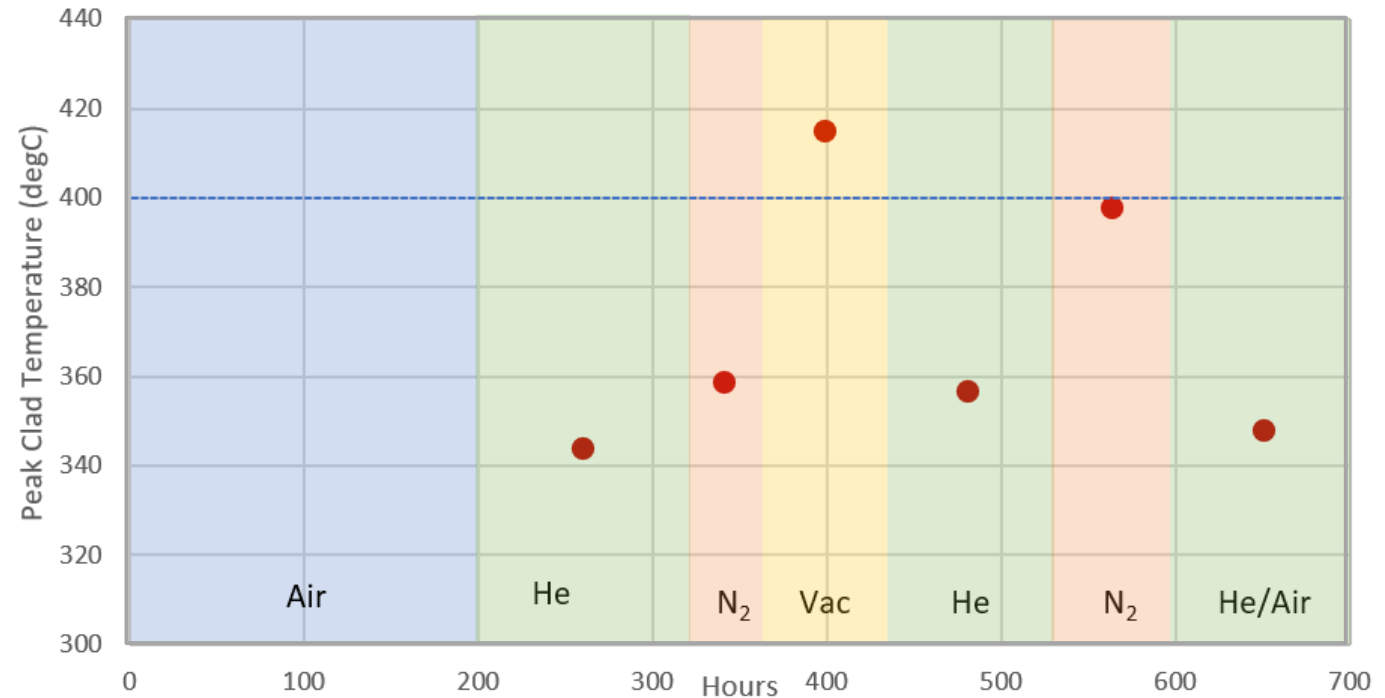
- Data reported from four different sites comprising:
 - BWR and PWR fuel
 - Burnups ranging from 9-35 GWd/MTU
 - Five different cask types
 - Dry storage periods ranging from 5-14 years prior to inspection
 - Wet-dry-wet fuel storage scenario
 - Fuel examined before and following a beyond-design-basis event

Fuel condition at inspection found to be comparable to pre-loaded condition

Idaho National Laboratory

Castor V/21 containing 15x15 Surry PWR fuel opened after ~14 years

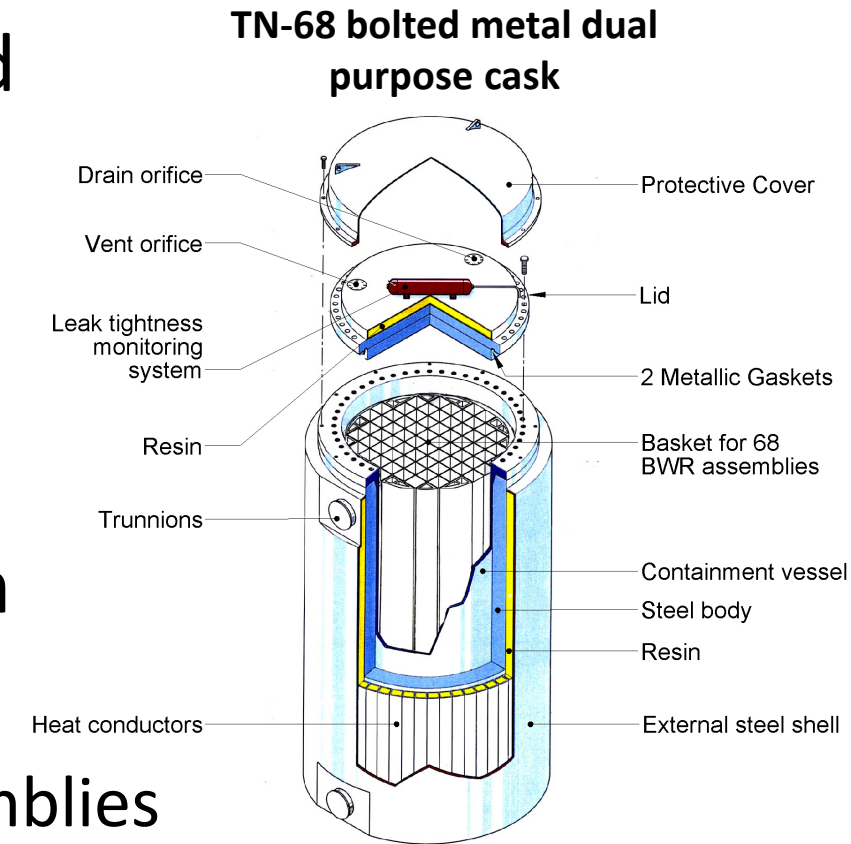
- Cask and fuel initially used for backfill environment performance testing
- Subjected to different fill gases, cask orientations, and temperature cycling
- Visual inspection and detailed examination found no degradation of either fuel or cask
- 12 rods selected for more testing including detailed visual, oxide adhesion, profilometry, internal gas analysis, metallography, microhardness, creep testing



Atypical start of storage period, but no long-term effects noted

Peach Bottom Atomic Power Station

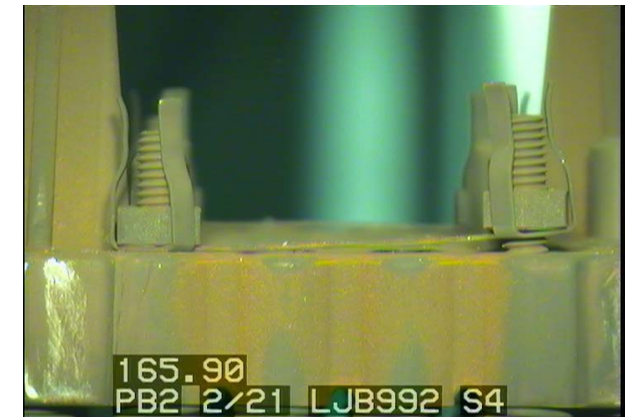
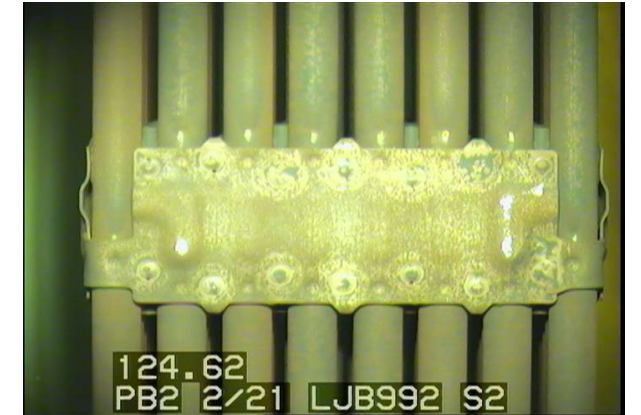
- TN-68 containing 68 BWR assemblies opened after ~10 years
 - Conservative decision to return to pool following pressure monitoring system alarm
- Inspection found fuel to be in good condition
 - Gas sampling found no evidence of failures
 - Confirmed through vacuum sipping of all assemblies
 - Visual inspection found no change from loading condition for all fuel assemblies



Used with permission from Orano TN

Peach Bottom Atomic Power Station

- Fuel returned to pool for storage following unloading
- One assembly was selected for inspection after ~10 years wet storage
 - No abnormalities identified
 - Fuel and hardware deemed structurally sound

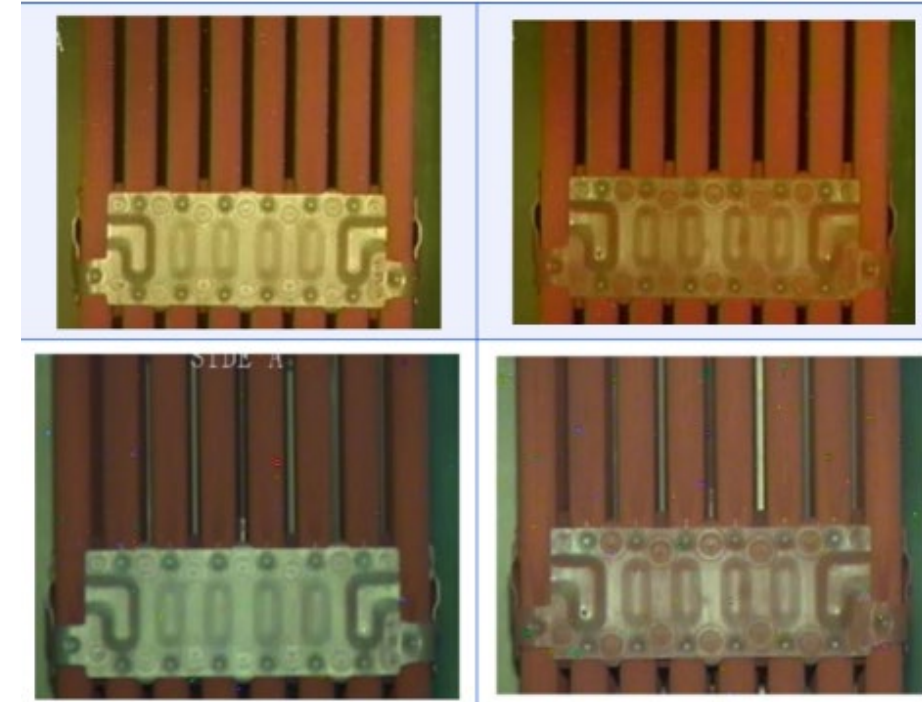


Transition through dry storage – rewetting – wet storage with no identifiable adverse effect

Tokai No2 NPS

- Hitachi Zosen cask containing 61 BWR fuel assemblies opened after 7 years – Cask opening planned as a confirmatory measure
- Cask found to be in good condition
 - Seal leak testing confirmed maintenance of containment
 - Examination of seals and surfaces found no evidence of degradation
- Two fuel assemblies selected for inspection & no significant changes observed

As
loaded
(2002)

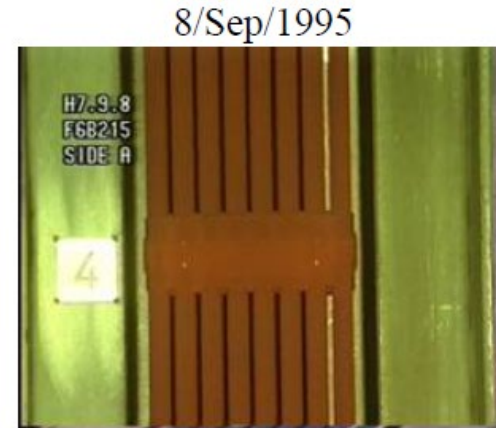
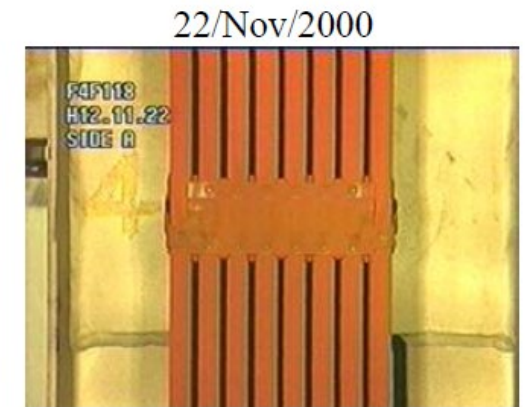


Inspection
(2009)

No indication of either fuel or cask degradation during storage

Fukushima Daiichi NPS

- Planned openings as confirmatory measure
 - KOBELCO medium type, 37 BWR after 5 years
 - KOBELCO large type, 52 BWR after 10 years
- Procedure involved:
 - Leak testing of primary lid
 - Cavity gas sampling
 - Examination of cask seal & sealing surface
 - Visual inspection of two highest heat generating fuel assemblies

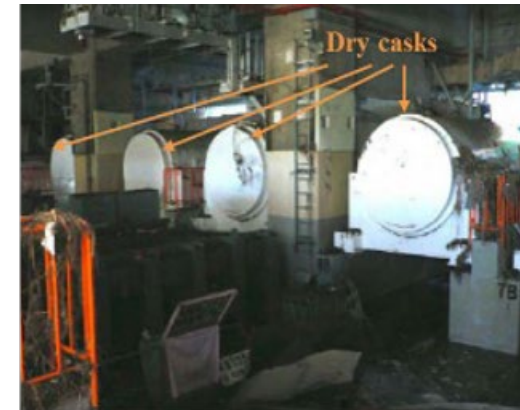


Images with permission from TEPCO

No indication of either fuel or cask degradation during storage

Fukushima Daiichi NPS

- Epicenter of 9.0 magnitude earthquake 112 miles from site
 - Max PGA values recorded at Unit 2
 - Horizontal 0.561g
 - Vertical 0.308g
 - Design basis 0.447g
- Site hit by 7 tsunamis, with max height 46-49 feet
 - Cask facility flooded with seawater & casks submerged

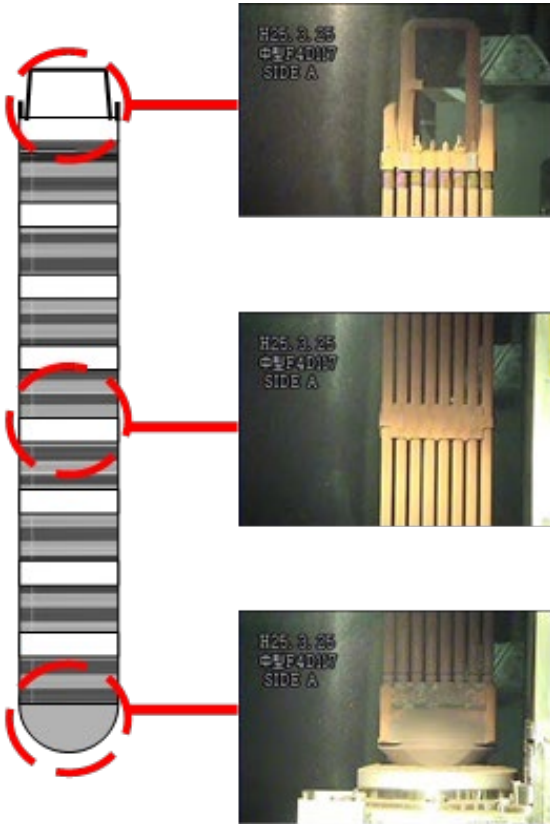
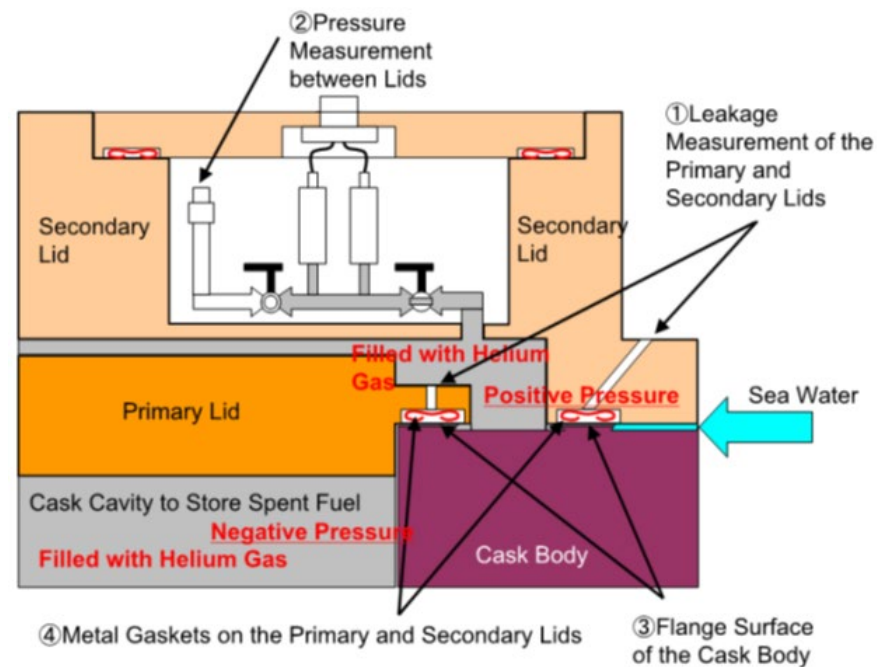


Images with permission from TEPCO

Accident conditions experienced beyond design basis

Fukushima Daiichi NPS

Inspection completed using 'representative cask'



Images from one of three fuel assemblies inspected.

No abnormalities observed such as deformation or damage.

Rods & hardware confirmed to be in good condition.

With permission from TEPCO

Cross-section of cask lid showing inspection points & entry point where seawater contacted secondary lid seal.

With permission from TEPCO

No loss of cask confinement or loss of fuel integrity identified

Summary

	Idaho	Peach Bottom		Tokai No 2	Fukushima Daiichi		
Fuel type	PWR	BWR	BWR	BWR	BWR	BWR	BWR
Storage time (Years)	14	10	10 (wet)	7	5	10	13
Burnup (GWd/MTHM)	24-35	9-30.3	32.2	31.8-33.5	≤33	≤33	≤33
Reason	Atypical storage conditions	Response to pressure alarm	Wet stored following dry storage	Confirmatory inspection	Confirmatory inspection	Confirmatory inspection	Post-accident
Findings	Fuel & cask in good condition, no evidence of loss of integrity or confinement						

- What next?
 - Will add additional case studies as become available
 - Will add examples of shorter term wet-dry-wet transitions

Report 3002029312 published March 2025 on EPRI.com



TOGETHER...SHAPING THE FUTURE OF ENERGY®

Transportation of Spent Nuclear Fuel

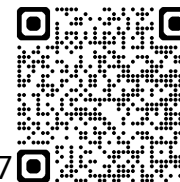


Dr. Joe Faldowski, DBA, PMP
Sr. Program Manager

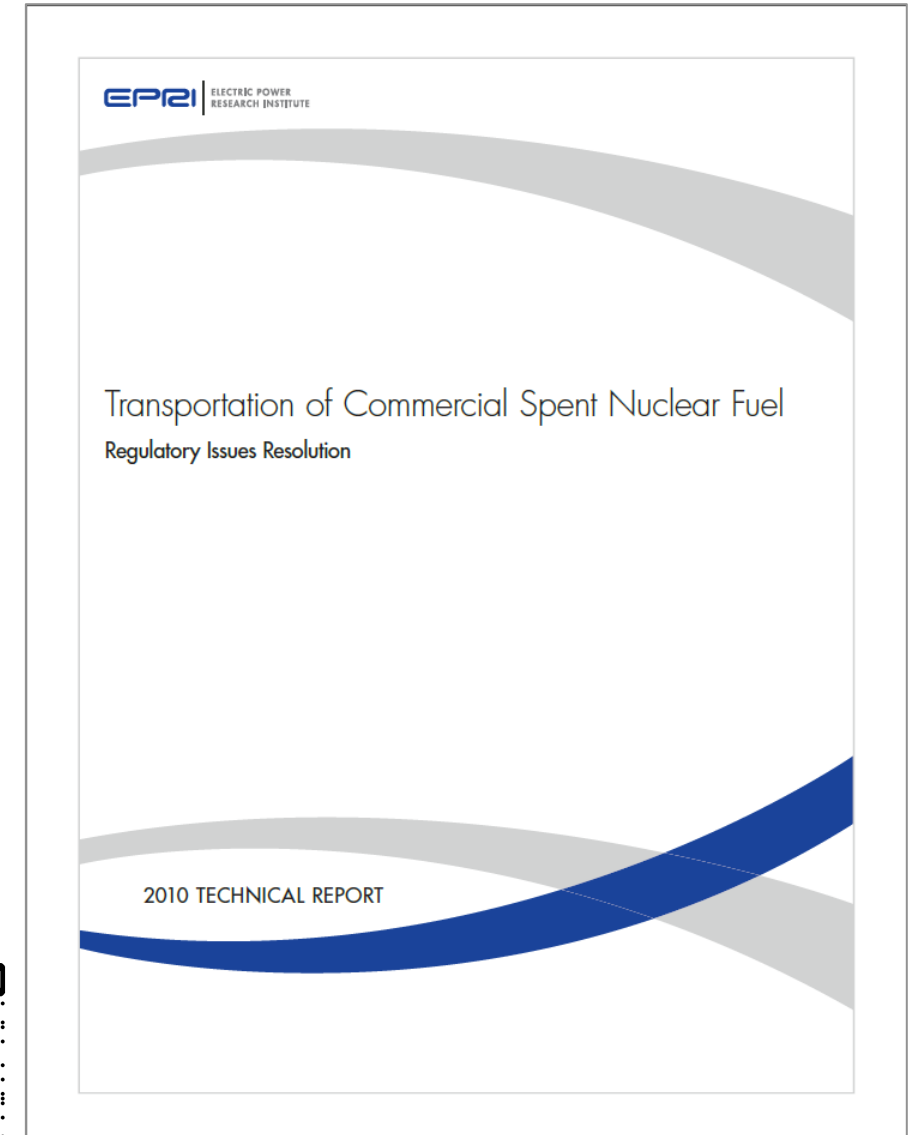
China Workshop
October 2025

2010 Technical Report

- Previous EPRI work on SNF Transportation was undertaken in 2010
- Identified issues relating to the transportation of HBU fuel (>45 GWd/tHM) and a path for their resolution:
 - Application of burnup credit
 - Fuel assembly burnup measurement
 - Application of moderator exclusion



1016637



2025 Technical Update



- Published July 2025
- Provides a snapshot of where we are now, issues that have been resolved and identifies forward-looking research areas to support transport of spent:
 - Current fleet LWR fuels
 - Accident tolerant fuels
 - Advanced reactor fuels

3002031701



Starting point for defining future work...

Regulatory Updates

- Captures updates to US NRC regulations made since publication of the 2010 Technical Report:
 - No changes to 10 CFR Part 71
 - Updates made to numerous NUREGs and SRPs to provide guidance to NRC reviewers and license applicants in relation to transportation of HBU fuel
- Internationally, IAEA issued revision to SSR-6 Transport Regulations in 2018 and its associated guidance
- Highlights differences in approach between US and international regulators for HBU transport

Current Fleet LWR Fuels

- Since 2010, significant progress made towards transporting HBU fuels with various casks effectively licensed to 62 GWd/MTU
- The three issues identified in 2010 effectively closed out

Table 1. Summary of Resolution of Issues Identified in EPRI 2010 Report [1]

Issue Identified	Resolved (Y/N)	Addressed In
Burnup credit methodology	Y	NUREG-2216 [13], NUREG-2224 [16], NUREG/CR-7194 [17], NUREG/CR-7224 [18], NUREG/CR-7251 [19], NUREG/CR-7252 [20], NUREG/CR-7240 [21], NUREG/CR-7306 [22]
Fuel assembly burnup measurement	Y	NUREG-2216 [13],
Moderator exclusion	Y	NUREG-2216 [13], NUREG-2224 [16]

Current Fleet LWR Fuels

- Identified two areas of ongoing work:
 - Impact of extended periods of dry storage on fuel and systems
 - Understanding how the fuel ages and the potential implications this can have on its handling.
 - Aging management programs have been devised and are undertaken to understand how dual and multipurpose systems will perform over and following long storage durations
 - Links to current HBU Demo Project
 - Managing storage-transport-storage (72-71-72) transition
 - Managing the interface between storage, transport, and continued storage, especially where the initial storage period was prolonged.
 - Determining what inspections, verifications, analyses are required to support above what is undertaken for storage

Research efforts underway

Accident Tolerant Fuels

- Categorized into 'near term' and 'long term' concepts
 - Near term: Those that can be approved to support min-2020s deployment based on existing data and models
 - E.g. coated cladding (Cr), doped pellets, higher burnup (75-80 GWd/MTU) and increased enrichment (up to 10% U-235)
 - LTAs introduced in several NPPs
 - Long term: Those that require more research and testing before implementation
 - E.g. uranium nitride pellets, silicon carbide cladding, extruded metal fuel
- Publication focuses on near term concepts

Accident Tolerant Fuels

- Four areas identified relating to either ongoing or upcoming work
 - Cladding properties and performance
 - Will cladding coatings or new pellet compositions affect mechanical behavior during loading, storage and subsequent transport?
 - Aging mechanisms in dry storage & impacts on transportation
 - Will there be an effect on aging mechanisms compared to current Zr-clad LWR?
 - Effect of high burnups (>62 GWd/MTU)
 - Increased burnups will lead to higher source terms and decay heats – how will this affect transportation strategies and logistics?
 - Impact of increased enrichments (U-235 > 5%)
 - Increased enrichments will need expanded benchmarks and methods for evaluation

Work ongoing to obtain data to support assessments

Advanced Reactor Fuels

- High level considerations given early stage of fuel development
- Looked at four fuel types:
 - Ceramic / oxide fuels – similar to current LWR
 - TRISO fuels – particle fuels in either prismatic blocks or pebbles for HTGR reactors
 - Metallic fuels
 - Liquid fuels – predominantly salts
- Differing levels of knowledge relating to them, but some commonalities on the issues relevant for transport.

Advanced Reactor Fuels

- Five general areas identified needing further work to address:
 - Fuel form / cladding properties and performance
 - What are the properties and performance of the different cladding and/or fuel materials?
 - Aging mechanisms in dry storage & impacts on transportation
 - How will these materials behave during storage periods and what is the impact of storage
 - Effect of high burnups
 - What impact will this have on thermal loads and source term?
 - Impact of increased enrichments, up to 25% U-235 (HALEU)
 - What benchmarks and methods for evaluation are needed to underpin criticality safety?
 - Chemical hazards
 - What non-nuclear hazards are presented, such as presence of sodium, that require assessment?

**LWR-SMR types are underpinned by existing fuels
For TRISO, work is underway on addressing these issues**

Conclusions



- Earlier current fleet issues have been resolved
- Forward-looking research areas have been identified to support transport of spent:
 - Current fleet LWR fuels
 - Accident tolerant fuels
 - Advanced reactor fuels



3002031701



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ESCP International Thermal Modeling Benchmark Project Results



Hatice Akkurt, PhD
Senior Technical Executive

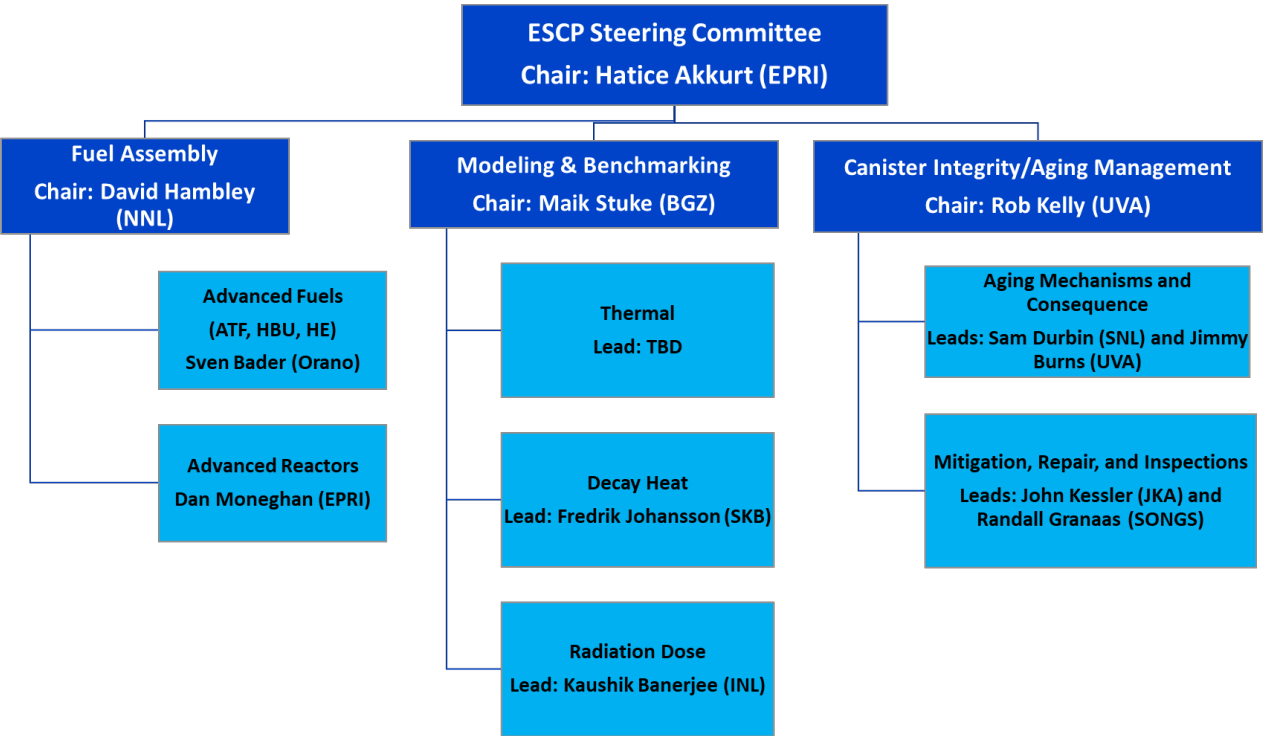
China Workshop
October 13-15, 2025

Acknowledgements

Organization	Participants
BGZ Company for Interim Storage (BGZ, Germany)	Özlem Aktas Özülüs, Maik Stuke
Centrales Nucleares Almaraz-Trillo (CNAT, Spain)	Rafael Sánchez, Andrea Cadenas
EDF, France	Max Fressonnet, Didier Colmont, Antoine Sicot
Equipos Nucleares, S.A., S.M.E. (ENSA, Spain)	Virginia Madrazo, Victor Gomez, Miguel Prieto, Alfonso Fernandez, Luis Moreno, Alejandro Palacio, David Castrillón
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS, Germany)	Marc Péridis, Daniel Nahm
Gesellschaft für Nuklear-Service (GNS Germany)	Roland Hueggenberg
Idaho National Laboratory (INL, USA)	Josh J. Jarrell, Fande Kong, Alexander Lindsay, Sterling Harper, Guillaume Giudicelli, Derek Gaston
Pacific Northwest National Laboratory (PNNL, USA)	David Richmond, Jim Fort
ÚJV Řež, a. s. (Czech Republic)	Martin Dostál, Jan Klouzal
University of Nevada Reno (UNR, USA)	Megan Higley, Mustafa Hadj-Nacer, Miles Greiner
WTI Wissenschaftlich Technische Ingenieurberatung (WTI, Germany)	André Leber, Sven Tittelbach

Thank you to all the participants and participating organizations!

Extended Storage Collaboration Program (ESCP)



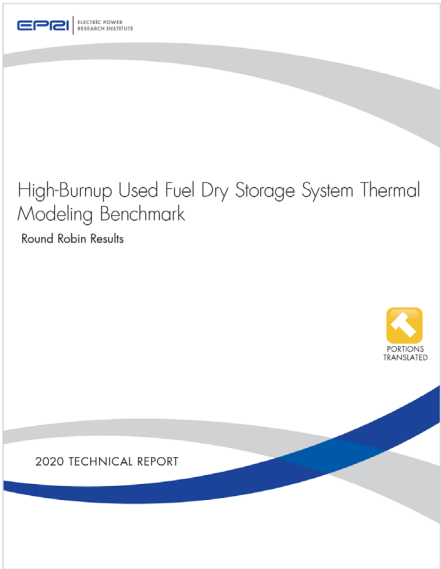
ESCP: Collaborative forum for addressing global challenges around dry storage and transportation

ESCP Subcommittees and Task groups formed, merged, sunset based on the global needs

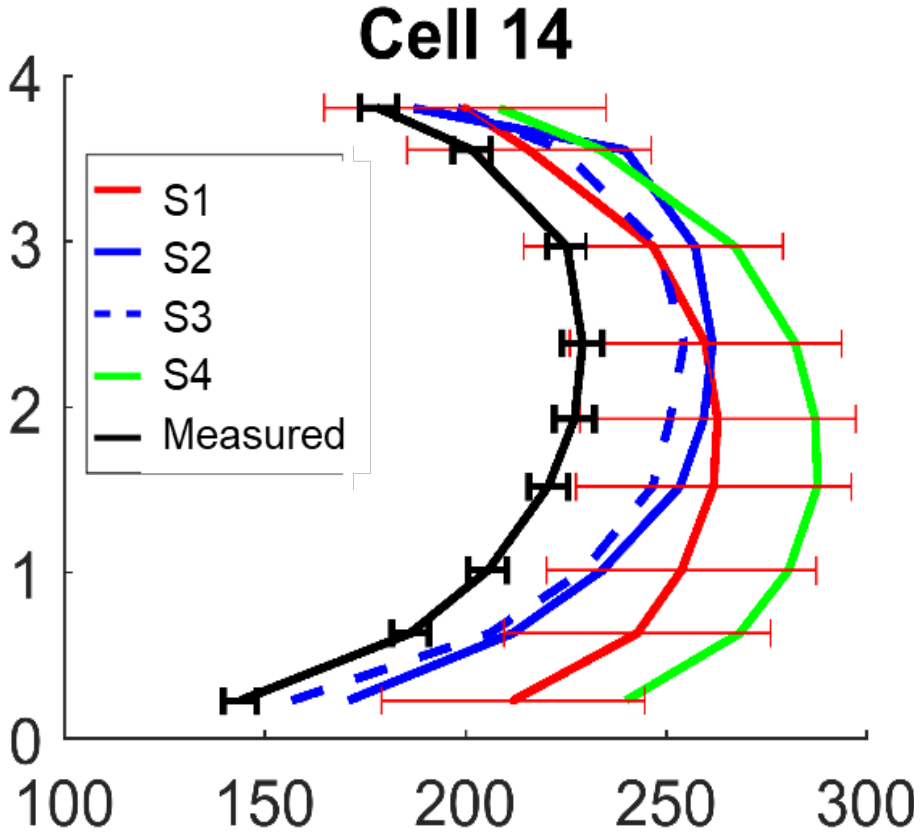
HBU Demo Showed Temperature Predictions are Overestimated



Parameter	FSAR	LAR	Best-Estimate	HBU Cask Meas.
PCT	348°C	318°C	254-288°C	229°C
Total Heat Load (kW)	36.96	32.934	30.456	30.456
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?



EPRI report, **3002013124**, published in April 2020 and publicly available – includes blind benchmark results



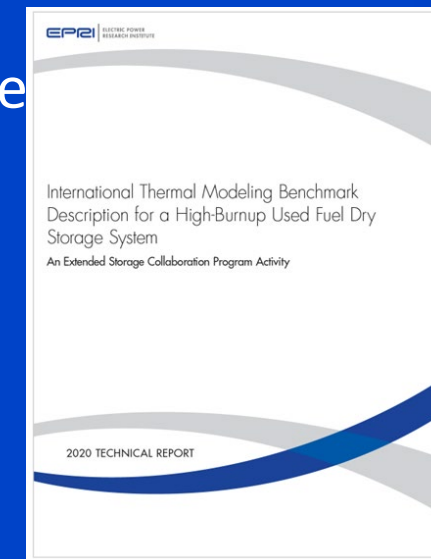
Modeler	Code
S1	ANSYS Fluent
S2	STAR-CCM+
S3	COBRA
S4	ANSYS APDL

ESCP International Thermal Modeling

- **Objectives:** Perform benchmark calculations using publicly available information – not a blind benchmark.
- **Desired outcomes** include better understanding of:
 - Code-to-code variation in predictions
 - User-to-user variation (same code, varying users/organizations)
 - Ability to compare impact of using publicly available information versus proprietary design data

EPRI report, **3002018498**, provides a description of the benchmark:

- Based on publicly available information
- Includes a recording of the description
- Participants were asked to follow description for easier comparison of the results
- Report is publicly available from [epri.com](https://www.epri.com)



Summary of Participating Organizations and Codes

Solution Method	Code(s)	Organization(s)
Finite Element Method (FEM)	ANSYS Mechanical	CNAT ENSA WTI
	ABAQUS	UJV**
	SYRTHES*	EDF*
Finite Volume Method (FVM)	ANSYS Fluent	UNR**
	GOTHIC	CNAT
	STAR-CCM	PNNL
Finite Difference Method (FDM)	COBRA-SFS	GRS PNNL BGZ*
FEM & FVM	MOOSE	INL

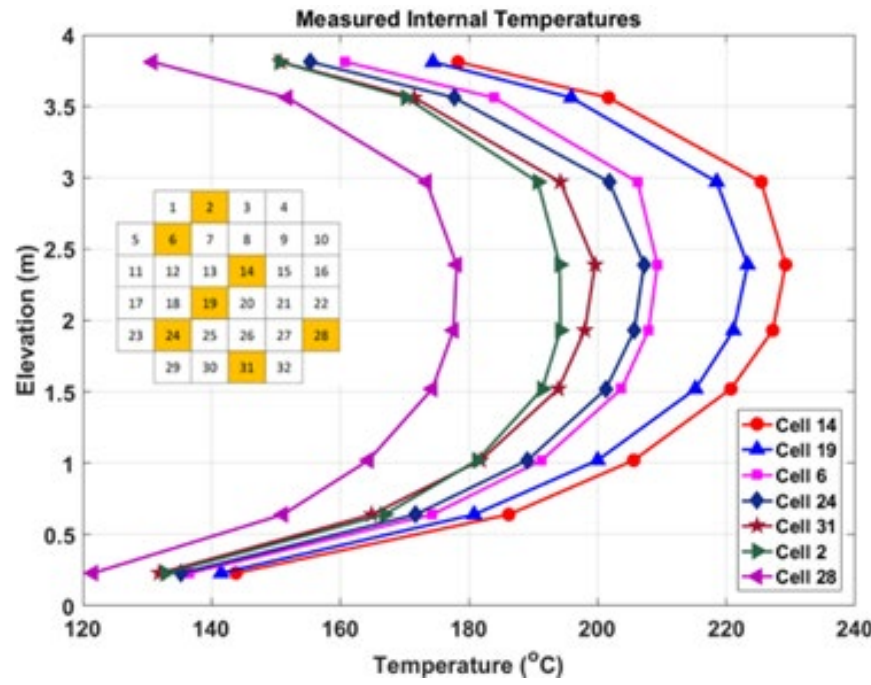
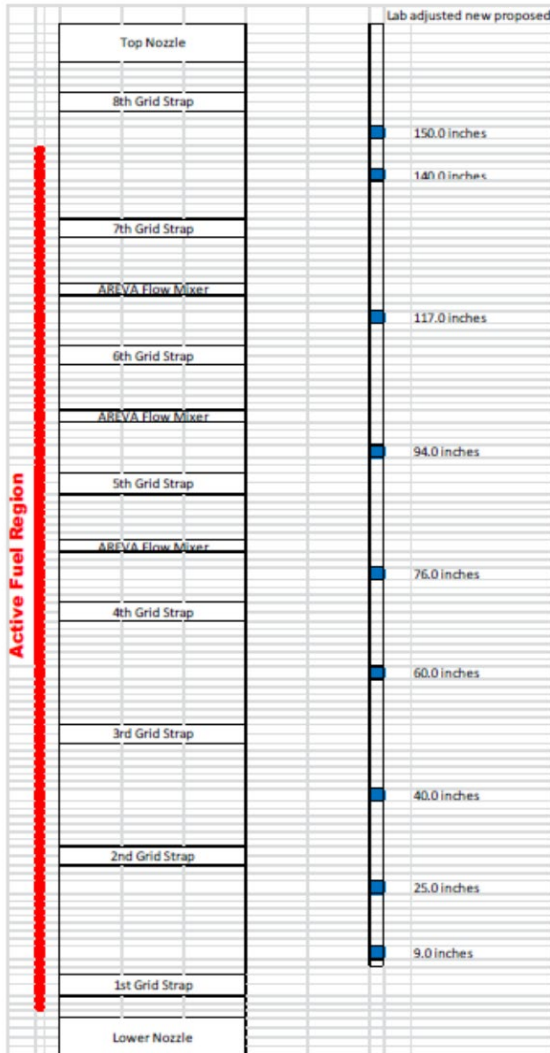
*New participant
(After Phase I
completion)

**Revised results
for Phase I

10 organizations, 8 codes, and 12 submissions with 4 different solution approaches

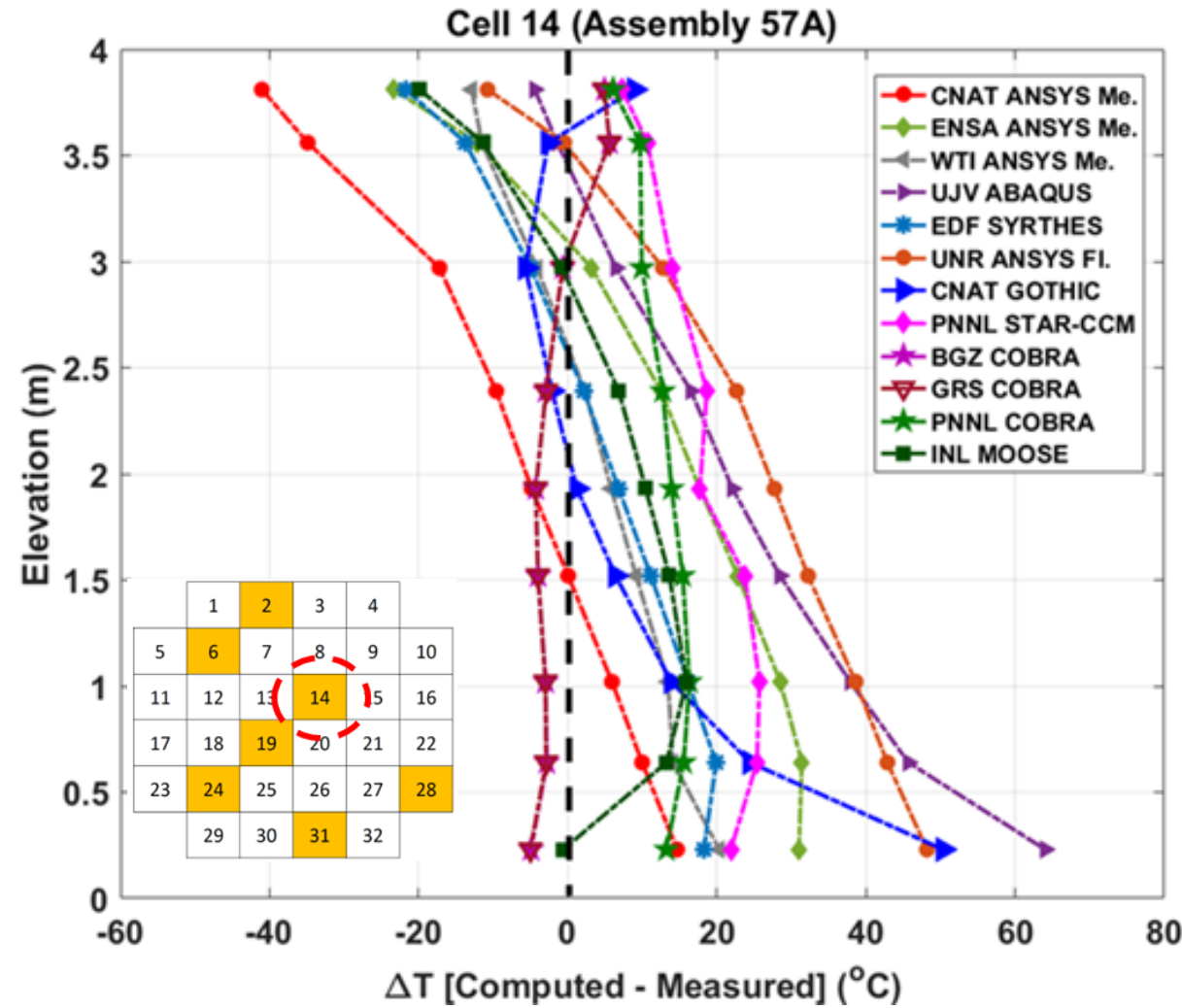
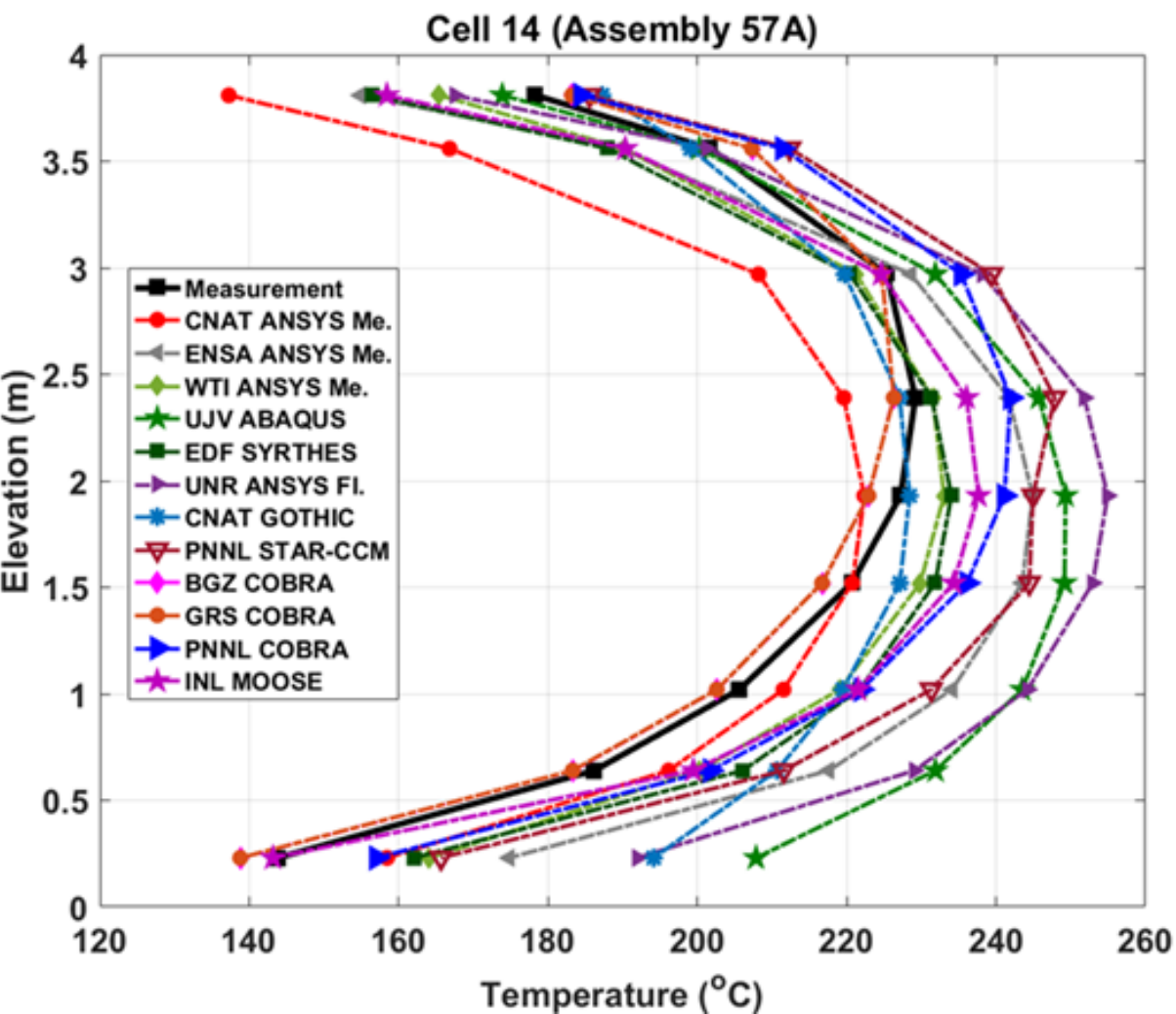
Fuel Loading Map & Thermocouple Locations

	1 6T0 NAIF/P+Z Zirlo, 54.2 GWd 4.25%/3 cy/12.1 yr 912.2 W	2 (TC Lance) 3K7 AMBW M5, 53.4 GWd 4.55%/3 cy/8.7 yr 978.2 W	3 3T6 NAIF/P+Z Zirlo, 54.3 GWd 4.25%/3 cy/12.1 yr 914.4 W	4 6F2 NAIF/P+Z Zirlo, 51.9 GWd 4.25%/3 cy/13.5 yr 799.5 W	Drain Port
5 3F6 NAIF/P+Z Zirlo, 52.1 GWd 4.25%/3 cy/13.5 yr 800.9 W	6 (TC Lance) 30A AMBW M5, 52.0 GWd 4.55%/3 cy/7.2 yr 1008.6 W	7 22B AMBW M5, 51.2 GWd 4.55%/3 cy/5.7 yr 1142.4 W	8 (PRA) 20B AMBW M5, 50.5 GWd 4.55%/3 cy/5.7 yr 1121.2 W	9 5K6 AMBW M5, 53.3 GWd 4.55%/3 cy/8.7 yr 975.1 W	10 5D5 NAIF/P+Z Zirlo, 55.5 GWd 4.20%/3 cy/17.7 yr 814.5 W
11 (Vent Port) 5D9 NAIF/P+Z Zirlo, 54.6 GWd 4.20%/3 cy/17.7 yr 802.6 W	12 28B AMBW M5, 51.0 GWd 4.55%/3 cy/5.7 yr 1135.0 W	13 (PRA) F40 LOPAR Zry-4, 50.6 GWd 3.59%/3 cy/30.6 yr 573.8 W	14 (TC Lance) 57A AMBW M5, 52.2 GWd 4.55%/3 cy/7.2 yr 1037.0 W	15 (PRA) 30B AMBW M5, 50.6 GWd 4.55%/3 cy/5.7 yr 1124.8 W	16 3K4 AMBW M5, 51.8 GWd 4.55%/3 cy/8.7 yr 941.3 W
17 5K7 AMBW M5, 53.3 GWd 4.55%/3 cy/8.7 yr 961.7 W	18 (PRA) 50B AMBW M5, 50.9 GWd 4.55%/3 cy/5.7 yr 1131.1 W	19 (TC Lance) 3U9 NAIF/P+Z Zirlo, 53.1 GWd 4.45%/3 cy/10.6 yr 920.2 W	20 (PRA) 0A4 NAIF Low-Sn Zry-4, 50.0 GWd 4.00%/2 cy/23.2 yr 646.2 W	21 15B AMBW M5, 51.0 GWd 4.55%/3 cy/5.7 yr 1135.8 W	22 6K4 AMBW M5, 51.9 GWd 4.55%/3 cy/8.7 yr 941.2 W
23 3T2 NAIF/P+Z Zirlo, 55.1 GWd 4.25%/3 cy/12.1 yr 934.7 W	24 (TC Lance) 3U4 NAIF/P+Z Zirlo, 52.9 GWd 4.45%/3 cy/10.6 yr 914.2 W	25 (PRA) 56B AMBW M5, 51.0 GWd 4.55%/3 cy/5.7 yr 1133.7 W	26 54B AMBW M5, 51.3 GWd 4.55%/3 cy/5.7 yr 1136.3 W	27 6V0 AMBW M5, 53.5 GWd 4.40%/3 cy/8.7 yr 988.2 W	28 (TC Lance) 3U6 NAIF/P+Z Zirlo, 53.0 GWd 4.45%/3 cy/10.6 yr 916.9 W
	29 4V4 AMBW M5, 51.2 GWd 4.40%/3 cy/9.1 yr 914.2 W	30 5K1 AMBW M5, 53.0 GWd 4.55%/3 cy/8.7 yr 968.0 W	31 (TC Lance) 5T9 NAIF/P+Z Zirlo, 54.9 GWd 4.25%/3 cy/12.1 yr 927.7 W	32 4F1 NAIF/P+Z Zirlo, 52.3 GWd 4.25%/3 cy/13.5 yr 804.3 W	



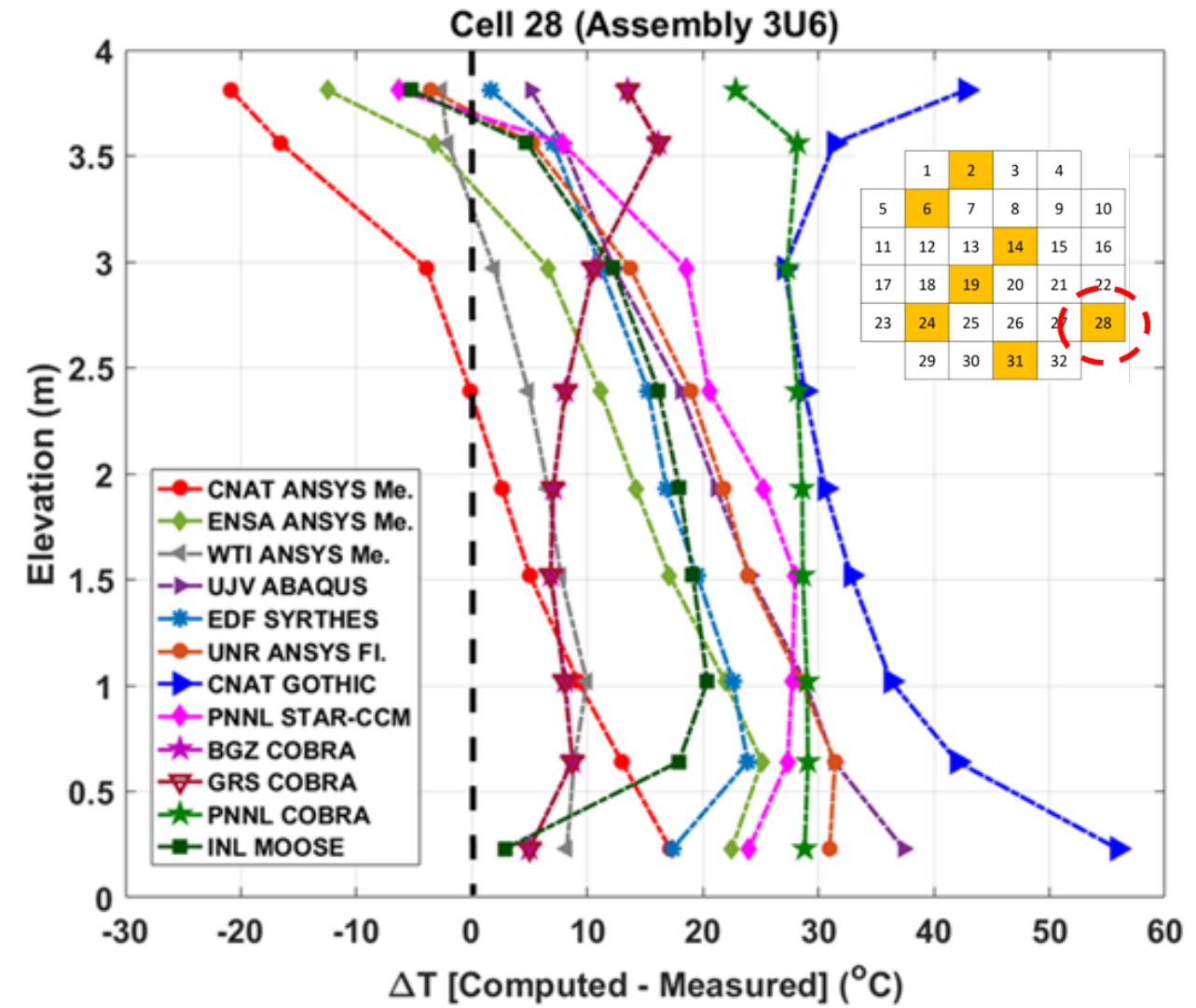
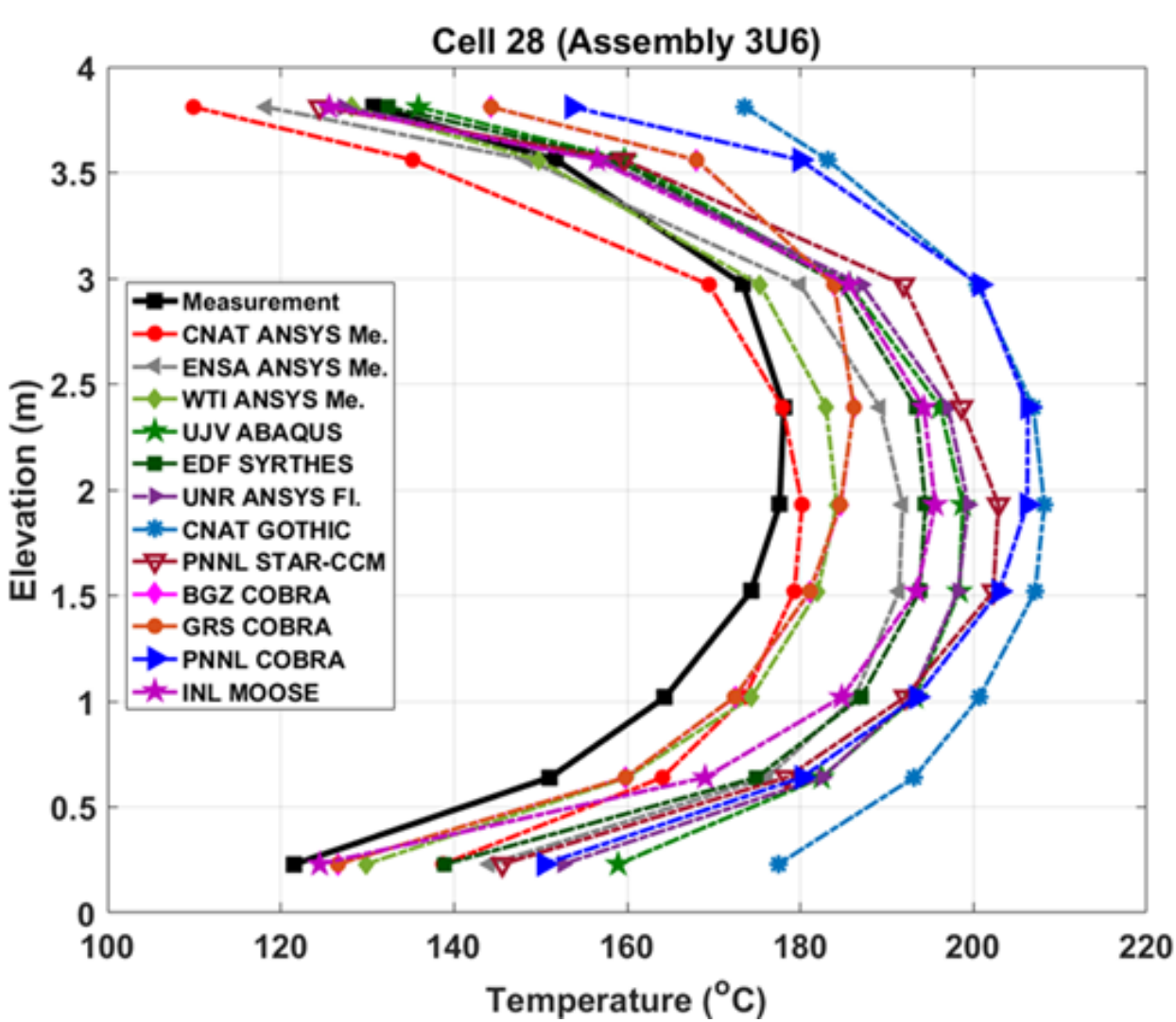
Temperature measurement locations: Cells 2, 6, 14, 19, 24, 28, 31

Cell 14 - Interior Cell



Shape is in general predicted well; however, mostly underprediction for top and overprediction for bottom

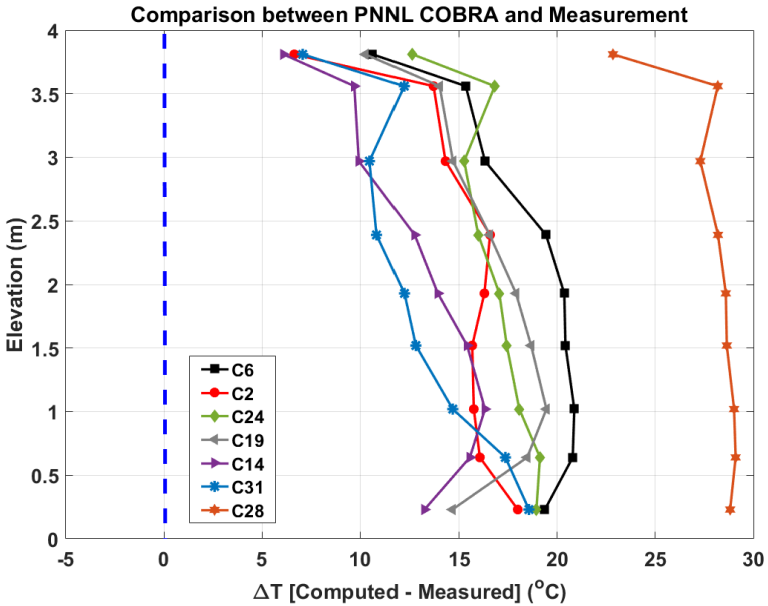
Cell 28 – Exterior Cell



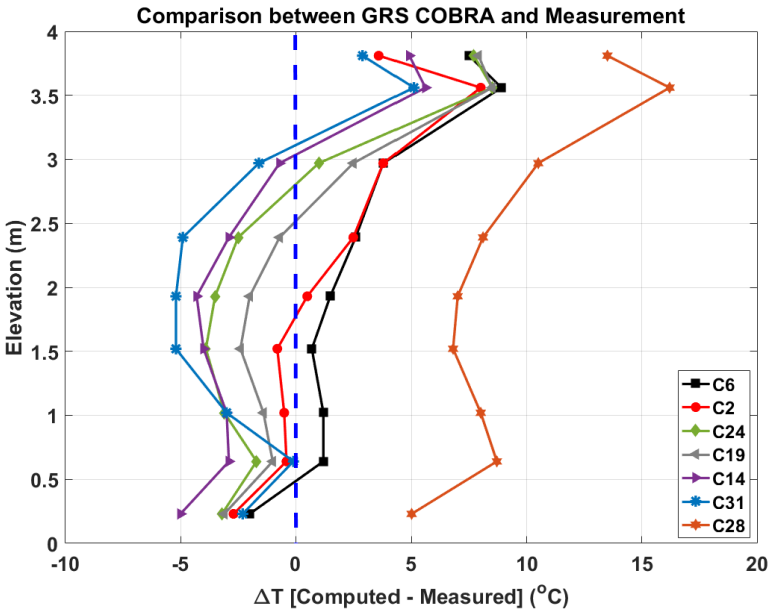
Mostly overprediction for exterior cell

Same Code, Different Users: COBRA-SFS

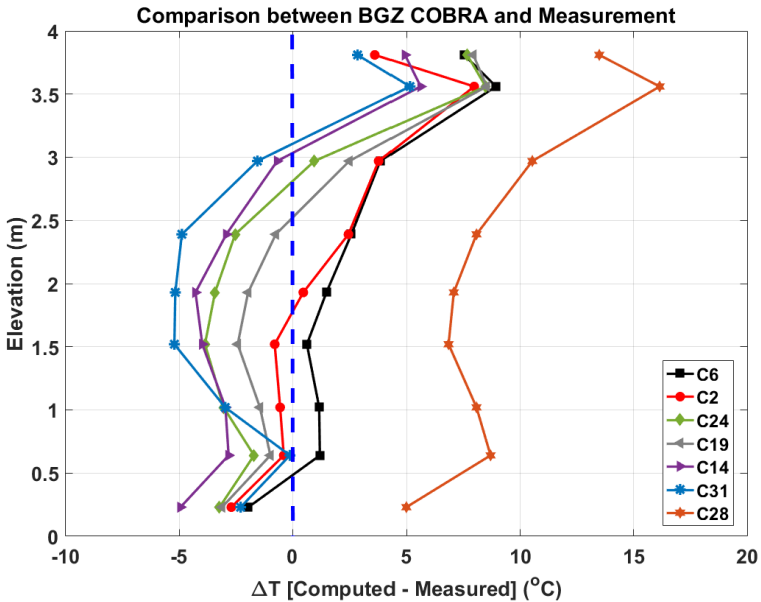
	1	2	3	4	
5	6	7	8	9	10
11	12	13	14	15	16
17	18	19	20	21	22
23	24	25	26	27	28
29	30	31	32		



PNNL Results



GRS Results



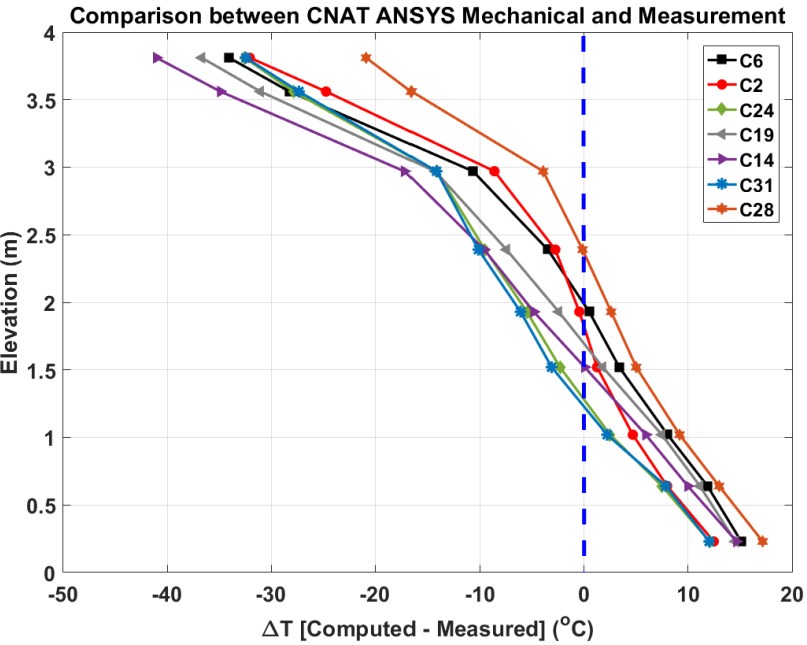
BGZ Results

PNNL results show consistent overprediction while BGZ and GRS results, mostly, shows mixture, except Cell 28. Better agreement between BGZ and GRS COBRA-SFS results.

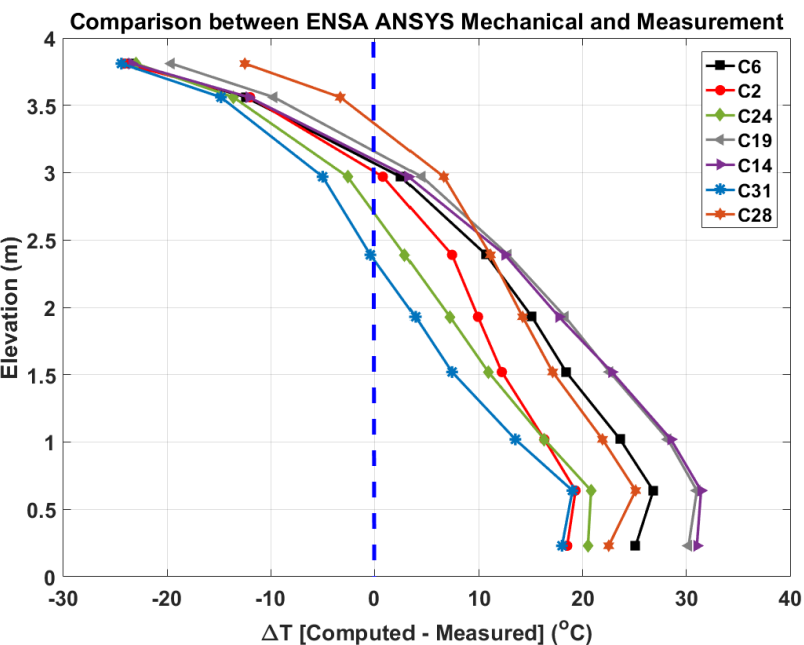
For all three organizations, Cell 28 is significantly overestimated.

Same Code, Different Users: ANSYS Mechanical

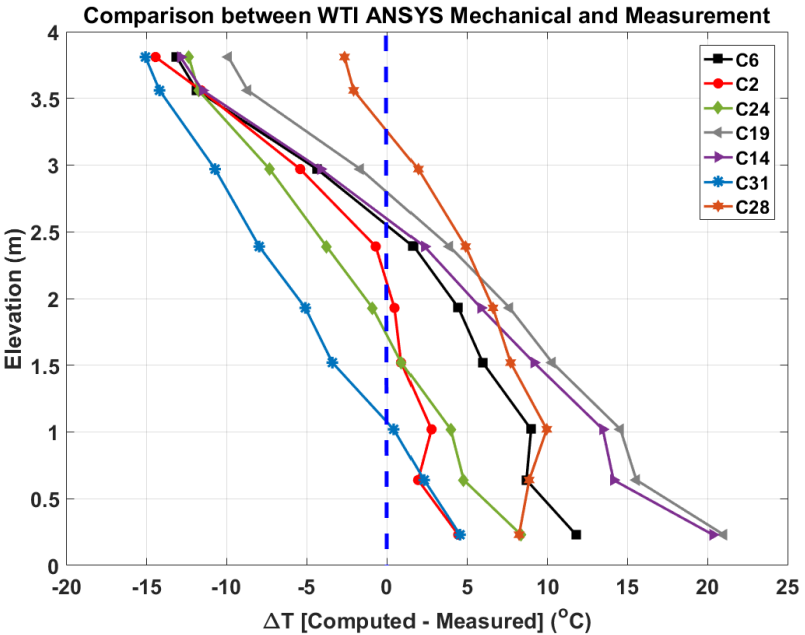
	1	2	3	4	
5	6	7	8	9	10
11	12	13	14	15	16
17	18	19	20	21	22
23	24	25	26	27	28
	29	30	31	32	



CNAT Results



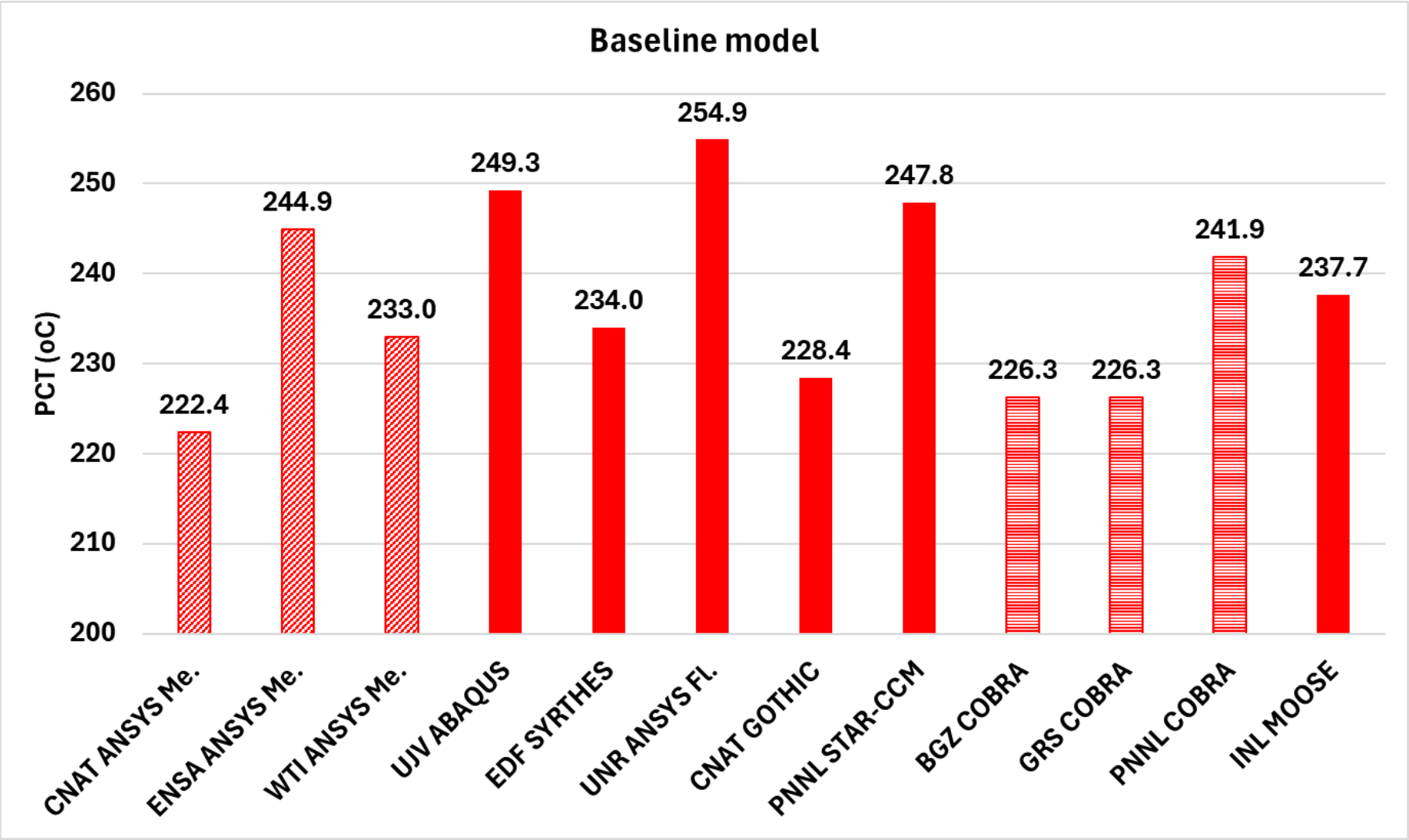
ENSA Results



WTI Results

Varying results between different organizations using the same code

Correlation Between Codes and Results



ANSYS Mechanical
results provided by:

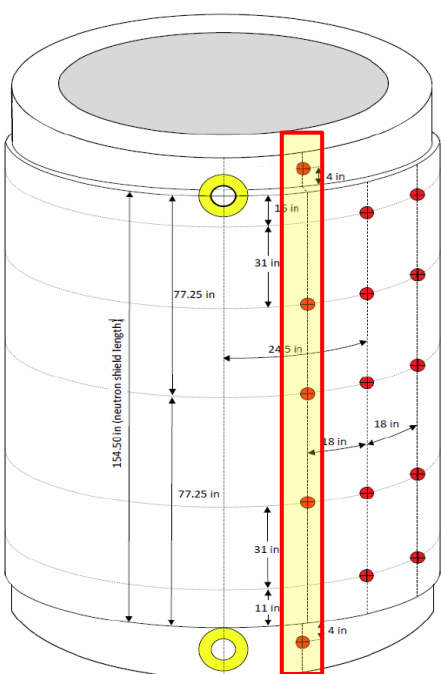
- 1. CNAT
- 2. ENSA
- 3. WTI

COBRA-SFS results
provided by

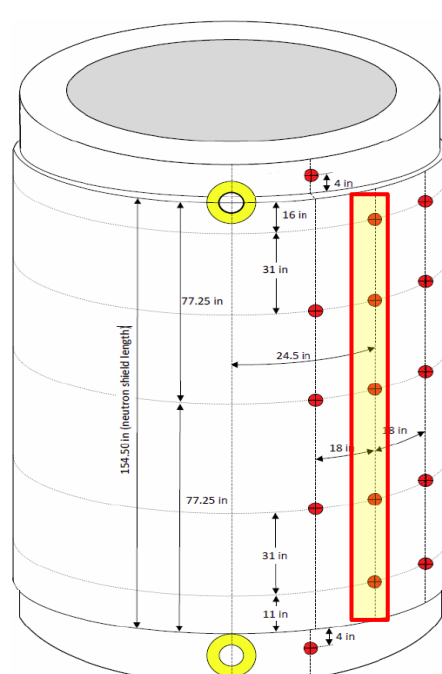
- 1. GRS
- 2. PNNL
- 3. BGZ

Significant variations in the results submitted by different organizations, even using the same code

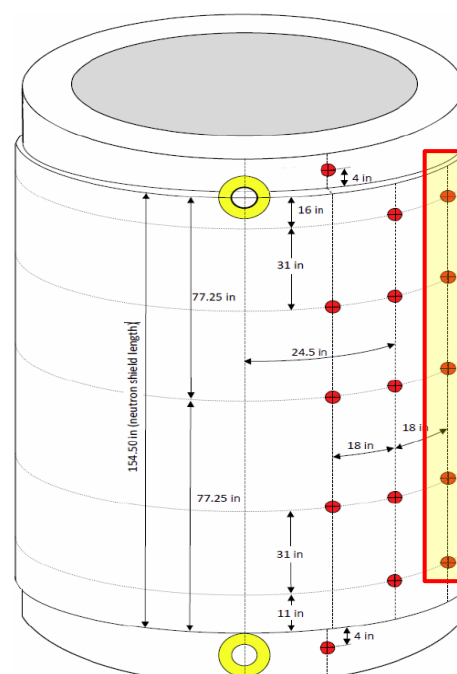
External Temperature Measurements



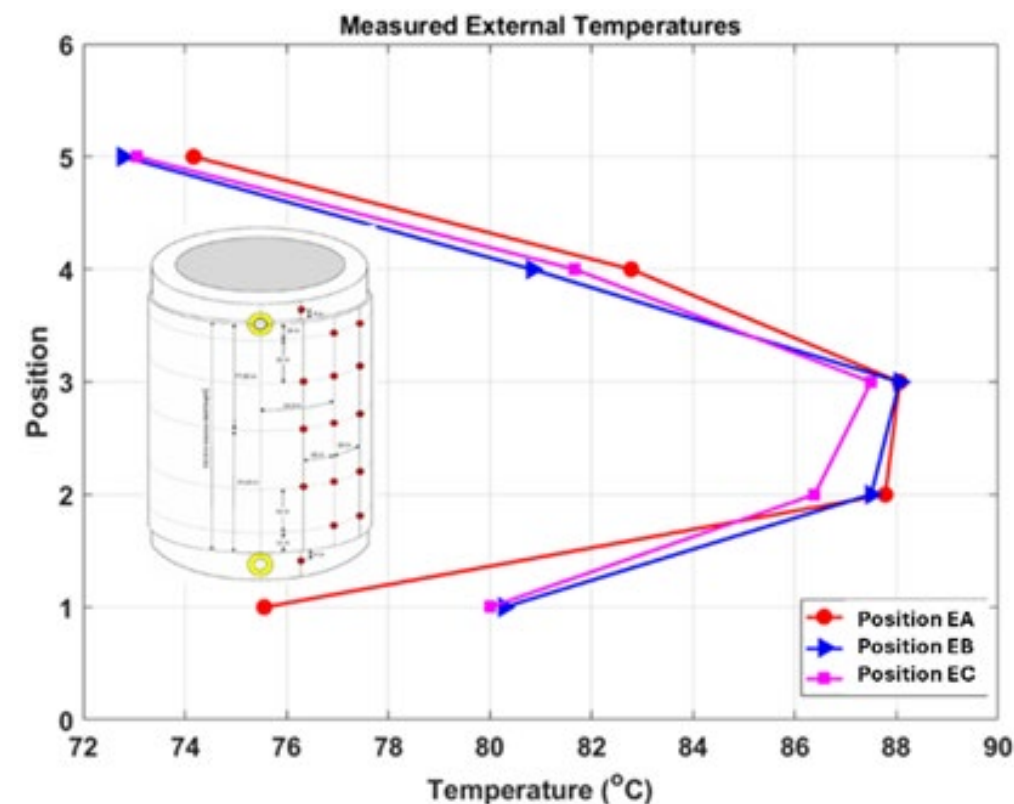
EA (left)



EB (center)

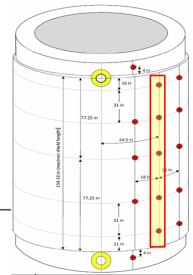


EC (right)

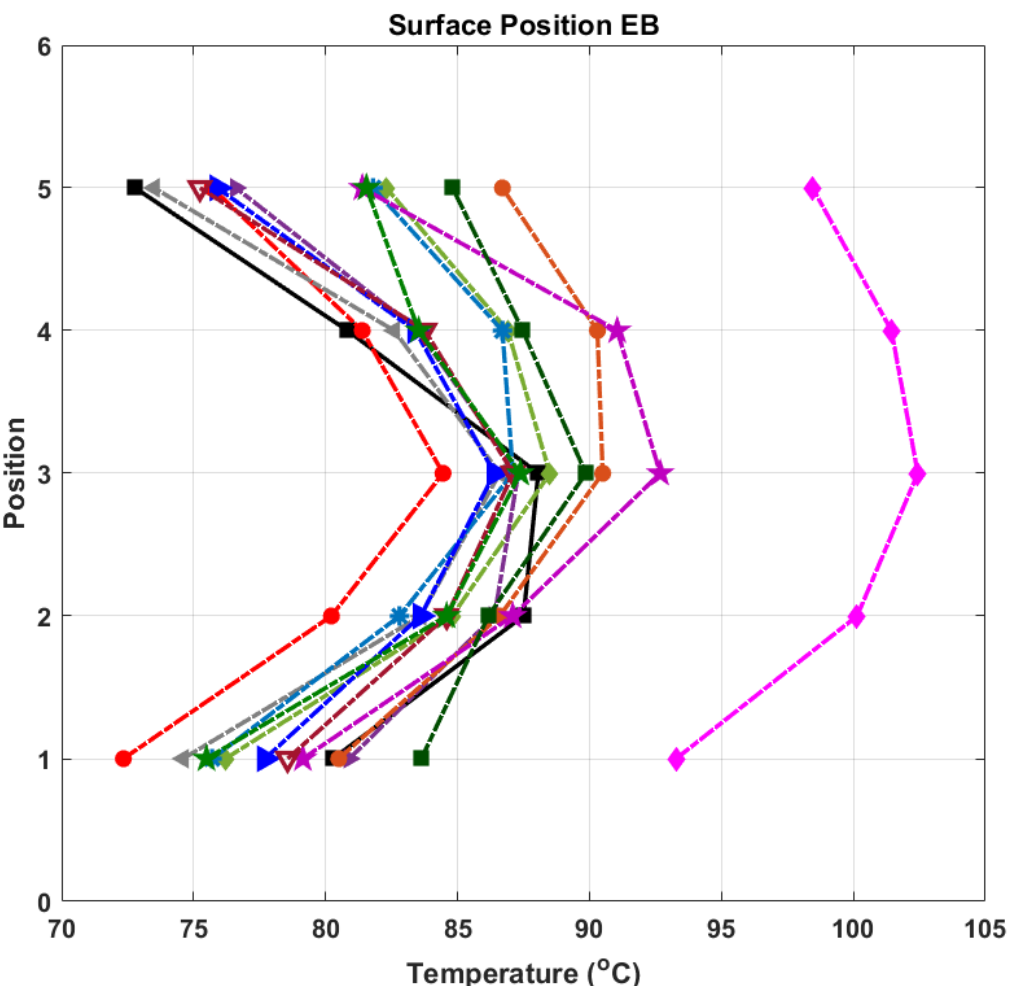


External temperature measurement locations and measured temperatures

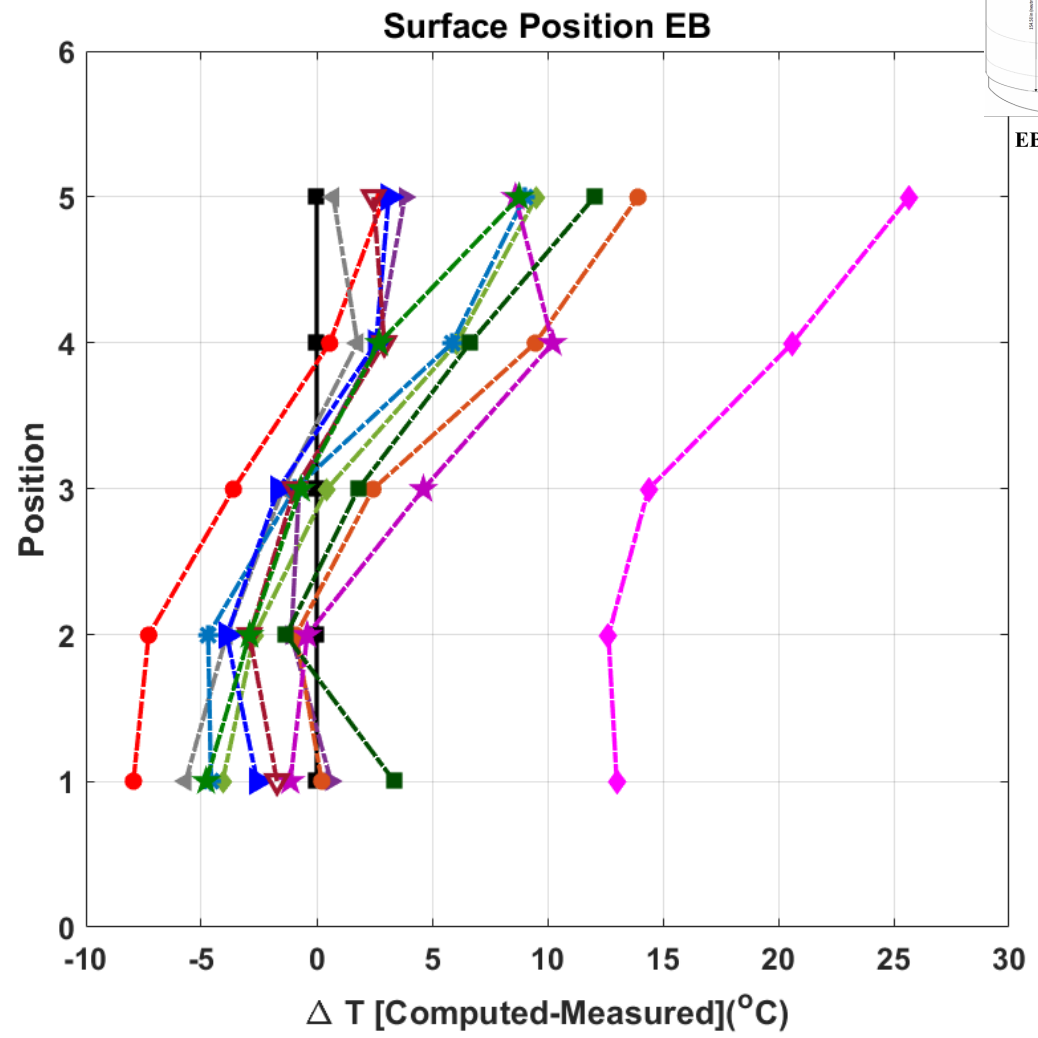
External Temperatures – Surface Position EB



EB (center)



- Measurement
- CNAT ANSYS Me.
- ENSA ANSYS Me.
- WTI ANSYS Me.
- GRS COBRA
- BGZ COBRA
- PNNL COBRA
- PNNL STAR-CCM
- CNAT GOTHIC
- UJV ABAQUS
- UNR ANSYS FI.
- INL MOOSE
- EDF SYRTHES



Gothic code shows the highest overestimation

Key Takeaways from Baseline Model Results

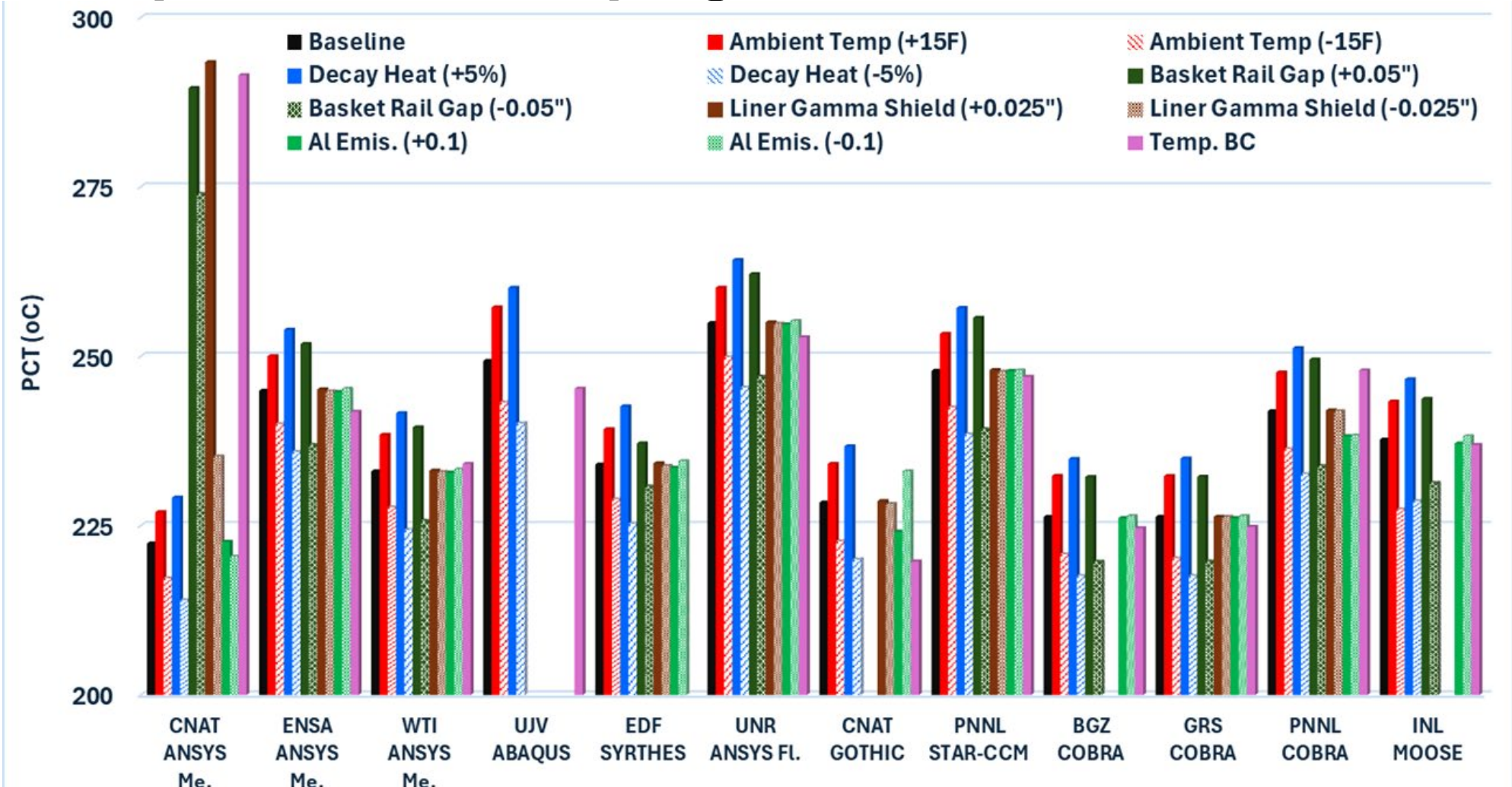
- Wide variation in temperature predictions
 - Between different codes
 - Between different organizations, using the same code
 - Higher degree of variation in the exterior assemblies and exterior surface predictions
- No correlation between computational time, details of the model and accuracy of the results
 - Surprisingly, COBRA-SFS shows the most reasonable estimations, compared to very detailed codes like STAR-CCM+ and others
- Most groups predicted the shape well
 - Generally skewed lower at high elevations

Phase II Sensitivity Parameters

- **Ambient Temperature:** $75^{\circ}\text{F} \pm 15^{\circ}\text{F}$ ambient (90°F , 60°F)
- **Decay Heat:** $\pm 5\%$ of base decay heat – baseline: 30.456 kW
- Gap between transition rail and basket -0.05 to 0.15 (0.1 ± 0.05)
- Gap between inner liner base and gamma shield – base 0.125 (range: ± 0.025)
- Emissivity of aluminum (current spec 0.2 adjust ± 0.1)
- Baseline: Specified surface temperature boundary condition

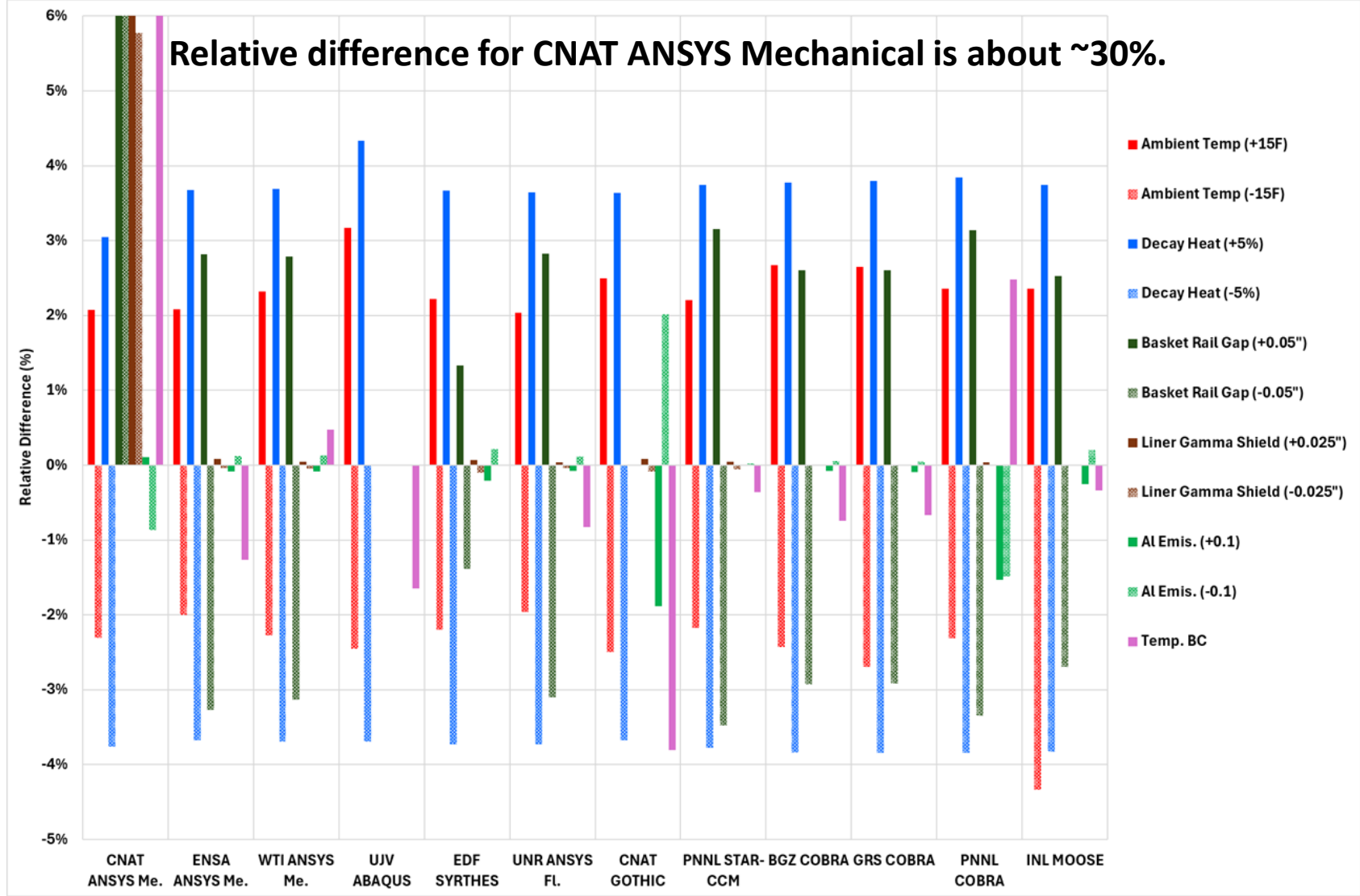
Received sensitivity calculation results from all the participants. Analysis is in final stages. Results will be published in an updated publicly available EPRI report (Phase I and Phase II results combined).

Sensitivity of PCT to Varying Parameters



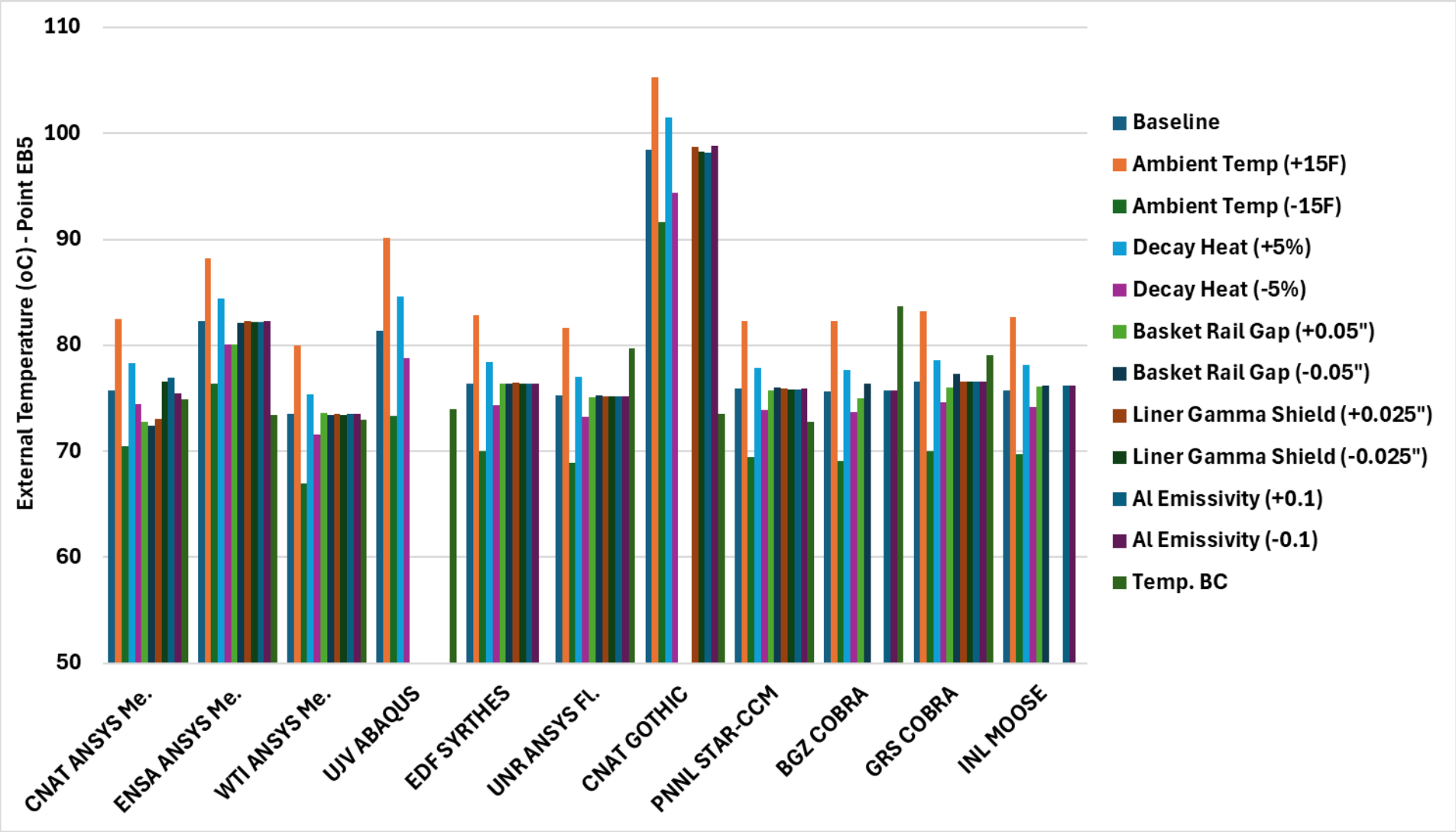
CNAT ANSYS Mechanical shows the largest sensitivities

Sensitivity of PCT to Varying Parameters



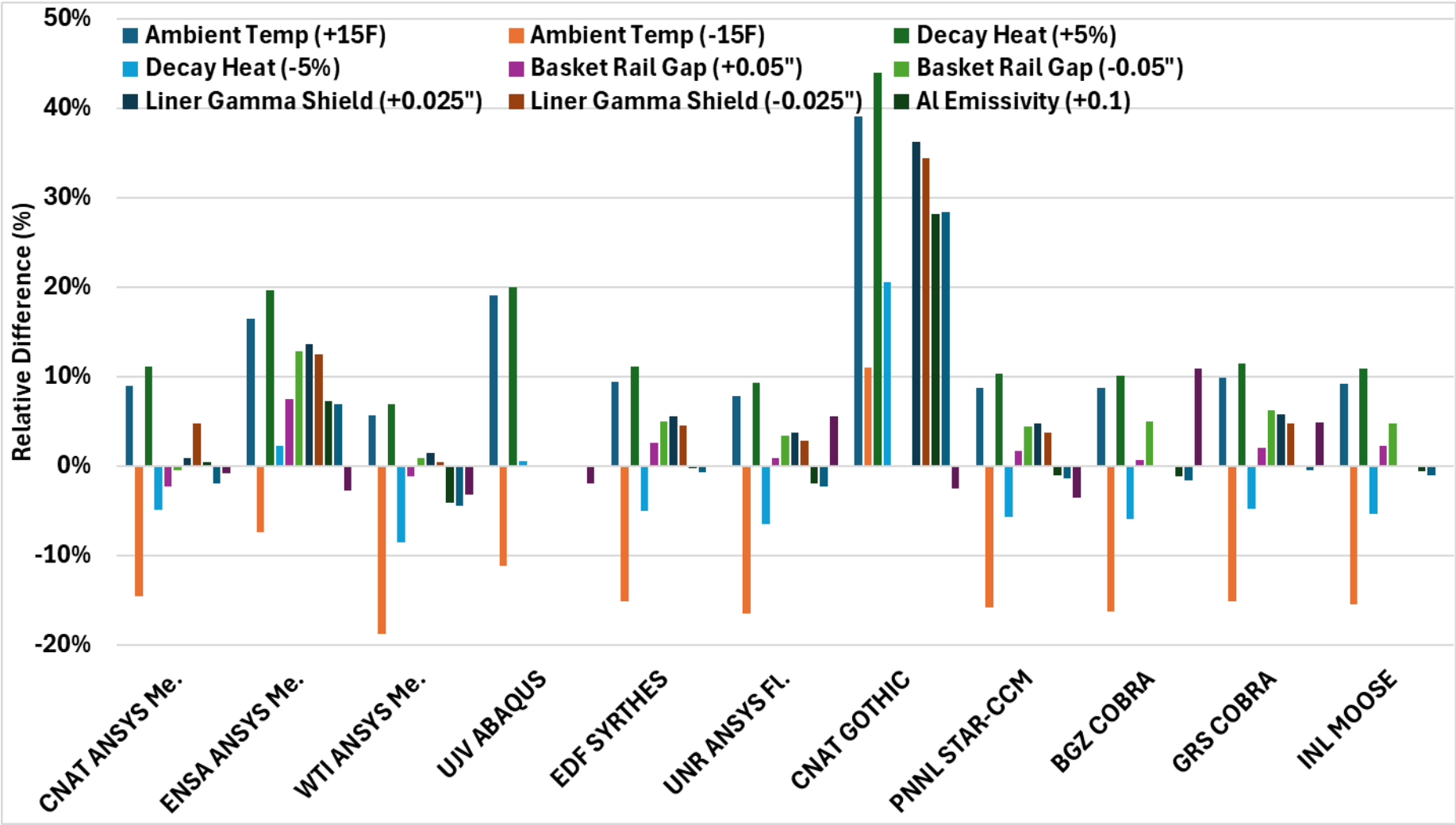
In general, highest sensitivity is due to decay heat followed with ambient temperature variations

Sensitivity of External Temperature to Varying Parameters



CNAT GOTHIC shows the largest sensitivities

Sensitivity of External Temperature to Varying Parameters



Highest sensitivity is due to ambient temperature followed with decay heat

2025 Upcoming Deliverable

- 3002032045, *ESCP International Thermal Modeling Report*, October 24, 2025

2025 Publications to Date

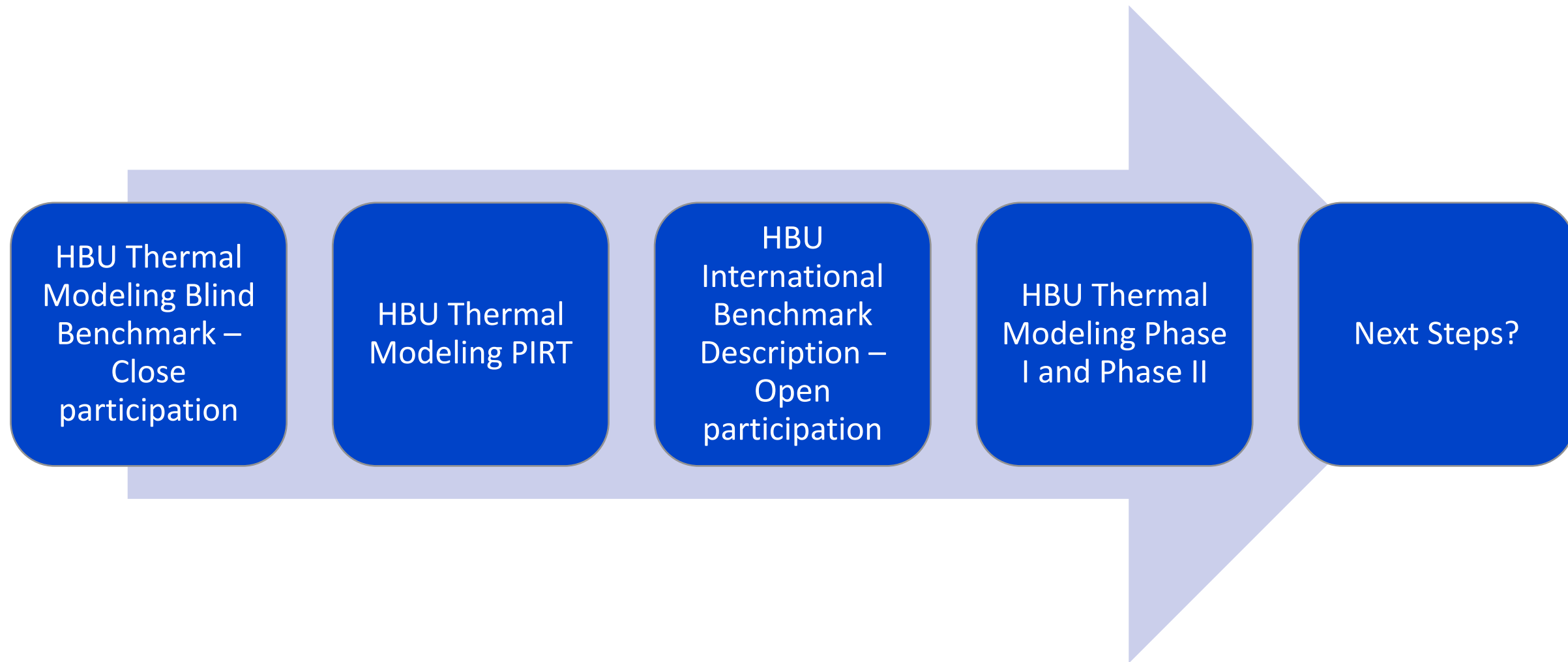
- Hatice Akkurt and Maik Stuke, “*ESCP International Thermal Modeling Benchmark Project Results*”, Proceedings of PATRAM 2025, July 2025.
- Hatice Akkurt and Maik Stuke, “*ESCP International Thermal Modeling Project: Comparison of PCT and External Surface Temperature Values with Varying Sensitivity Parameters*” accepted for inclusion in IHLRWM 2025 conference proceedings, November 2025.

Summary and Conclusions

- International thermal modeling Phase I and Phase II results received from
 - 10 organizations using 8 different codes
 - In total 12 submissions with 4 different solution approaches
- Some of the participants joined during Phase II (BGZ & EDF), provided results for Phase I and Phase II
- **Analysis show**
 - Large variations between codes
 - Large variations, even when the same code is used by different organizations
- **Phase II sensitivity analysis show significant sensitivity to changes in**
 - Decay heat
 - Ambient temperature
 - Basket gap
- No sensitivity to AI emissivity, with some exceptions, which will be reviewed with participants

Final report expected to be published in 2025 as a publicly available EPRI report (will supersede EPRI report 3002023976)

ESCP Thermal Modeling



Each step is resulting with more questions than answers? Next steps will be discussed here and at ESCP 2025 meeting



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