ELECTRIC POWER RESEARCH INSTITUTE

Thermal Modeling and Phenomena Identification and Ranking Tables (PIRTs)

Fuel/Cladding Performance
Decay Heat Modeling & Uncertainty
Thermal Modeling & Uncertainty

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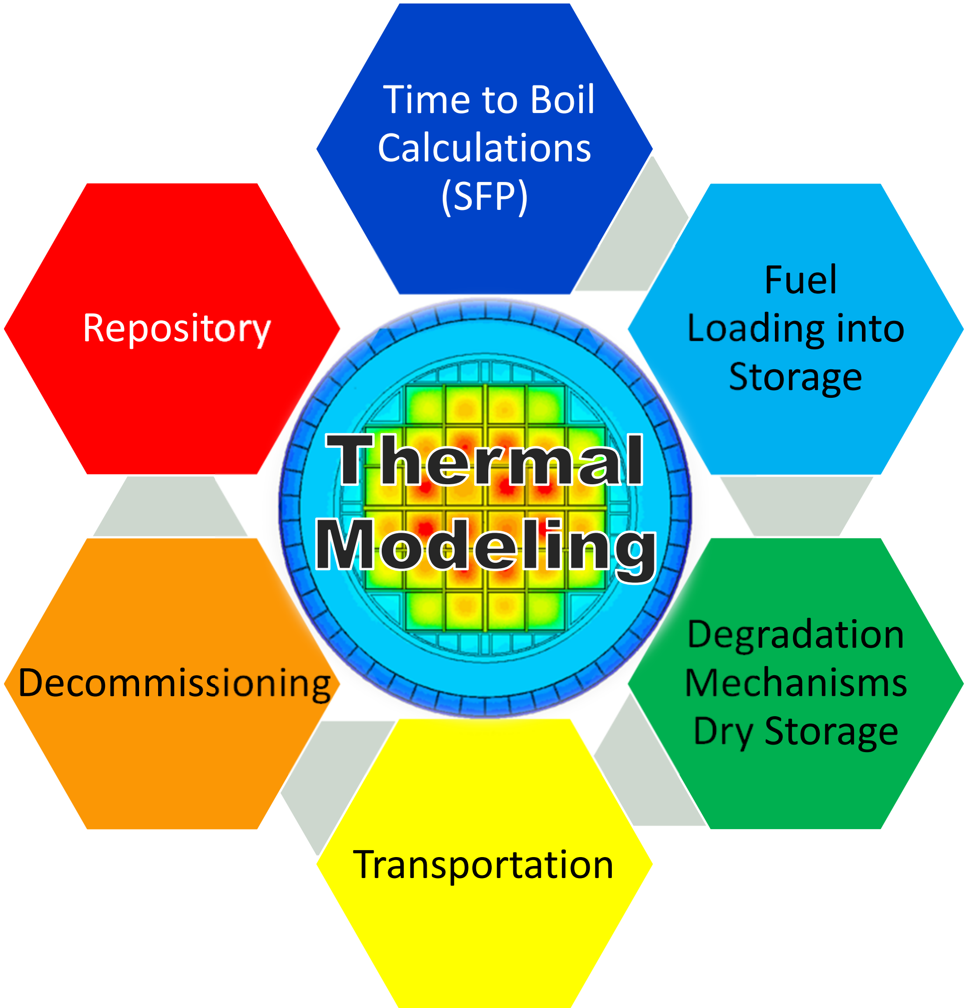
NRC Workshop on Spent Fuel Performance Margins

Benefits of Improved Thermal Models

- Occupational dose benefits:
  - Temporary shielding restrictions (blankets)
  - Time limits to keep mating device door open
- Dry storage operational benefits:
  - Storing hotter fuel sooner
  - More flexible SNF loadouts
  - Drying time limits and time to boil
  - Supplemental cooling requirements
  - Vent surveillance requirements
  - Fuel and canister degradation mechanisms
  - Risk informing aging management
- Reactor operations/safety benefits:
  - Reduced SFP temperatures/time-to-boil
- Accelerate decommissioning:
  - Pool to pad sooner (active to passive cooling)
- Informs repository loading footprint



ESCP Thermal Modeling Overview

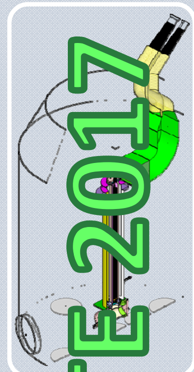
ESCP Steering Committee
Chair: Hatice Akkurt (EPRI)

Canister Integrity/Aging Management Subcommittee
Chair: Jeremy Renshaw (EPRI)

Fuel Assembly Subcommittee
Chair: Mike Billone (ANL) /
Vice-Chair: Sven Bader (Areva)

Thermal Modeling Subcommittee
Chair: Al Csontos (EPRI)
Vice-Chair: Sam Durbin (SNL)

International Subcommittee
David Hambley (NNL) Maik Stuke (GRS),
Woo-seok Choi (KAERI), Brady Hanson (PNNL)

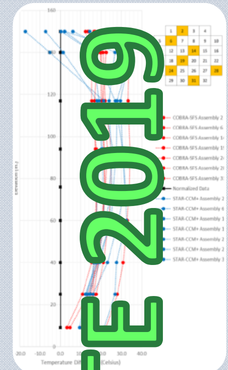


COMPLETE 2017

Phase I
BWR DCS Simulator
NRC/DOE Lead

COMPLETE 2019

Phase IIa
HBU Demo Cask Round Robin
EPRI Lead



COMPLETE 2019

Phase IIb
HBU Cask Sensitivity and Transient Analyses
DOE Lead

Q4 2019 Kickoff

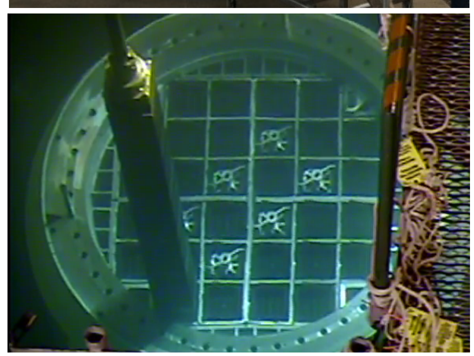
Phase IIc
Phenomena Identification Ranking Table (PIRT) Gap Analysis
EPRI Lead

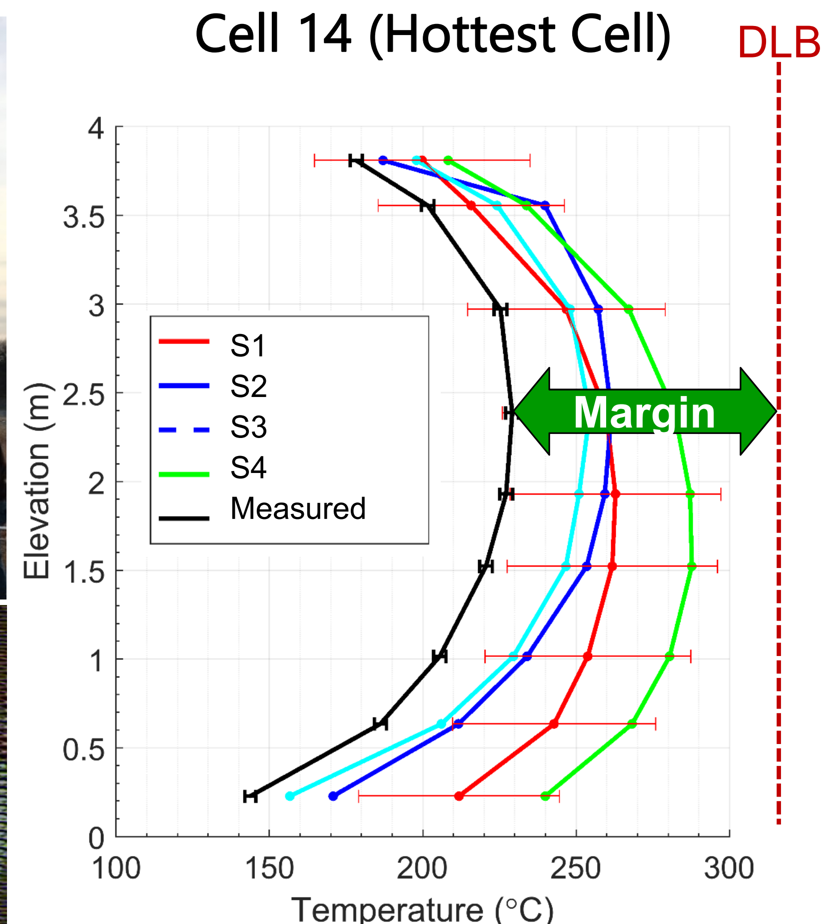
Q1 2020 Kickoff

Phase IId
Int'l HBU Demo Cask Round Robin
EPRI Lead

Phase II Blind Benchmark to HBU Demo Cask Overview

- Blind thermal modeling benchmark to actual measurements:
  - HBU Demonstration Project
- Phase II Results:
  - Reasonable surface temperatures
  - Reasonable PCT axial distribution
  - Best-estimate PCT biased high due to limiting design licensing basis inputs and assumptions
- Since 2017, substantial R&D on SNF integrity:
  - Temperatures and pressures lower than originally thought
  - Cladding more robust and less susceptible to aging





PIRT Objectives, Scope, and Goals

- PIRT Product Objectives:
  - Provide an independent, objective, and technically defensible reference from a committee of recognized subject matter experts
  - Provide technical insights for developing margin assessments
- PIRT Scope:
  - Thermal & Decay Heat Modeling / Fuel Performance Nexus (PCT Limit)
- PIRT Panel Meetings:
  - Fuels/Cladding Performance Team: 10/14-17/19
  - Thermal and Decay Heat Modeling Teams: 10/22-24/19
- Schedule:
  - Draft Final PIRT Reports: March 2020
  - Final PIRT Reports: June 2020

PIRT Structure

Establish Committee Scope, Leadership, and SMEs

Steering Committee
NRC/DOE/EPRI/ Stakeholders

Roles & Responsibilities
Define the problem (e.g., licensing, operational, or programmatic)
Define the specific objectives
Define the hardware and scenario
Define the evaluation criterion
Ensure resources are available - experts and expert reviewers to participate on panel(s)

Project Management

Project Manager(s)
Al Csontos (EPRI)

Roles & Responsibilities
Project management of the Committee members to achieve the PIRT objectives

SME Develop PIRTs, Analyses, & Report

Thermal Model Inputs & Uncertainty Quantification Team
David Richmond (PNNL)

Decay Heat Modeling & Uncertainty Quantification Team
Hatice Akkurt (EPRI)

Fuels/Cladding Performance Team
Keith Waldrop (EPRI)

Roles & Responsibilities
Identify plausible phenomena
Identify & review available tech data
Rank importance and rationales
Assess phenomenon uncertainty
Develop Independent PIRT report

NRC PIRT Process Steps

1. Define issue needing PIRT
2. **Define specific objectives**
3. **Determine scenarios**
4. **Establish evaluation criteria (figures of merit)**
5. Identify, compile, and review current data
6. Identify phenomena
7. Rank importance and provide rationale
8. Assess knowledge level (i.e., uncertainty)
9. Document results

Thinking Outside the Box

- Most panelists thought outside the box, but, within the operational and practical licensing constraints provided by the observers:
  - Guidance written in pencil and regulations written in pen
  - Input from observers for operational and practical considerations
  - Provided opportunities for reducing uncertainty and improving margins
- Generic recommendations:
  - Follow-on PIRT/workshop to clarify the definition of “gross rupture”
  - Hold a synthesis PIRT after the 3 PIRTs to address the issue of cumulative impact of overlapping bounding inputs, assumptions, and uncertainties through the process

Fuel/Cladding Performance: Phenomena

- Experts identified 16 degradation phenomena to be considered
- Reviewed these potential degradation mechanisms stand-alone
- Ranked each phenomena by
  - Credible/Non-credible
  - Knowledge
  - Confidence
  - Significance

Fuel/Cladding Degradation Phenomena
Low-temperature creep
Thermal creep
Diffusion-controlled cavity growth
Delayed hydride cracking
Thermal fatigue
Mechanical fatigue
Radiation embrittlement
Hydride reorientation / Ductile-to-brittle transition
PCI / Stress corrosion cracking
Annealing
H_2 migration
Mechanical overload
Oxidation of UO_2
Oxidation of the Cladding – ID
Oxidation of the Cladding – OD
Helium pressurization

Fuel/Cladding Performance: Key Takeaways

- Expert panel agrees there is no cliff-edge effect associated with the 400°C limit *"a continuum"* for fuel/cladding performance:
  - Onset of fuel failure is not abrupt
  - Exceeding 400°C does not mean that a large number of rods will fail simultaneously
- Identified knowledge gaps to go beyond the 400°C limit
- Beyond 400°C, there is a competition between phenomena (synergetic, competitive and aggravating effects) that should be further explored
- An opportunity exists for a graded approach
- Only 2 phenomena identified as having a medium significance:
  - Hydride reorientation with loss of ductility
  - Mechanical overload
- Only 1 phenomenon identified as having a high significance:
  - UO_2 oxidation in fuel with pre-existing failures (hairline cracks/pinholes)

Fuel/Cladding Performance: Opportunities

- Relax or eliminate the thermal cycling limits in ISG-11 Rev. 3:
  - 65°C and 10 cycles
- Average temperature on a percentage of cladding instead of PCT for a single point on a single rod
- Use of hoop stress analysis as a secondary justification when approaching the 400°C limit for HBU fuel
- Potential for graded approach
  - Different limits for different cladding materials
  - Possible different CoC criteria for intact vs. undamaged fuel

Decay Heat Modeling: Summary

- RG 3.54 R1, released in 1999, valid up to 45 GWD/MTU:
  - Significant overestimation, compared to decay heat
- RG 3.54 R2, released 2018, burnup range extended:
  - Improvement compared to R1 but still overestimation
- Cask Loader:
  - Extended Regulatory Guide – significant overestimation compared to ORIGEN
  - Version 3 offers ORIGEN as alternative option
- ORIGEN:
  - Potential for very accurate estimation, provided very detailed modeling & specific cross section generation

- **Parameters Important for Decay Heat Calculations**
  - **Operation History**
    - Burnup (axial, radial, assembly average)
    - Number of cycles, discharge time
  - **Assembly Design**
    - Enrichment
    - Dimensions
  - **Assembly Materials**
    - UO_2 density
    - Cladding material
    - Burnable absorber; Control rod history
  - **Reactor environment**
    - Moderator density
    - Temperature (Fuel, clad, moderator)
    - Boron concentration (PWR)
  - **Nuclear Data**
    - Cross sections
    - Decay constants
    - Fission yields

Decay Heat PIRT: Key Take-aways

- Regulatory Guide 3.54 R1 and R2 overestimate decay heat
- Decay heat measurements cover a range for validation purposes
- When ORIGEN is used, decay heat can be estimated within few percentages, assuming:
  - User generates specific cross section libraries
  - Performs detailed modeling
  - The impact of pre-generated libraries is being evaluated

- **Opportunities**
  - Provide Thermal PIRT with several axial decay heat profiles, along with corresponding uncertainties
    - To determine sensitivity to axial decay heat profile variation
  - Evaluation of impact of detailed vs. simplified analysis on accuracy and uncertainty
    - Generation of specific cross sections versus impact of using predefined libraries
  - **Performing decay heat measurements for higher burnup and shorter cooling times**
    - Improve validation space

Thermal Modeling: Phenomena/Parameters Considered

- **Geometry**
  - General sizing and tolerances
  - Gap thickness
- **Boundary Conds**
  - Ambient air temp
  - Wind vector
  - Ground temperature and ground/pad thermal resistance
  - Atmospheric pressure
  - Insolation
  - Pool/cooling jacket temperature
  - Fluid pressurization (vacuum for short term operations)

- **Material Prop. and Source Term**
  - Solid properties (including temperature dependence)
  - Fluid properties (equations of state)
  - Surface radiative properties
  - Decay heat

- **Physics Eqns**
  - External (ventilation air) convection
    - Flow, turbulence, heat transfer
    - Boundary correlation
  - Internal thermal-fluid modeling
    - Explicit (pin-by-pin CFD)
    - Subchannel code
    - K-effective (porous media)
  - Thermal radiation
  - Gap heat transfer model
  - Contact conductance

- **Numerical Soln**
  - Space discretization (mesh)
  - Time discretization

- **Other**
  - Materials degradation
  - Phase change
  - Cask interactions
  - Individual modeler variability

Thermal Modeling: Opportunities

	Storage bolted	Storage vert vent	Storage horiz vent	Short term ops	Transport
Gap Thickness	x		x		x
Ambient Air Temperature	x	x	x	x	
Insolation	x	x	x		
Pool/Cooling Jacket Temp				x	
Fluid Pressurization				x	
Fluid Properties				x	
Decay Heat	x	x	x	x	x
External (Ventilation Air) Convection: Flow/Turbulence/Heat Transfer		x	x		
Porous Media	x	x		x	
Contact Conductance			x		x
Mesh	x	x	x	x	x
Materials Degradation					x
Individual Modeler Variability	x	x	x	x	x

Thermal Modeling: Opportunities

- Prioritization of Opportunities for Reducing Uncertainty:
  - Decay Heat: accurate methods exist, but, may not be practical
  - Ambient Temperature: site/load specific possible with high confidence
  - Mesh Refinement: modified GCI graded approach
  - Short Term Operations: most operational limits driven by loading and/or drying temperatures
- Technical Specifications of the Future:
  - Cask Load Specific Calculations: Heat Load and/or Site Specific
  - Full Spectrum Temperature Limits: Temperature/cladding stress calcs and/or percentage of cladding surface area vs. PCT at a singular point
  - Sensors: Online Monitoring (Licensing vs. Inspection)

Thermal/Fuel Nexus: Possible Metrics Worth Exploring

Fuels PIRT:

- Average temperature on a percentage of cladding instead of PCT for a single point on a single rod
- Use of hoop stress analysis (similar for low burnup fuel) as a secondary justification when approaching the 400°C limit
- Potential for graded approach
  - Different limits for different cladding materials
  - Possible different CoC criteria for intact vs. undamaged fuel

Thermal Modeling PIRT:

- Average temperature on a percentage of cladding can be modeled and estimated similarly to PCT currently
- Hoop stress analysis:
  - Can provide additional input for the thermal/fuel performance nexus review
- Potential:
  - Sensors for real-time monitoring and alternative to conventional licensing approach
  - Graded approach for GCI

Thermal Modeling/Fuel Performance Regulatory Nexus

Near Term (2 Year): Vendor Amendments

<u>PIRT/Gap Analysis:</u>

- ▪ Technical Gaps:
- - Thermal Model Inputs
- - Decay Heat Models
- - Fuel Performance Nexus
- ▪ PIRT Reports Q2 2020
- ▪ Examine approaches for speedier utility impacts
- ▪ Implement through vendor amendments and/or 72.48
- ▪ Coordination with Spent Fuel Performance Margins Effort

Mid Term (2-3 Years): ISG-11 R3 PCT Limits

<u>Follow-on PIRTs:</u>

- ▪ Additional topics as identified by the teams
- ▪ Provide defensible technical basis for guidance updates

<u>Regulatory Vehicles:</u>

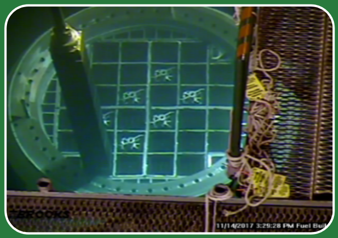
- ▪ NRC Reg Guide or Topical Report for NRC Review
- ▪ Vendor amendments

Long Term: Topical Report

<u>Topical Report for NRC Review:</u>

- ▪ Establish generic approach for use of actual data vs. design licensing basis approach for thermal and other modeling

Summary

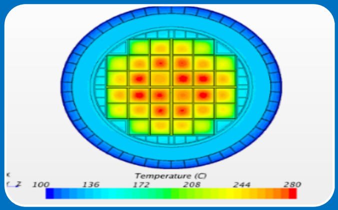


High Burnup Demo: An Opportunity

- Early value for cask Loaded in 2017
- Data used for blind benchmarking of models
- Licensing biases identified in thermal models

PIRTs

- Thermal/Decay Heat Modeling and Fuel/Cladding Performance
- Significantly reduced concerns with HBU fuel/cladding performance
- Opportunities exist in Thermal Modeling/Fuel Performance Nexus



Next Steps

- PIRT as a vehicle for regulatory considerations
- PIRT Reports expected publication Q2 2020
- Cooperation to NRC/NEI Spent Fuel Performance Margins Efforts

Together…Shaping the Future of Electricity