

Panel: Light water Reactor Research Capabilities and Needs

David Andersson (LANL), Nathan Capps (ORNL), Bob Salko (ORNL), Pierre-Clément Simon (INL), Laurent Capolungo (LANL), Benjamin Spencer (INL) and Matthew Jessee (ORNL)



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Panelists



Moderator: David Andersson, LANL



Panelist: Nathan Capps, ORNL



Panelist: Bob Salko, ORNL



Panelist: Pierre-Clément Simon, INL



Panelist: Laurent Capolungo, LANL



Panelist: Benjamin Spencer, INL



Panelist: Jesse, Matthew, ORNL



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Near-term and Long-term Priorities for LWR Technology & Deployment

Presenter: Nathan Capps¹

Technical Contributors: David Kamerman² and Dan Wachs²

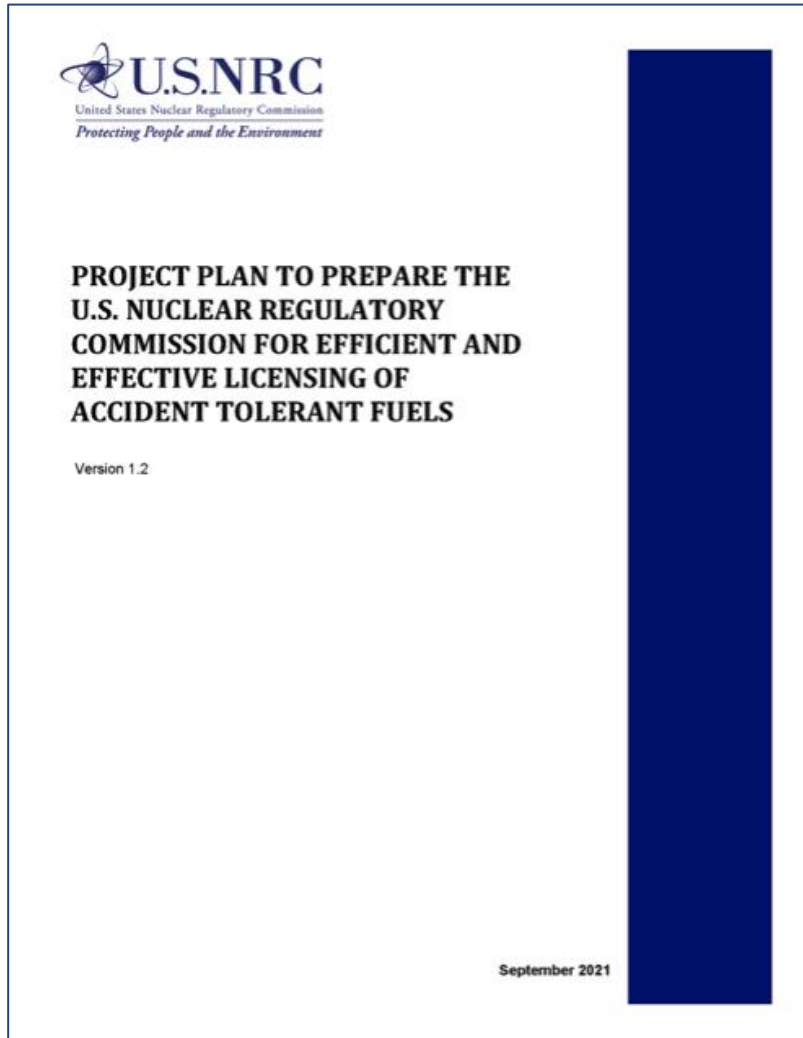
¹Oak Ridge National Laboratory

²Idaho National Laboratory

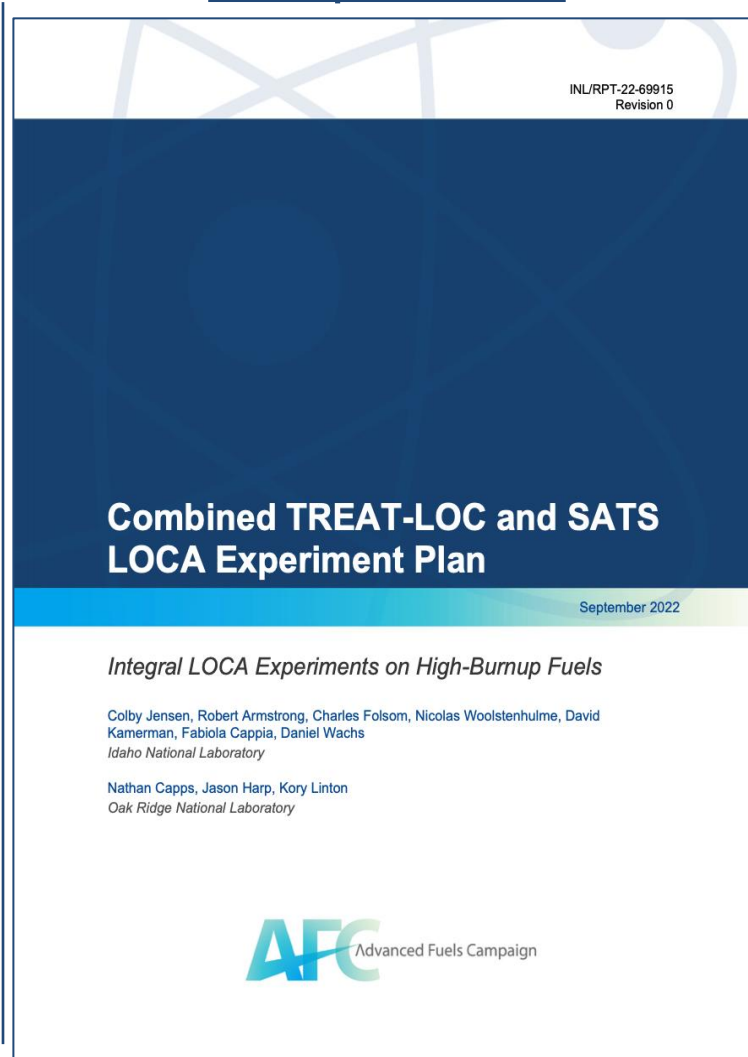
Advanced Fuels Campaign - Near Term Priorities to Enable Expansion of LWR Energy

Objective: To establish and utilize advanced capabilities to acquire critical data supporting burnup extensions and increased operating margins, while defining performance metrics that utilities can leverage to reduce conservatisms and enable extended power uprates for the existing reactor fleet.

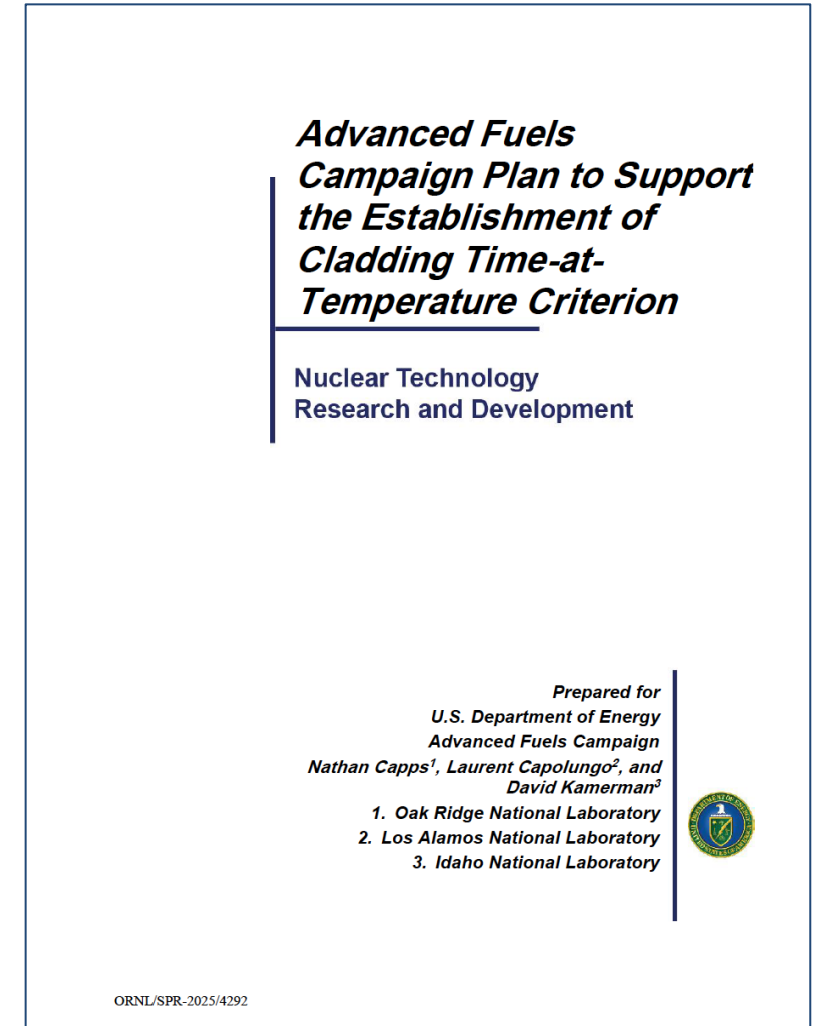
Accident Tolerant Fuel



Burnup Extension

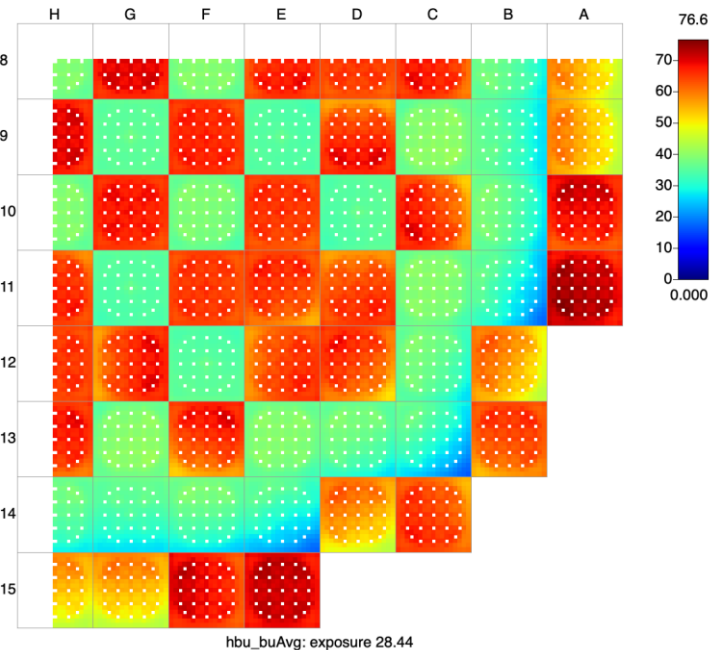


Extended Power Uprates



Perceived Strategy of the LWR Industry

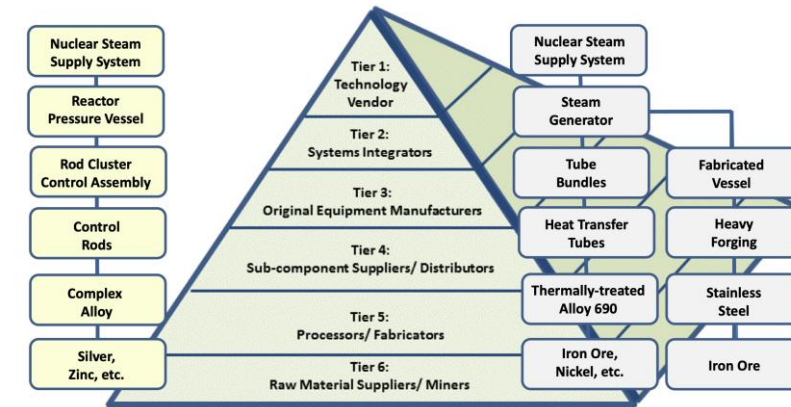
Extend PWR Cycle Lengths and Remove CHF for BWRs



Plant Modifications, Extended Power Upgrades, and 120 Year Operation



Supply Chain and Workforce Development



AI Investment into New Nuclear



Long Term R&D Priorities to Enable Expansion of LWR Energy

- Historical Operational Concerns
 - PCI resulting from extended cycles and power uprates
 - Increased CRUD buildup resulting from high powers and increased cycle lengths
- Operational Improvements
 - Burnable Absorbers
 - Advanced fuel assembly designs – PWR: 19x19 and 21x21, BWRs >11x11
 - High Burnup ATF Performance – New burnup limit?
 - Margin Identification through best estimate plus uncertainty
- Beyond 80 years of Operation
 - Increase in fluence as a result of cycle lengths and power uprates (fluence and higher temperatures)
- AFQ -> AI assessed qualification
 - Adding meta data to supplement experimental data to identify high priority data

Light Water Reactor Highlights for Multiphysics

Bob Salko, ORNL

FY25-26 Contributors:

*ORNL: Ian Greenquist, Nick Herring, Aaron Wysocki, Mehdi Asgari, Will Gurecky, Nathan Capps,
Shane Henderson, Bob Salko (WPM)*

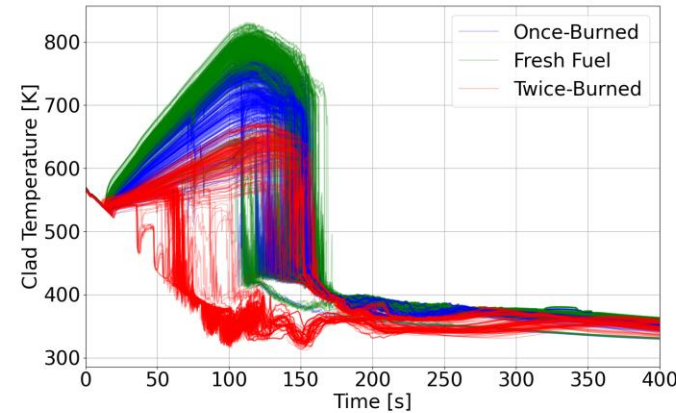


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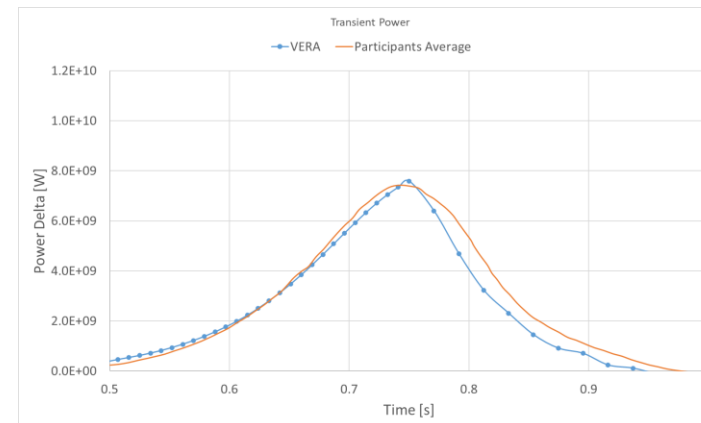
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FY25 Accomplishments

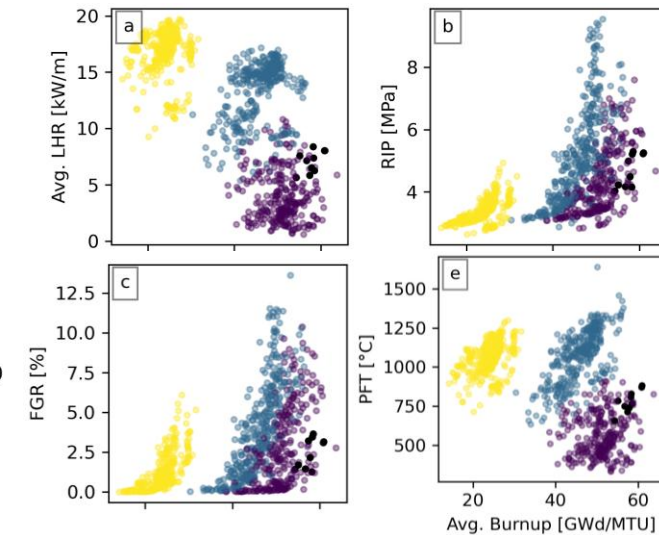
- VERA BWR FFRD analysis completed
 - Modeling of 3 cycles of Limerick with high burnup fuel
 - Modeling of large- and small-break LOCA using TRACE
 - Burst susceptibility analysis performed with BISON for ~1k fuel rods
- VERA analysis of Peach Bottom Turbine Trip benchmark performed
 - Demonstration of ability to model transients of interest for time-at-temperature
 - Good comparison with benchmark participants
 - Modification to cause dryout and modeling of dryout/re-wet pins with BISON
- Assessment of MAMBA for PWR crud prediction
- Engagement with industry stakeholders
 - EPRI CRAFT meetings, BWROG meetings, ANFM VERA training, Constellation VERA training, GEV/Constellation calls on FFRD work, WEC/Framatome/GEV calls on t@T problem



TRACE prediction of clad temperature during LBLOCA



VERA prediction of power insertion during turbine trip



BISON prediction of fuel rod parameters prior to LBLOCA

FY26 and beyond

	FY26	FY27	FY28	FY29
FFRD	PWR/BWR analysis using latest BISON models			
t@T	Development of industry benchmark activity	Develop models and execute for BWR	Develop models and execute for PWR	Update results with latest FP models
	Demonstration of VERA for BWR AOO	BWR AOO with UQ	Demonstration of VERA for PWR AOO	PWR AOO with UQ
CRUD	Demonstration of new MAMBA boiling model	Leverage new model using high burnup models	Validation using plant data	

Other activities on the radar: BWR validation improvements, Vessel and concrete analysis, SMRs

NEAMS LWR Fuel Performance WG Annual review

NEAMS Light Water Reactor Fuel Performance Working Group

Technical Contributors:

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Los Alamos National Laboratory

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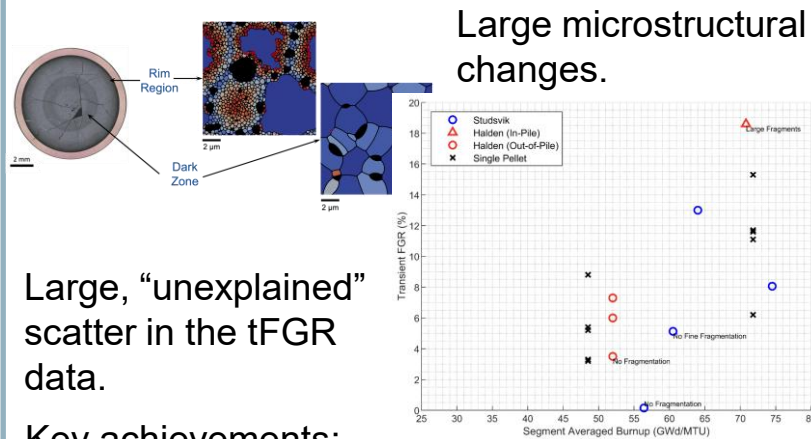


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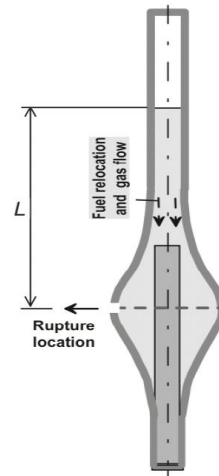
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Main goals and achievements from FY25 to FY26

High burnup extension



Bonding and axial gas comm.



Predict fuel relocation, bonding, and axial gas communication to better model ballooning and performance during LOCA*.

Key to following regulation guidance.

Key achievements:

- Improved capabilities for 1.5D axial gas communication in BISON
- Implementation of fuel bonding model in BISON
- Impact of bonding on ballooning
- Blind predictions of LOCA and t@T

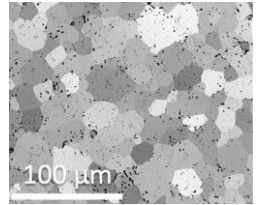
Doped fuel

Dopants can positively affect fuel microstructure and properties, making doped fuels a great option for LWR advanced fuels.

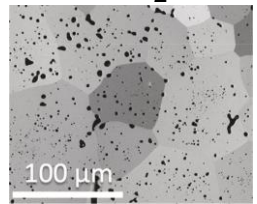
But data is limited and uncertainty is high.

Key achievements:

- Demonstrate new plasticity models for doped UO₂ that capture dislocation mechanisms + UQ
- Integration of LLS model in BISON and successful comparison against MATPRO models and experimental data (AI)



UO₂



Cr-doped UO₂

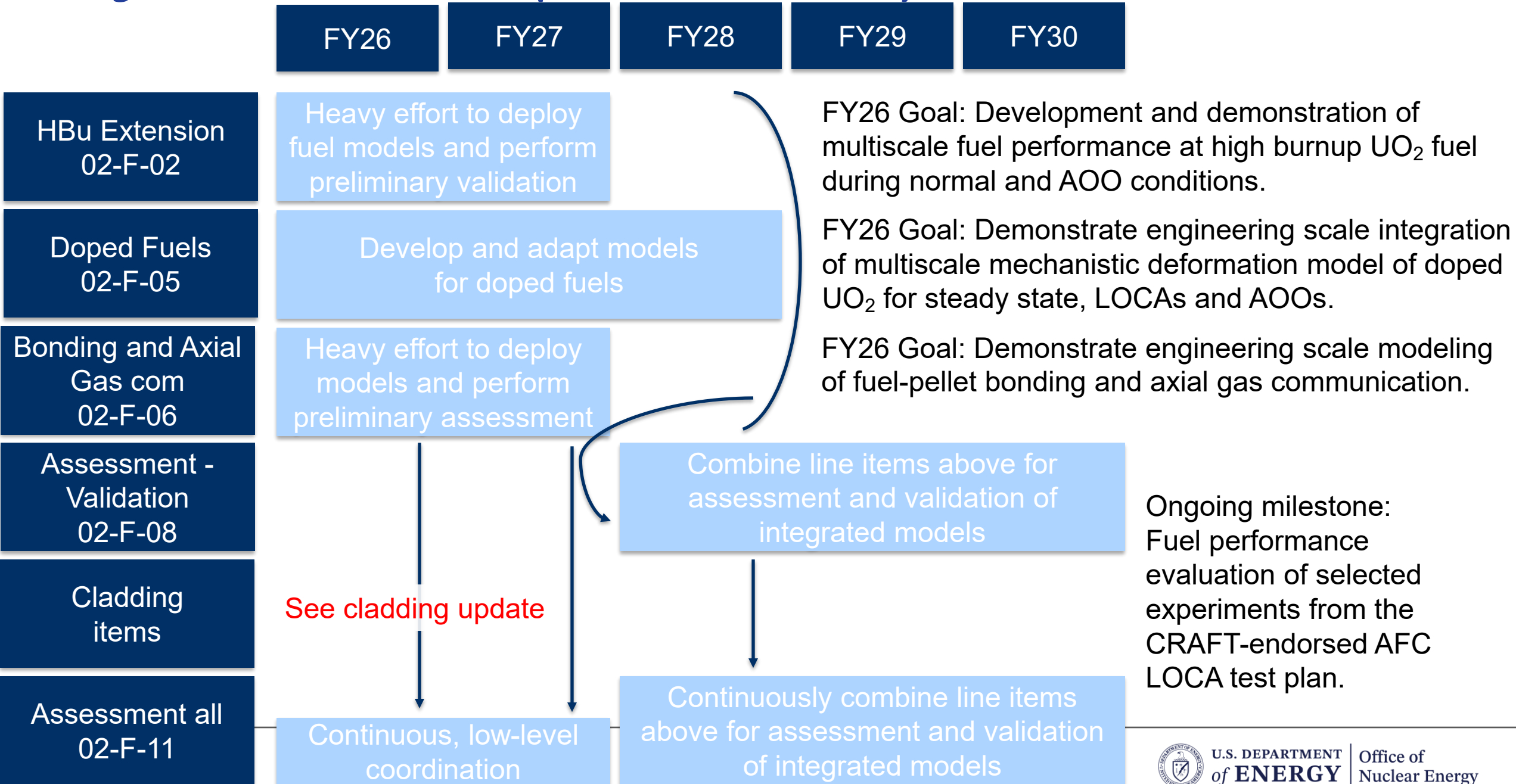
- + AFC collaboration for CRAFT-endorsed LOCA test plan
- + CRUD with VERA-MAMBA
- + Shareholder engagements (CRAFT, EPRI, LWR owners' group, multiphysics TA, etc.)



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Alignment with IPL items (not all are included) and coordination



List of milestones in FY26 (aligned with IPL)

Area

Milestone Title

HBu

Complete **lower-length-scale** parameterization of mechanistic **transient gas release model** for UO_2 with uncertainty quantification

Full-phase-space predictions of **intragranular bubble morphology** in UO_2 as a function of local operating history

Connect mechanistic modeling of high burnup **microstructural evolution** in UO_2 to fission gas release calculations.

Describe, through physics-based models, the **impact of IFBA on HBu structure**

Enabling data availability for **model validation** and fostering stakeholder engagement.

Development and demonstration of **fission gas release in high burnup UO_2 fuel** during normal and AOO conditions

Doped Fuel

Complete doped UO_2 **mechanistic deformation model** and test for improved PCMI performance

Demonstrate engineering scale integration of **doped UO_2 ROMs for steady state, LOCAs and AOOs** that address the impact on operating margins

AFC/NEAMS

Fuel performance evaluation of selected experiments from **the CRAFT-endorsed AFC LOCA test plan**

Axial Gas
Communication

Demonstrate engineering scale modeling of fuel-pellet **bonding and axial gas communication**.

CRUD

Implementation of **MAMBA3D** boiling modeling into VERA-MAMBA

Implementation of **MAMBA-3D CRUD modeling** capabilities in BISON

Cladding

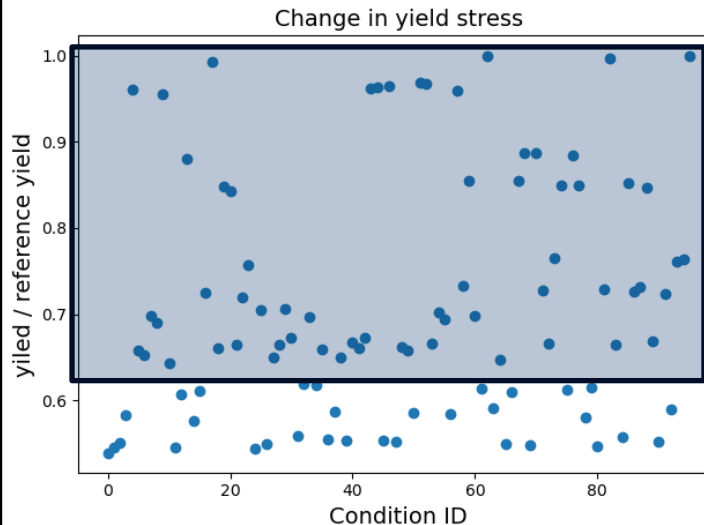
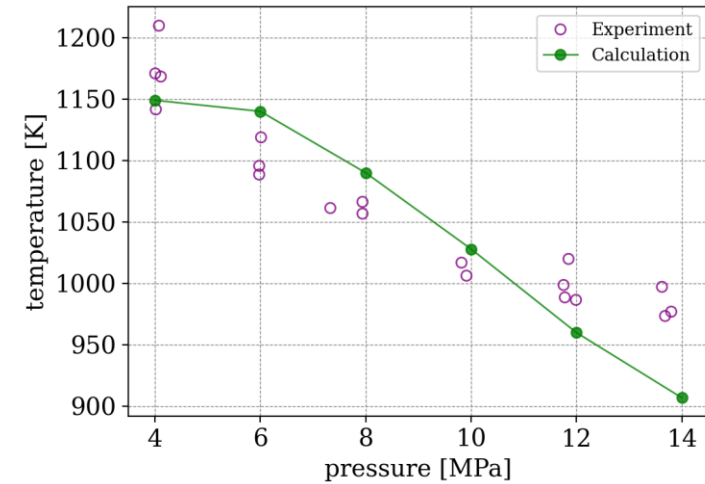
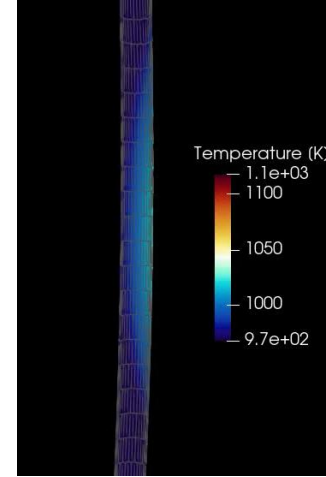
Implement **irradiation effects** in a mechanism-based constitutive model for Zircaloy and develop a machine-learning surrogate model to perform uncertainty quantification and support analysis of **high-burnup cladding and time-at-temperature transients**

Establish initial **zircalloy recrystallization model** to support predictions of cladding annealing and response for time at temperature

Application of **new engineering-scale models** of Zircaloy cladding

LWR cladding - key accomplishments

- ❑ A new microstructure aware polycrystal model for the thermal mechanical response (tensile and creep) of Zircaloy was developed and validated.
- ❑ Deployed the model to rationalize the potential effect of time at temperature on mechanical behavior
- ❑ New surrogate models were developed and integrated into MOOSE/BISON
- ❑ The surrogate models were deployed to assess REBEKA (Clad) and IFA (Clad and Fuel) tests and shown to perform very well
- ❑ A new approach, LAMIE, was introduced to integrate cluster dynamics simulations into polycrystal models.



Top: BISON simulation of the REBEKA LOCA tests.

Left: Polycrystal predictions of the effect of $t@T$ on yield strength.



Future directions

Vision

Overall, the steady state performance of LWR fuel clad assembly is well understood. One of the most critical needs lies in enabling industry, the nuclear engineering and materials science communities to:

- ☐ Measure the risk associated with high burnup scenarios.
- ☐ Comprehend the likely effects of $t@T$ and other off normal events on the performance/lifetime of the fuel/clad assembly

Proposed milestones

- ☐ Forward propagate the uncertainty in both surrogate and other model parameters (rupture)
- ☐ Extend our modeling capabilities to consider static and dynamic recrystallization
- ☐ Extend our ability to predict irradiation effects (coupling with cluster dynamics)
- ☐ Extend the framework to consider H effects (high burnup applications)
- ☐ Develop and validate predictive rupture criteria.



Light Water Reactor Highlights for Thermal Fluids

Bob Salko, ORNL

FY25-26 Contributors:

ORNL: Vineet Kumar, Will Gurecky, Bob Salko (WPM)

NCSU: Aidan Furlong, Xu Wu

University of Tennessee: Davide Rotilio, Xingang Zhao

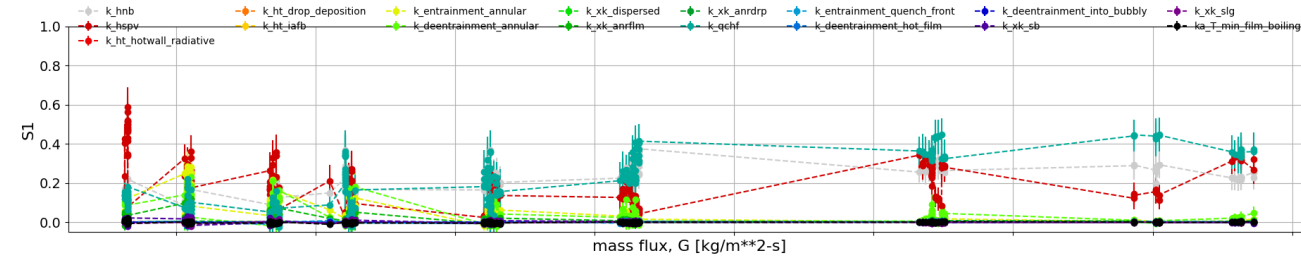


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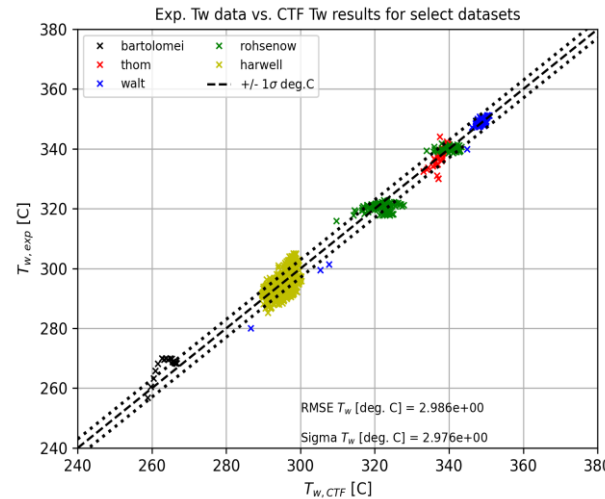
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FY25 Accomplishments

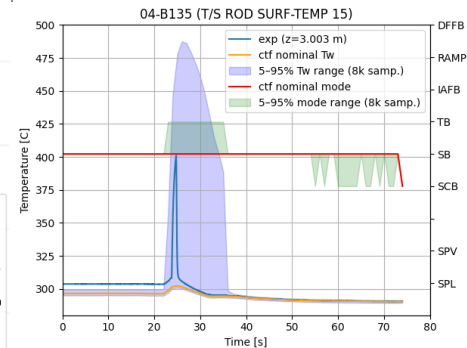
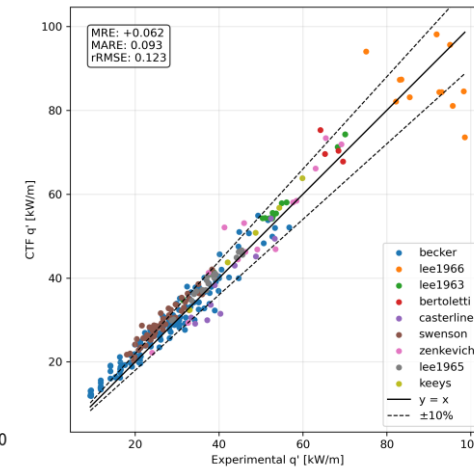
- Assessment of CTF for time-at-temperature
- Performed sensitivity analysis using validation database to identify high impact models
- Validation database expansion
- Use of Bayesian inference for model uncertainty quantification
- Development of ML-based models for predicting CHF and implementation into CTF



Model importance for prediction of post-CHF temperature



Expansion of validation database

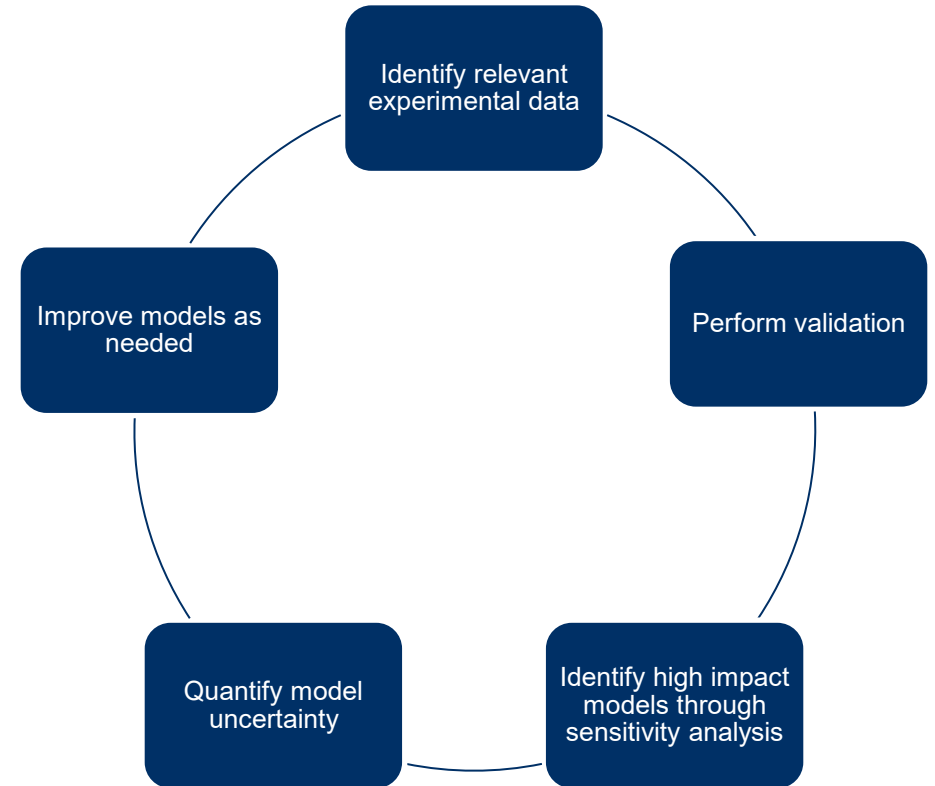


Impact of model uncertainty



FY26 and beyond

- FY26:
 - Improve validation of post-CHF heat transfer
 - Assess sensitivity and UQ
 - CTF V&V manual update
- FY27:
 - Expansion of post-CHF validation with PWR focus
 - Model improvements
- FY28:
 - Post-CHF PWR UQ
 - Model improvements
 - Natural circulation to support SMR
- FY29:
 - SMR modeling



Guiding strategy



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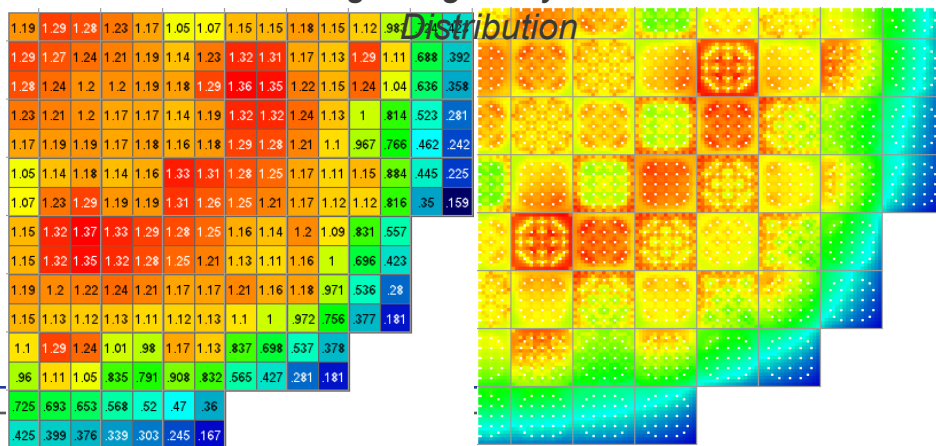
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NEAMS Reactor Physics

LWR capabilities

- VERA/MPACT is an established QA'd, validated whole-core transport solver
- VERA/Shift is integrated/automated for ex-core dose assessment at each statepoint after full-core multiphysics solve

WB1C14 Beginning-of-Cycle Radial Power Distribution

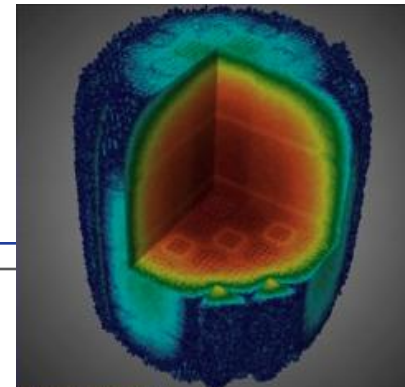


Industry Method

VERA/MPACT

Current and future work

1. FY26 BWR neutronics: Continue control blade cusping analysis
2. FY26 Post Closure Criticality: Start criticality analysis of TN-32B High Burnup Research Cask
3. Renewed interest in VERA/Shift
 - Reference solutions (PWR and BWR) for new fuel designs
 - Online ex-core dose characterization



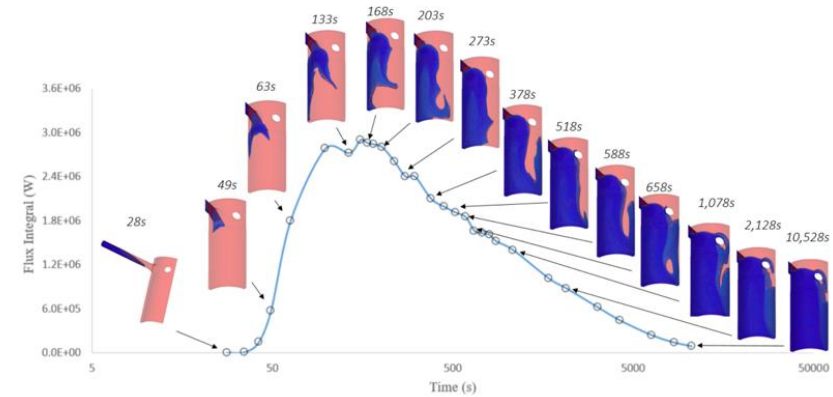
LWR Structural Materials & Chemistry Efforts

Objective: Predict integrity of critical structural components under long-term operation

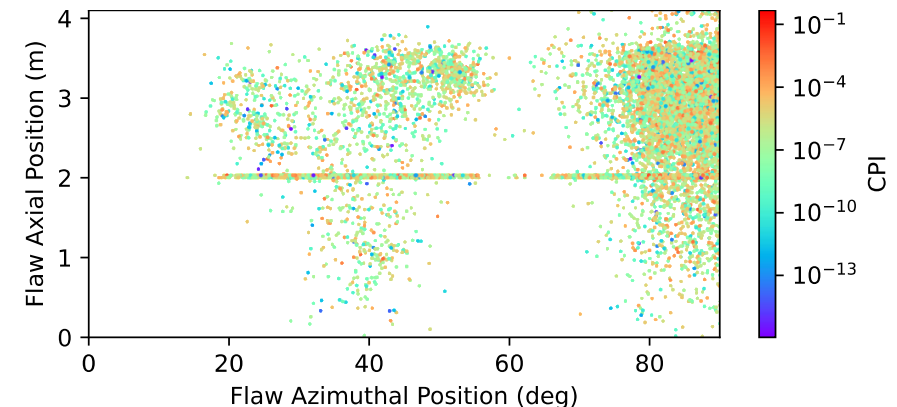
- Effort initiated in LWR program and continued in NEAMS has focused on life-limiting components:
 - Reactor pressure vessel (RPV): Fracture under thermal shock with degradation
 - Reinforced concrete structures: Radiation-induced expansion, alkali-silica reaction
 - Codes: Grizzly (controlled), BlackBear (open source)

Recently concluded: RPV coupled 3D plume study

- RPV probabilistic fracture models are currently 1D, neglect spatial variation in temperature
- Grizzly/Cardinal used to assess cold-plume effects with full 3D coupled CFD/fracture model
- Effect is significant; conditional probability of fracture in a medium-break LOCA increased from $3.60\text{e-}6$ to $1.05\text{e-}4$ when 3D effects were considered



Thermal solution from Cardinal CFD model, MBLOCA

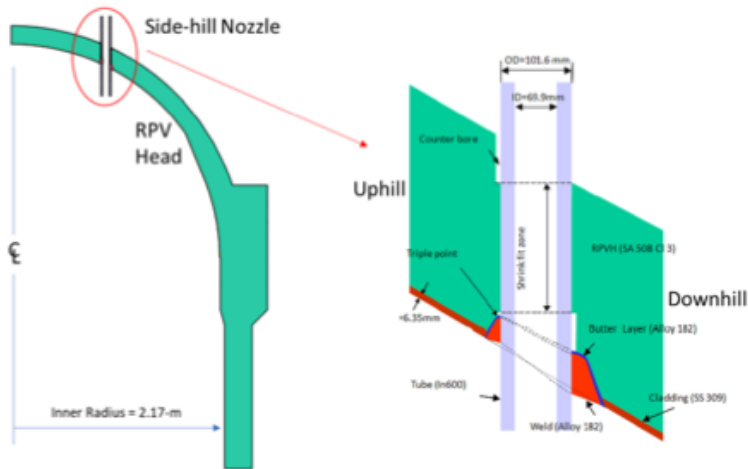


Sampled flaws with nonzero failure probability (Grizzly)

Current LWR focus: Crack growth in welded components

Problem of interest:

- Crack growth in components due to stress-corrosion cracking

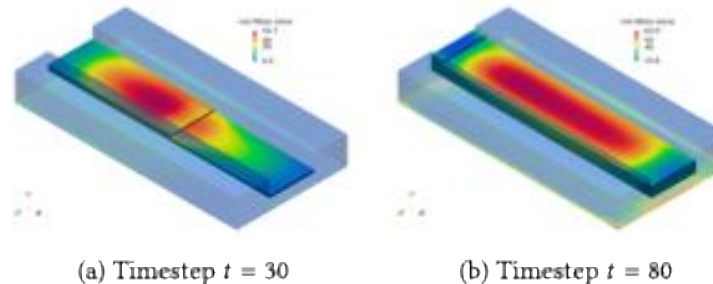


Welds around control-rod drive penetrations in LWR RPV head (Hill et al., TLR-RES/DE/CIB-2020-06)

- Ongoing efforts to demonstrate these capabilities used together (milestone in May 2026)

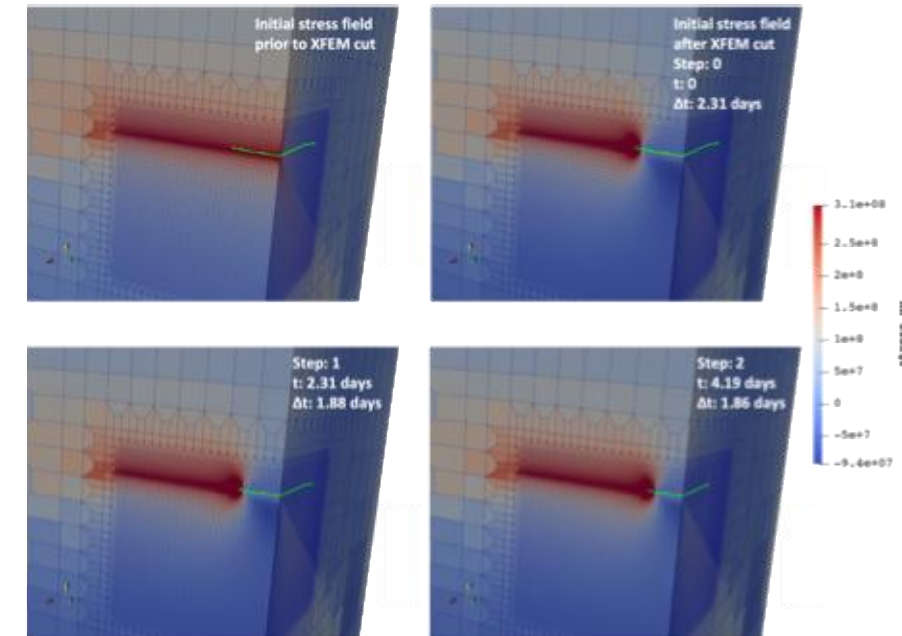
Weld residual stresses

- Tools being developed by ANL in MOOSE/BlackBear to simulate welding process, resulting residual stresses



Fracture propagation

- XFEM capabilities in MOOSE being developed to robustly handle complex 3D fracture growth





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