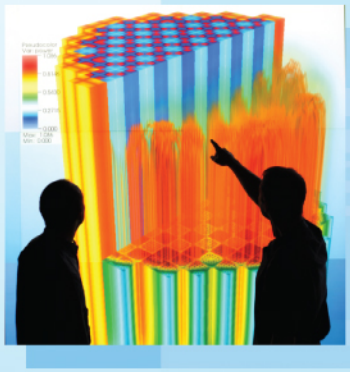
Power uprates
and plant life extension

CASL-U-2012-0054-000

Consortium for Advanced Simulation of LWRs



Engineering design
and analysis

L2:MPO.P4.03

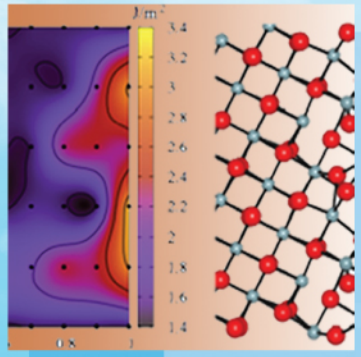
High Fidelity Fuel Performance Model Development: Focus on Benchmark & Validation activities for PCI and CRUD

Science-enabling
high performance
computing

Brian Wirth
University of Tennessee—Knoxville (UT-K)

Chris Stanek, Brian Kendrick
Los Alamos National Laboratory (LANL)

Robert Montgomery
Pacific Northwest National Laboratory (PNNL)



Fundamental science

Richard Williamson, Jason Hales, Derek Gaston, Richard Martineau
Idaho National Laboratory (INL)

Dion Sunderland, Joe Rashid
Anatech

Michael Short
Massachusetts Institute of Technology (MIT)

Plant operational data

Kurt Edsinger, and Dennis Hussey
Electric Power Research Institute (EPRI)

April 2, 2012

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

High Fidelity Fuel Performance Model Development: Focus on Benchmark & Validation activities for PCI and CRUD

Brian Wirth (UTK), Chris Stanek (LANL)
Robert Montgomery (PNNL),
Richard Williamson, Jason Hales, Derek Gaston,
Richard Martineau (INL),
Dion Sunderland, Joe Rashid (Anatech),
Brian Kendrick (LANL), Mike Short (MIT),
Kurt Edsinger, and Dennis Hussey (EPRI)

Nuclear Reactor Summit
Gaithersburg, MD
20 March 2012

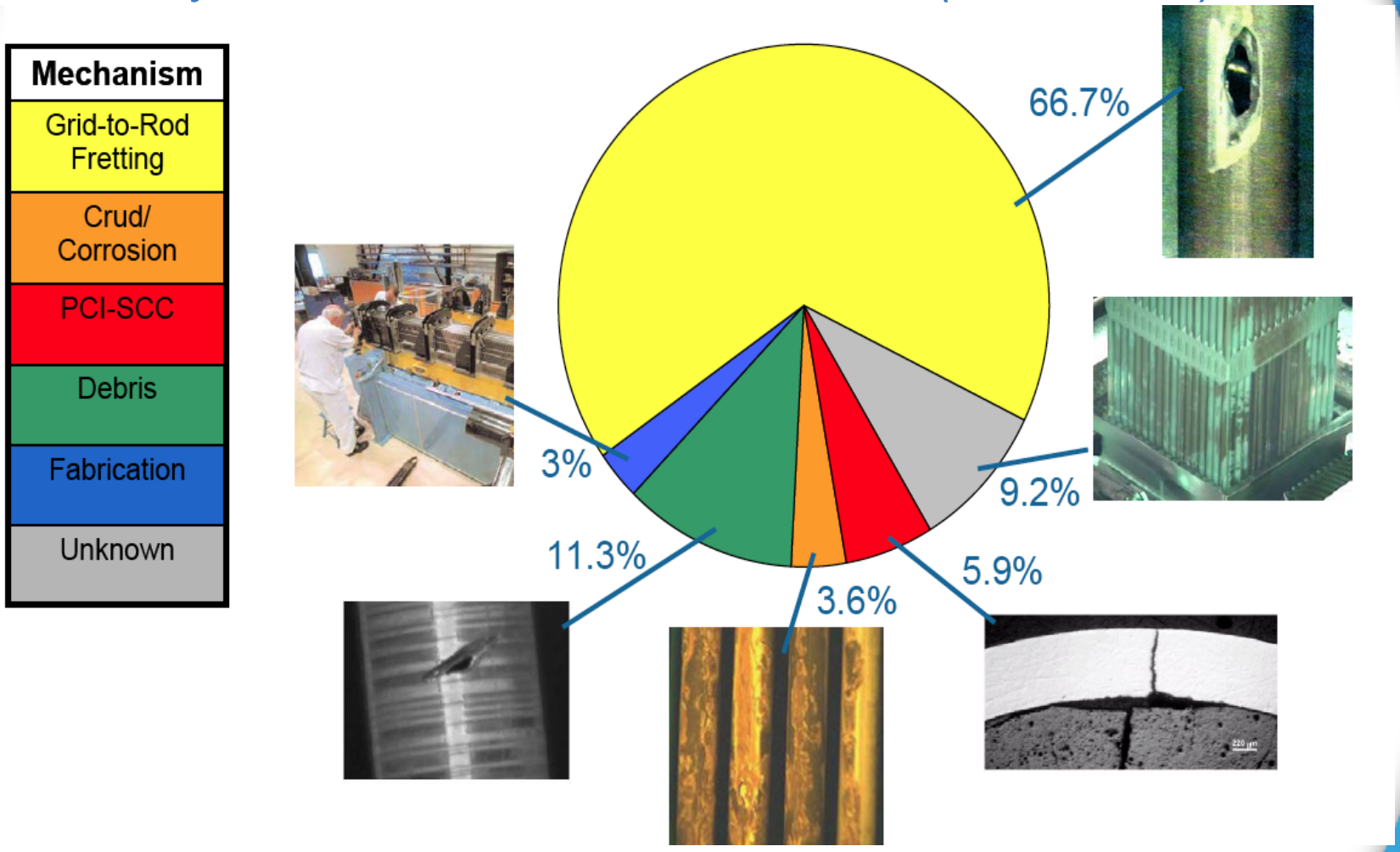
Consortium for Advanced Simulation of LWRs

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

CASL-U-2012-0054-000

CASL Challenge Problems

Summary of US fuel failure mechanisms (2000-2008)

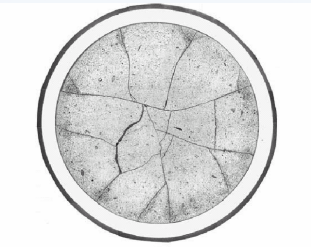


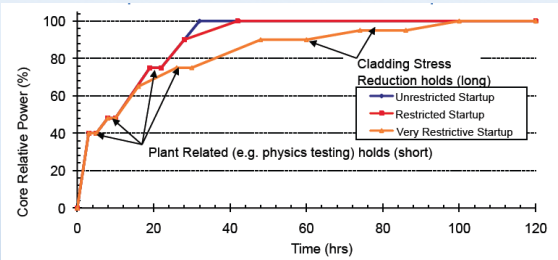
* Edsinger, Stanek, Wirth, JOM **63, no. 8** (2011)

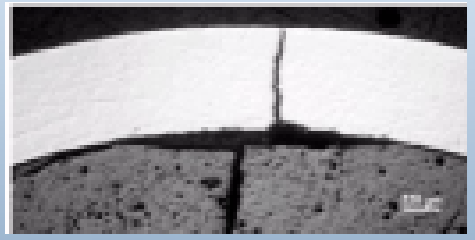
Fuel failure modes provide motivation for MPO activities

Materials Performance Optimization (MPO) focused on performance behavior that impacts the economics, fuel utilization and ultimately safety of nuclear power

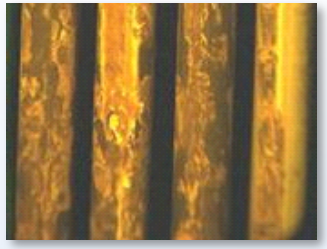
Pellet Clad Interactions

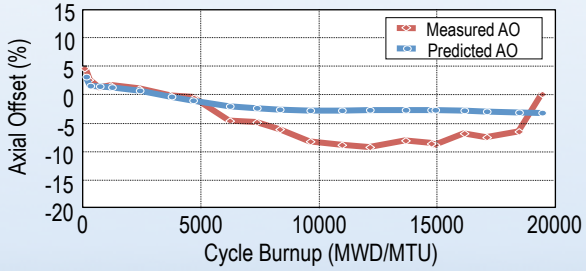


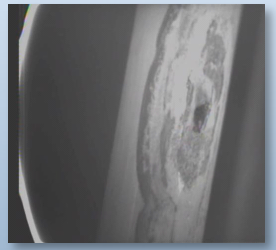


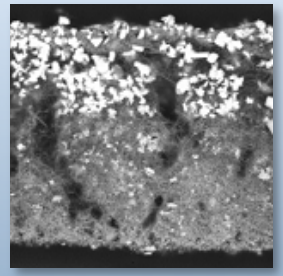


CRUD corrosion deposits

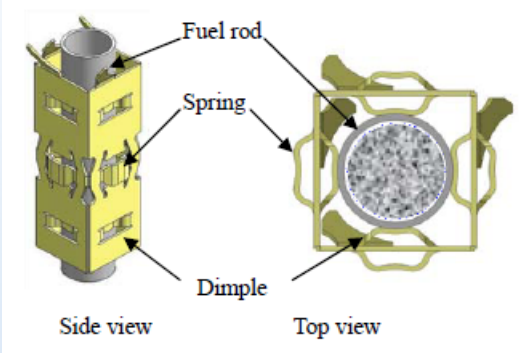








GTRF

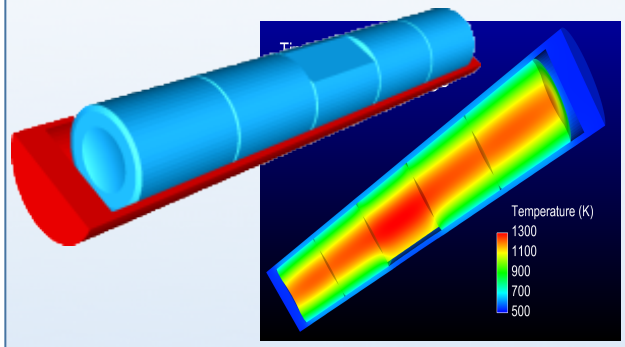


GTRF, CRUD & PCI responsible for the majority of failed fuel rods in pressurized water reactors

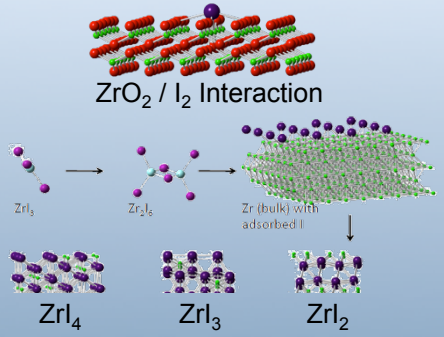
MPO delivers materials physics-based constitutive models to the virtual reactor for CASL challenge problems

For CRUD, GTRF and PCI, identify 3-D, high resolution coupled physics simulation capability for interface with virtual reactor;

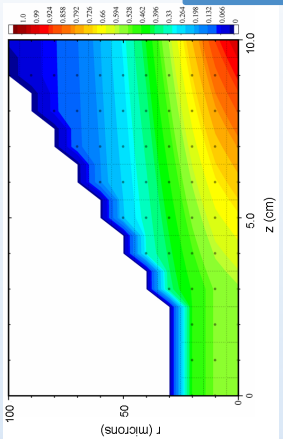
PCI

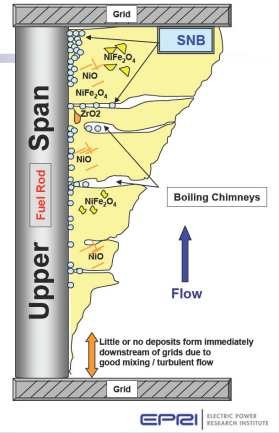


PEREGRINE
(FUEL PERFORMANCE)

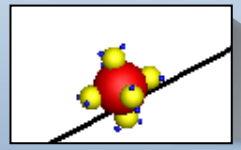


CRUD

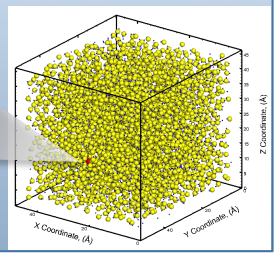




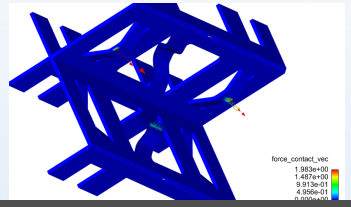
MAMBA
(MPO ADVANCED MODEL FOR BORON ANALYSIS)

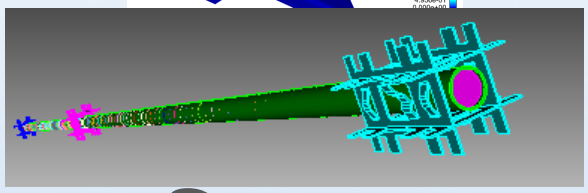


ΔH_{MD}

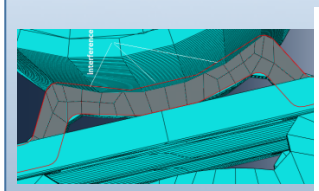


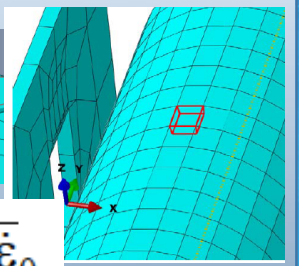
GTRF





SIERRA
(STRUCTURAL MECHANICS)





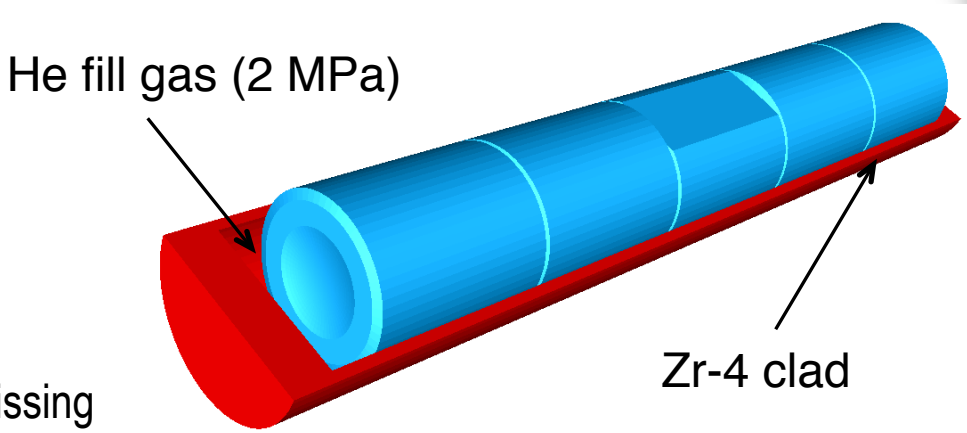
$$\dot{\bar{\varepsilon}} = \bar{M} : \bar{\sigma} + \dot{\bar{\varepsilon}}_0$$

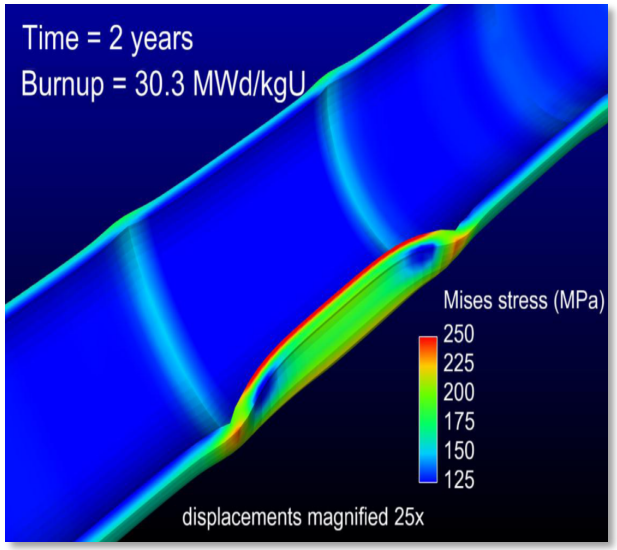
Initiate a series of microscale activities to provide mechanistic/ physical insight into complex degradation phenomena

Peregrine Simulation of Missing Pellet Surface

3D multiphysics fuel performance capability to assess Pellet Clad Interaction (PCI)

- CASL-developed capability = Peregrine (based on INL developed MOOSE/BISON/ELK)
- High resolution, 3D fuel performance calculation reveals the impact of a missing pellet surface (MPS) on stress state, temperature profile, etc. (*i.e.* full nuclear fuel performance) as a function of fuel history.
- Flexible framework will be used to systematically assess fuel performance during normal and transient operations and off-normal conditions:
  - *Evaluate effect of pellet irregularities on fuel performance*
  - *Optimize power maneuvers improving operational margins*

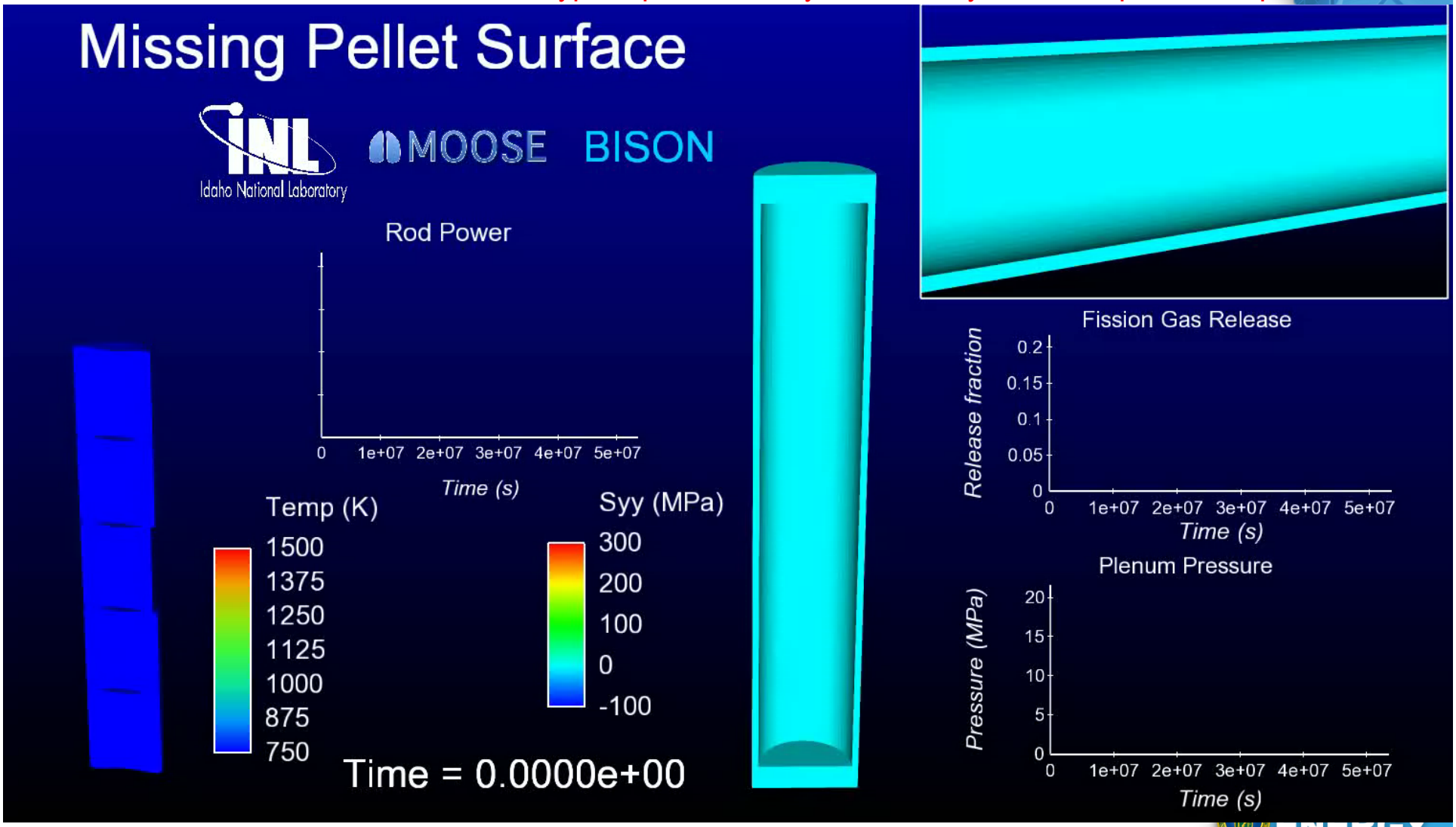




Von Mises Effective Stress

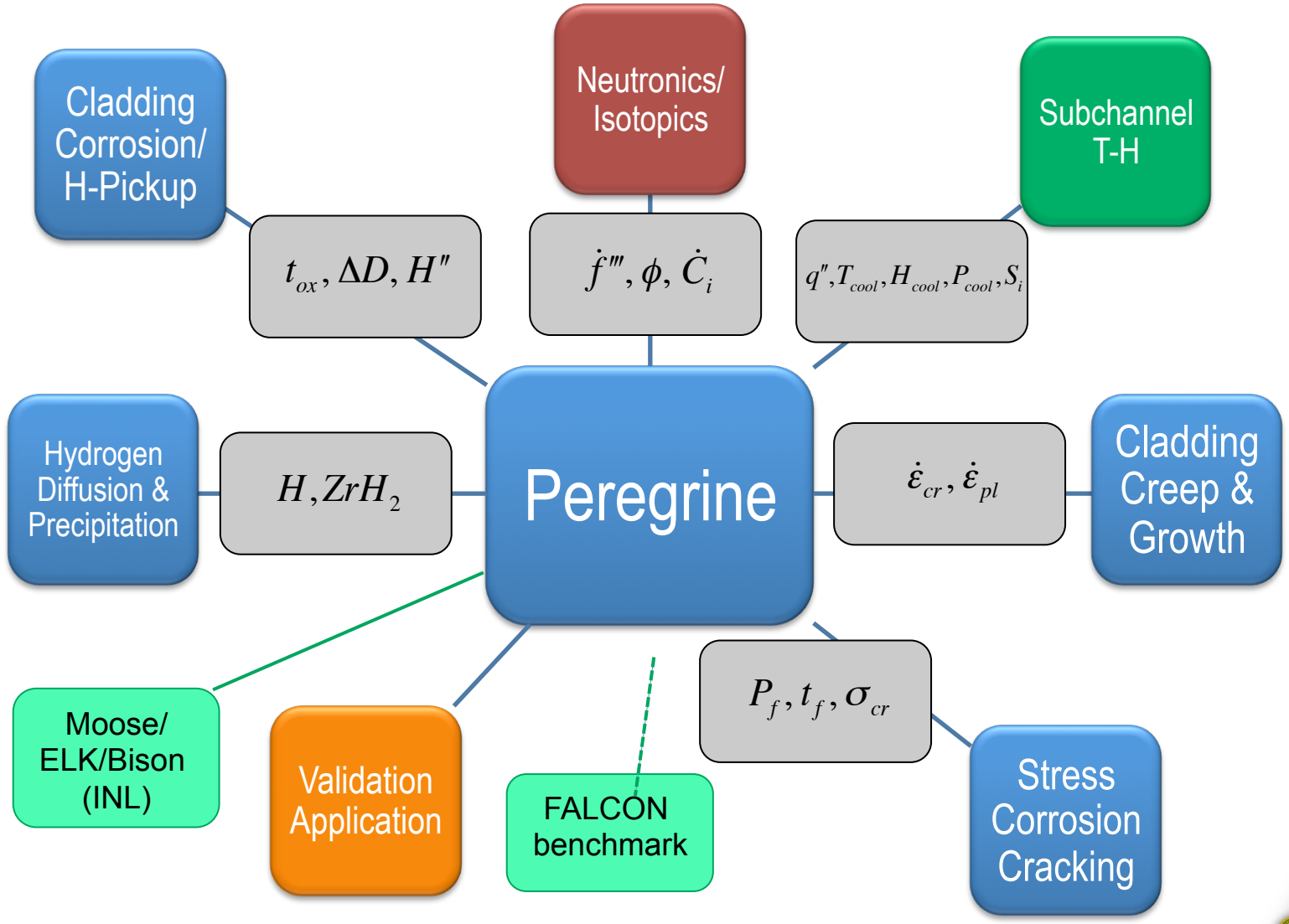
MPO developing 3-D, engineering scale fuel performance models to evaluate Pellet Clad Interaction

Simulation from fresh fuel state with a typical power history, followed by a late-life power ramp



Stress and temperature results are consistent with engineering scale calculations using 2-D fuel performance codes (EPRI 1012915)

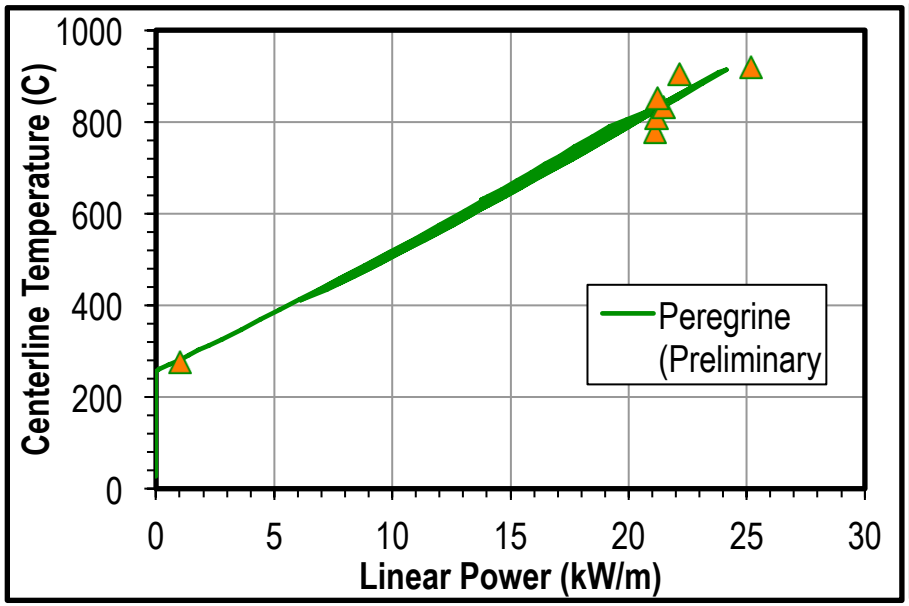
Peregrine Interface with other MPO (blue) and Virtual Reactor Activities

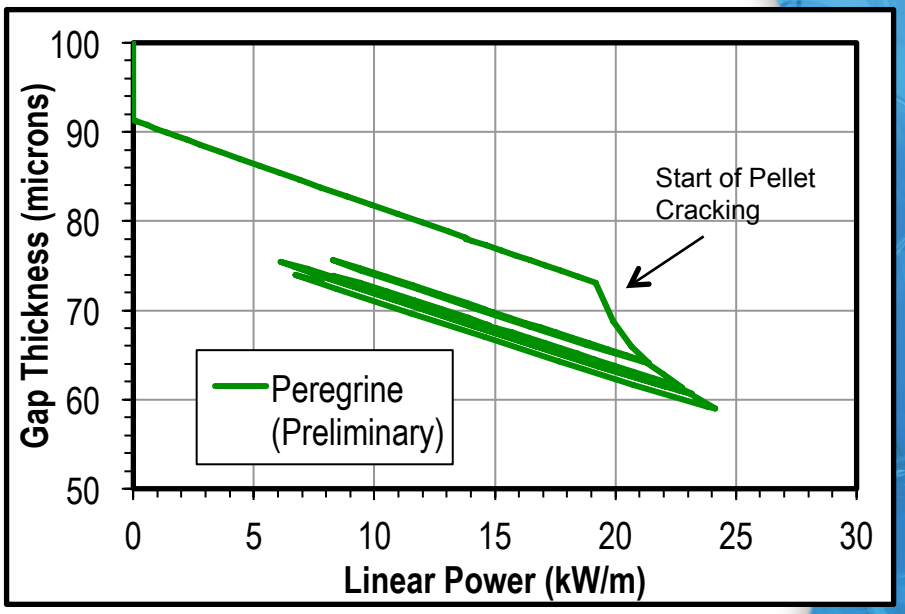


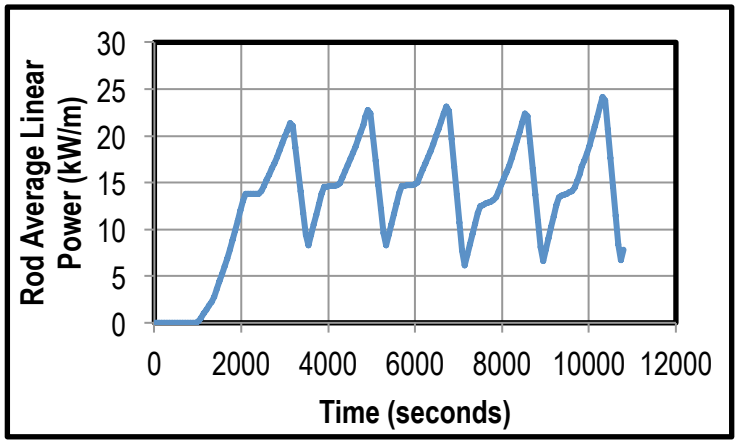
Challenge is to bridge scales effectively, as well as to benchmark & validate simulations

Peregrine Analysis of IFA-504 Rod 1 (He) Gas Flow Test

Benchmarking & Validation plan against Falcon & Test Reactor Data







Key Observations:

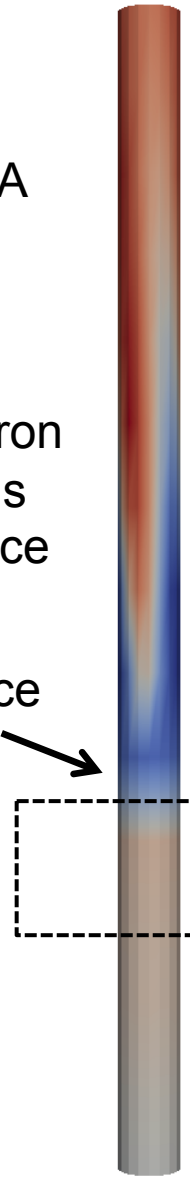
- Encouraging results for initial benchmarking
- Is engineering scale data adequate to develop high resolution models?

3D MAMBA + CFD Simulation of CRUD growth

Boron concentration within crud layer (colored contours) grown within MAMBA over 60 days of operation

Variations in crud thickness and boron due to T variations on cladding surface

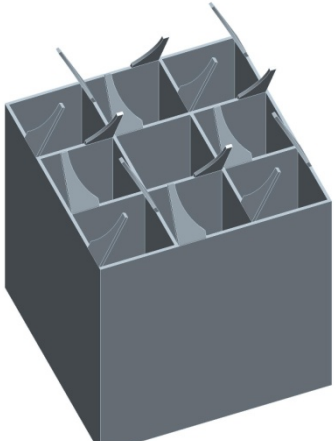
Reduced crud and boron due to turbulence behind mixing vanes

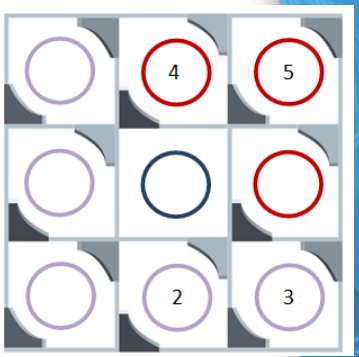


80 cm section of fuel rod

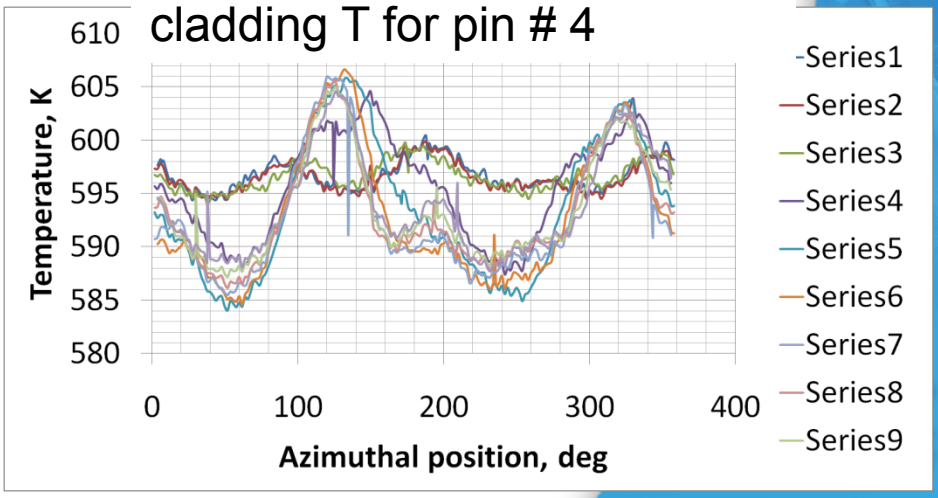
Large azimuthal variation in fluid/cladding temperature computed by STAR-CCM+ (U. Mich. group)

Spacer with mixing vanes



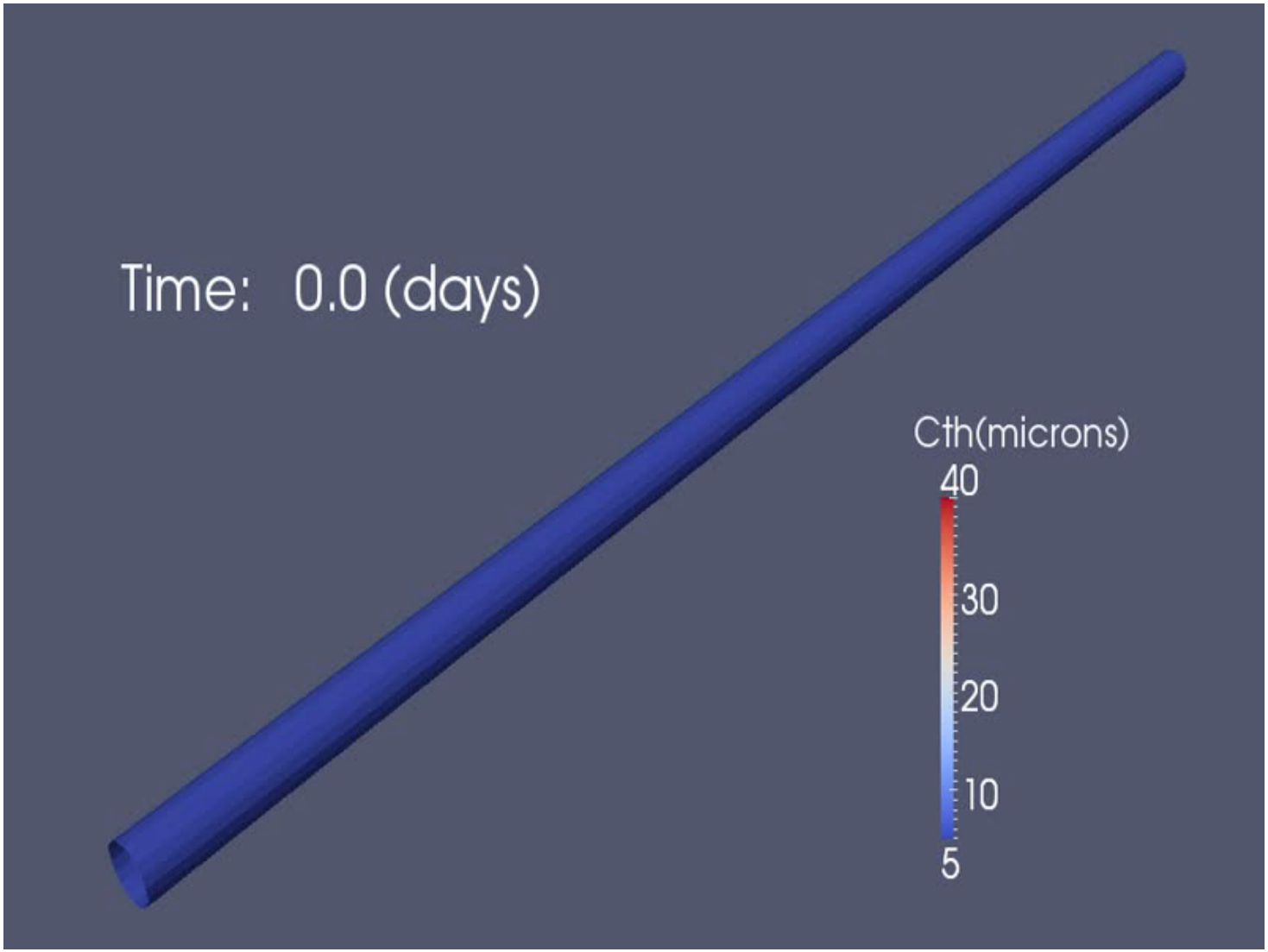


CFD (Star-CCM+) computed cladding T for pin # 4



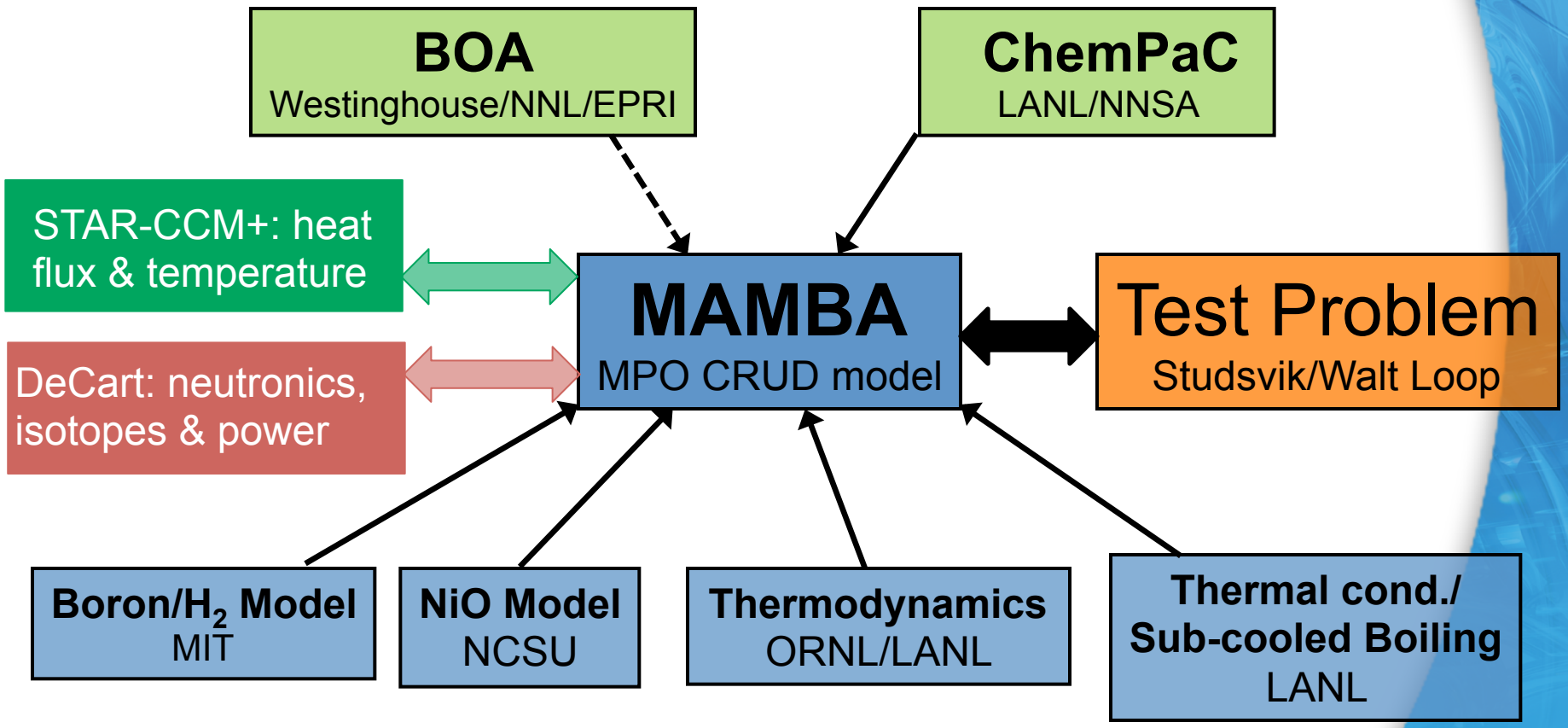
3D MAMBA + CFD Simulation (movie)

Simulation of full pin with 3-spacer grids – CRUD thickness varies due to T variation and surface erosion



Initial steps of coupling CRUD thickness predictions of B incorporation to DeCart for predicting Axial Offset Anomaly

Material Framework for Crud Test Problem



CASL MPO fuel performance efforts moving forward

Advantage of strong teaming relationship between Industry, National Laboratories and Universities & problem oriented focus

Continue scaling our fuel modeling activities towards High Performance Computing will enable efficient consideration of complex phenomena. Integrating fuel/materials, neutronics and thermal hydraulics within Virtual Reactor modeling of full assembly and reactor core will provide quantification of the margins and uncertainties that govern fuel performance and failure

Next steps

Build upon initial steps of benchmarking and validation against test loop and test reactor data, and continually benchmark as new physics-based constitutive relations are implemented from lower-length scale modeling activities; Expand validation efforts to power reactor data

Incorporate fuel phenomena at high temperature transient operation to provide high fidelity fuel performance tool for assessing accident tolerant fuel concepts

Intermediate and out-year effort

Predict operating windows and assess safety margins through validated, predictive performance modeling beyond initial challenge problems