CASL
Consortium for Advanced Simulation of LWRs

2015 Update
The Power of Use Inspired Advanced Modeling and Simulation Research

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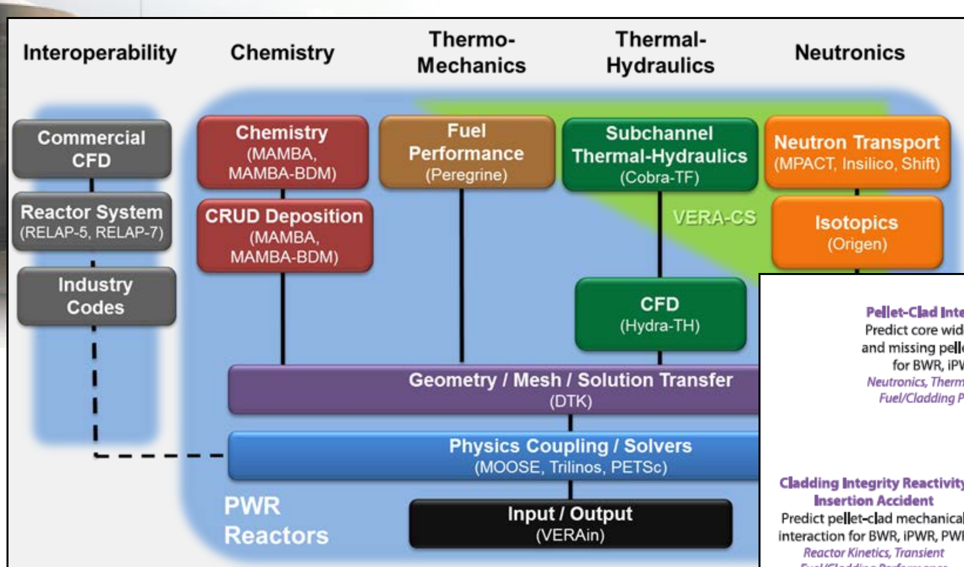
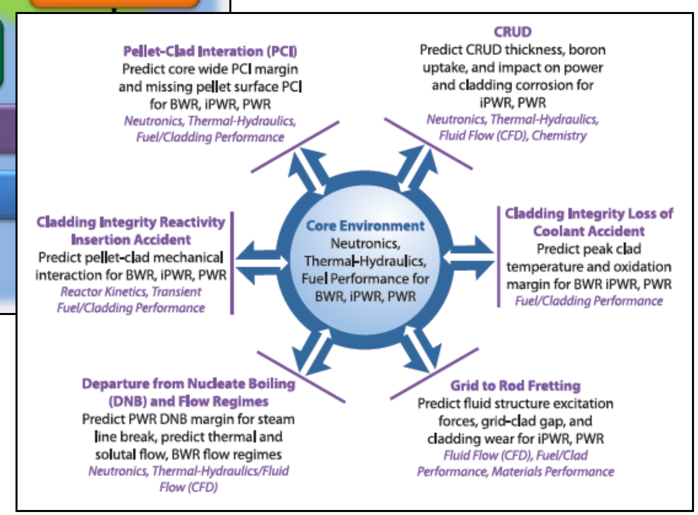
Office of Nuclear Energy
U.S. Department of Energy

In 2015, CASL Completed its First Five Year Phase

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

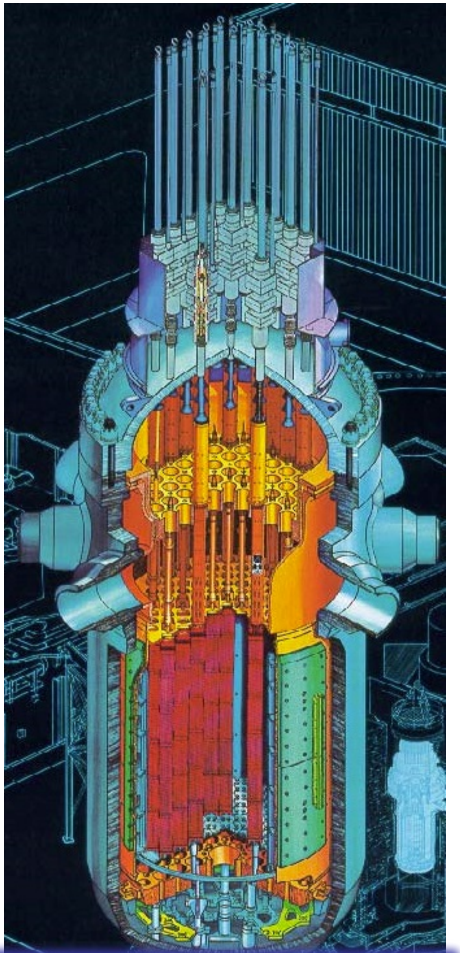
They Built a Virtual Version of the TVA Watts Bar #1 Reactor



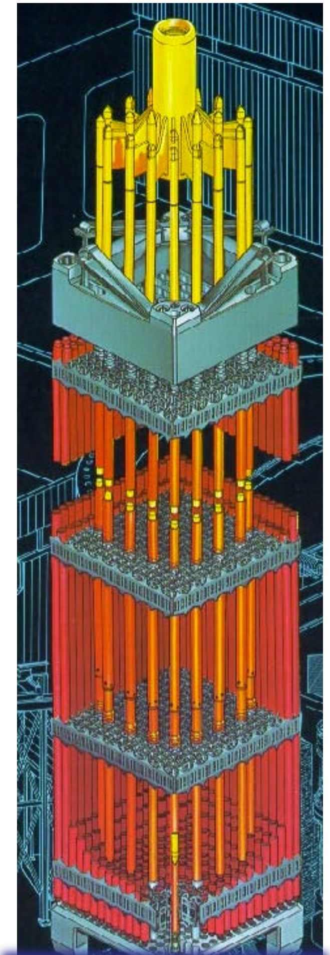


To Be Used to Address Industry Defined Performance and Safety Challenge Problems

TVA's Watts Bar #1 Westinghouse Pressurized Water Reactor (PWR)



reactor vessel and internals



17x17 fuel assembly

Core
- 11.1' diameter x 12' high
- 193 fuel assemblies
- 107.7 tons of UO_2 (~3-5% U_{235})

Fuel Assemblies
- 17x17 pin lattice (14.3 mm pitch)
- 204 pins per assembly

Fuel Pins
- ~300-400 pellets stacked within 12' high x 0.61 mm thick Zr-4 cladding tube

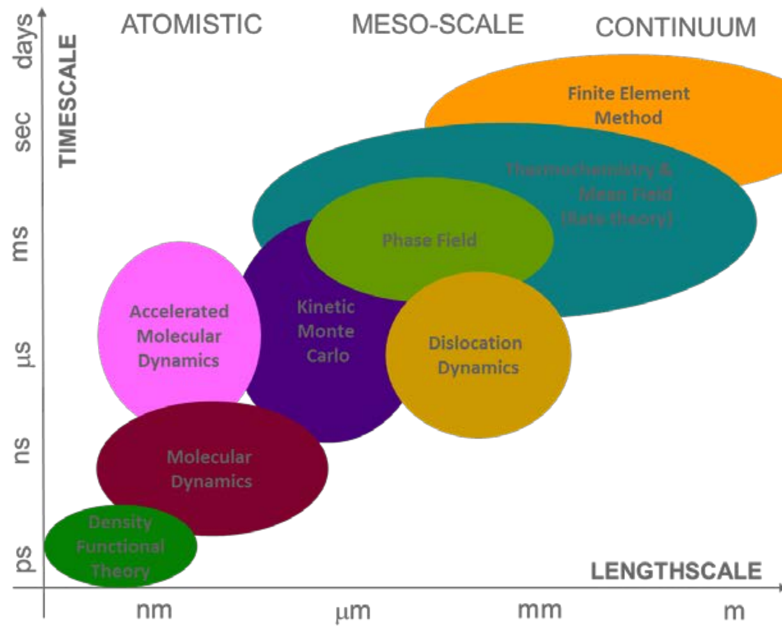
Fuel Pellets
- 9.29 mm diameter x ~10.0 mm high

Fuel Temperatures
- 4140° F (max centerline)
- 657° F (max clad surface)

~51,000 fuel pins and over 16M fuel pellets in the core of a PWR!

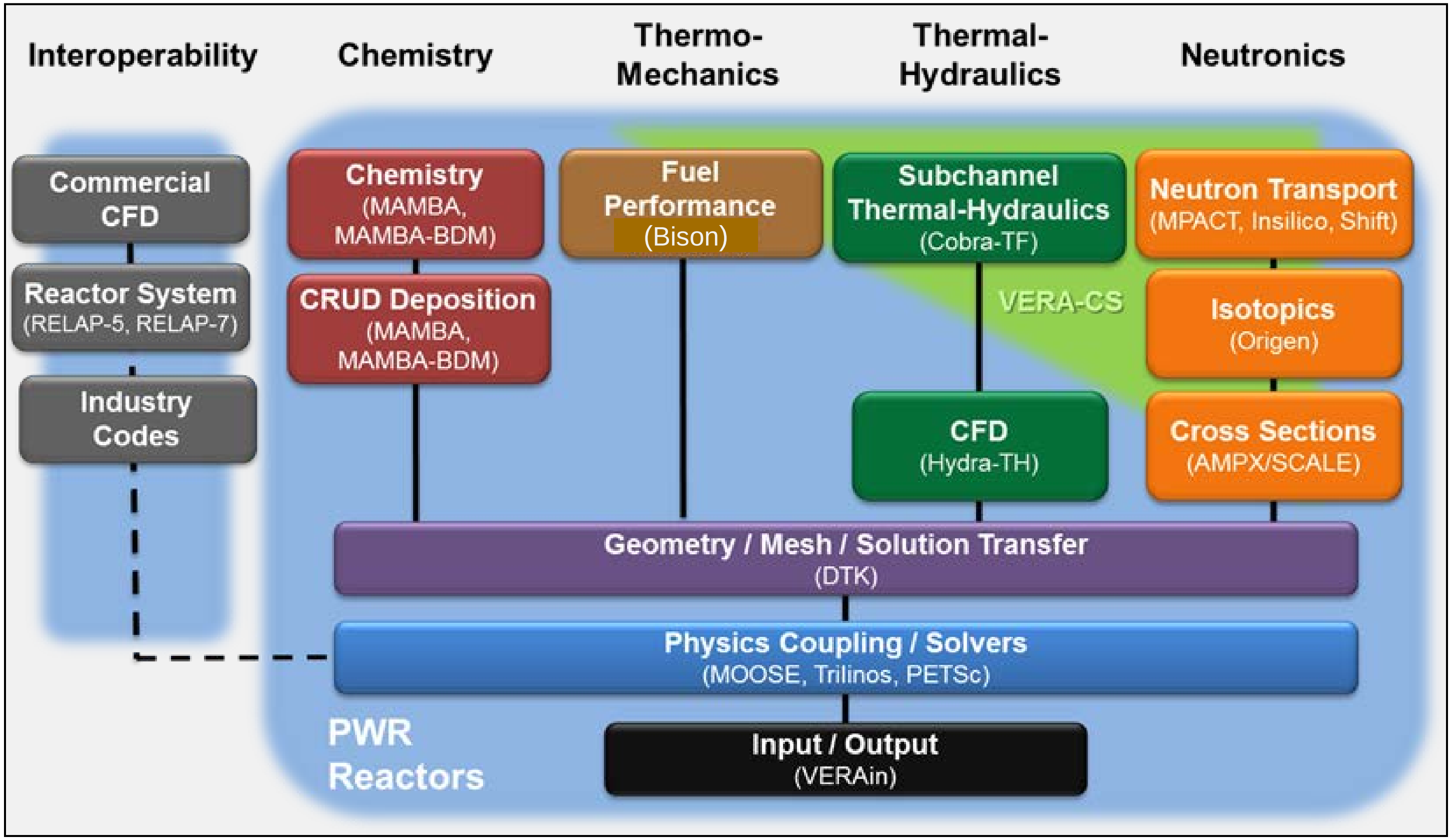
ModSim Challenges of Creating the "Virtual"

- **3-Dimensions (4D with time)**
- **Coupled Multi-physics, multi-scale**
- **High resolution**
- **High fidelity (as much 1st principle physics as possible)**
- **Sufficient simulation time**
- **Sufficient simulation space**
- **Enabled by high performance parallel processing computing**
- **Rigorous verification, validation & uncertainty quantification**

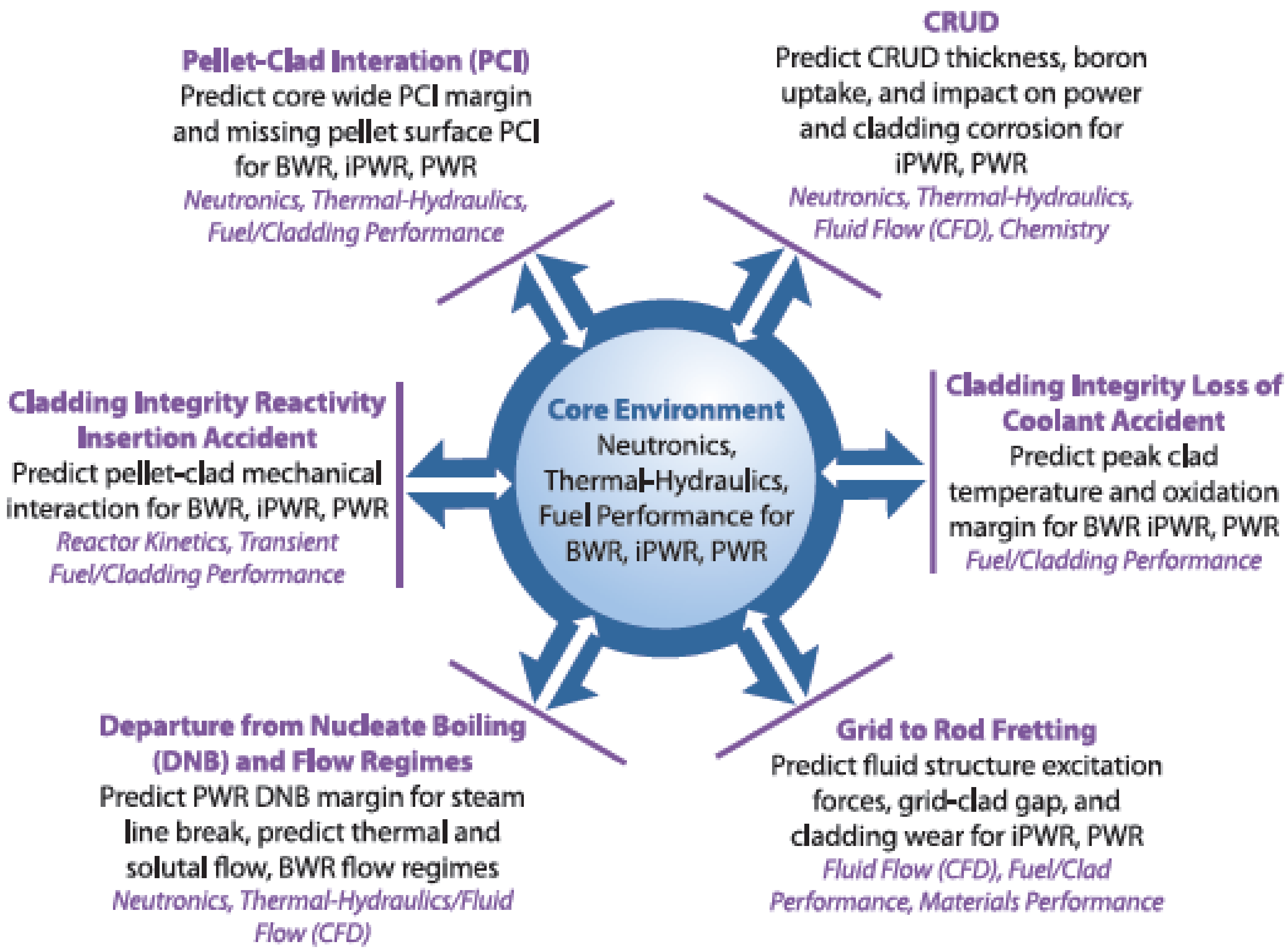


M. Stan, Materials Today, 12 (2009) 20.

CASL Virtual Reactor

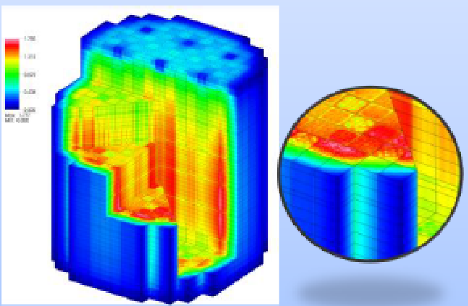


Used to Create Insights Into Industry Defined Challenge Problems

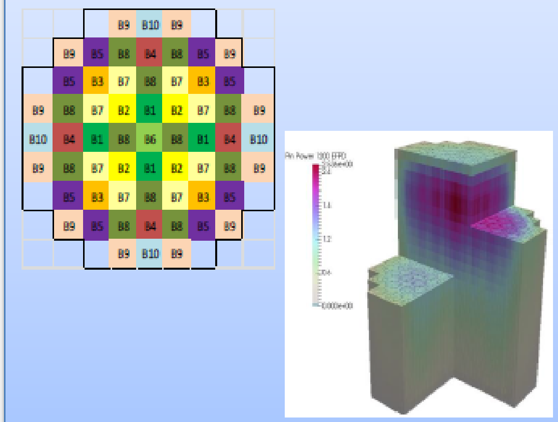


Key Accomplishments in FY15

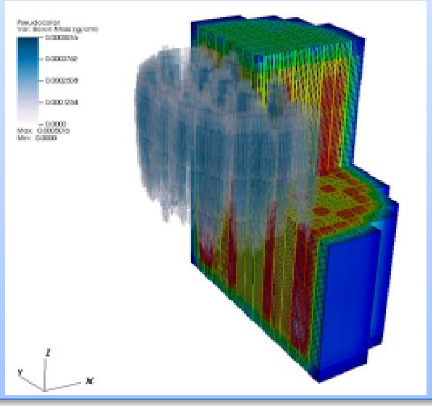
VERA Simulation of Watts Bar Nuclear Unit 1 Operational History



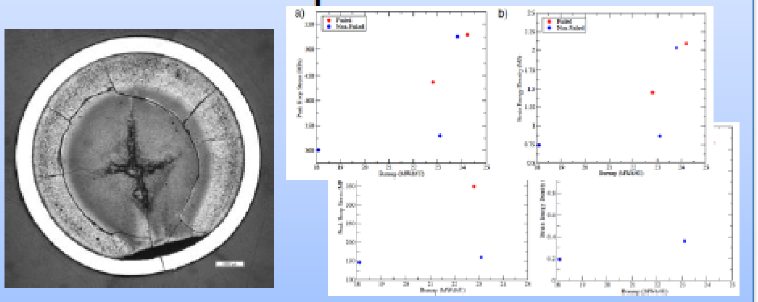
iPWR SMR Modeling Demonstration



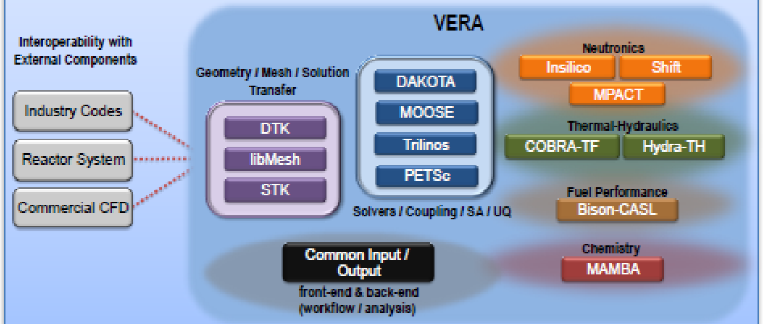
Simulation of Crud Induced Power Shift Challenge Problem (WBN1C7)



3D Modeling of Pellet-Clad Interaction and Comparison with Braidwood Experience

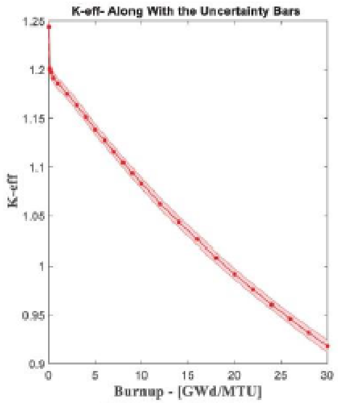


Second Major Externally-available Release of VERA

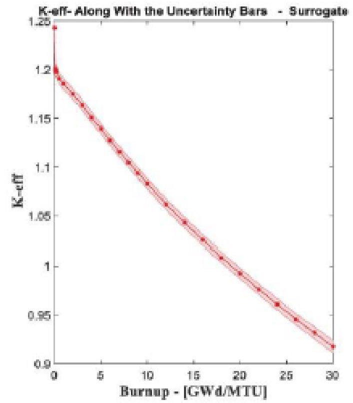


Joint Uncertainties– Depletion Dependent

Keff

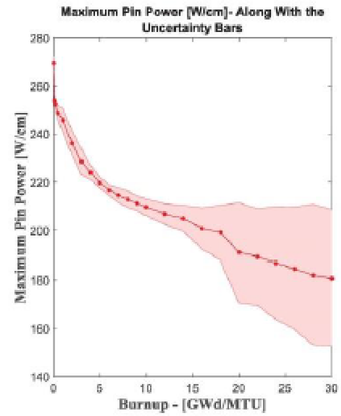


Monte Carlo

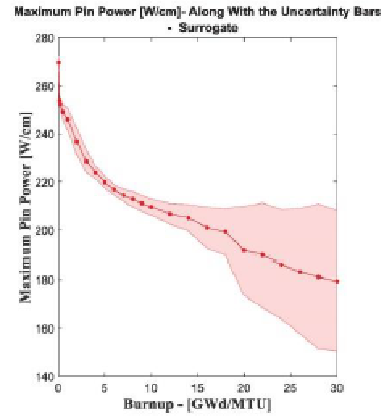


Surrogate

Maximum Pin Power

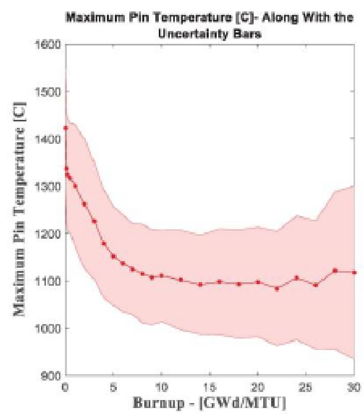


Monte Carlo

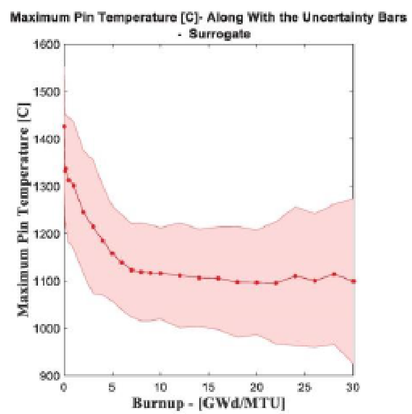


Surrogate

Maximum Pin Temperature



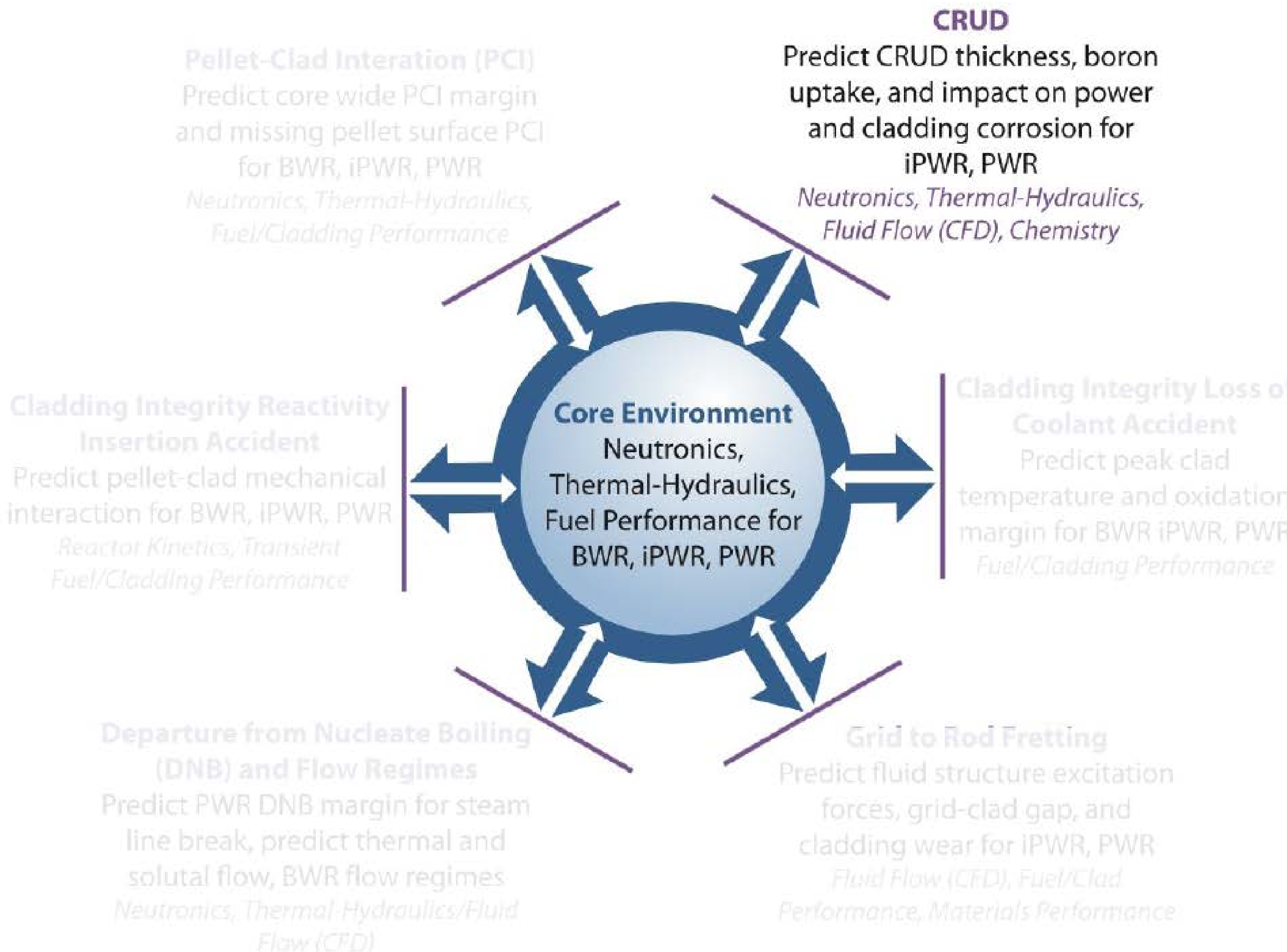
Monte Carlo



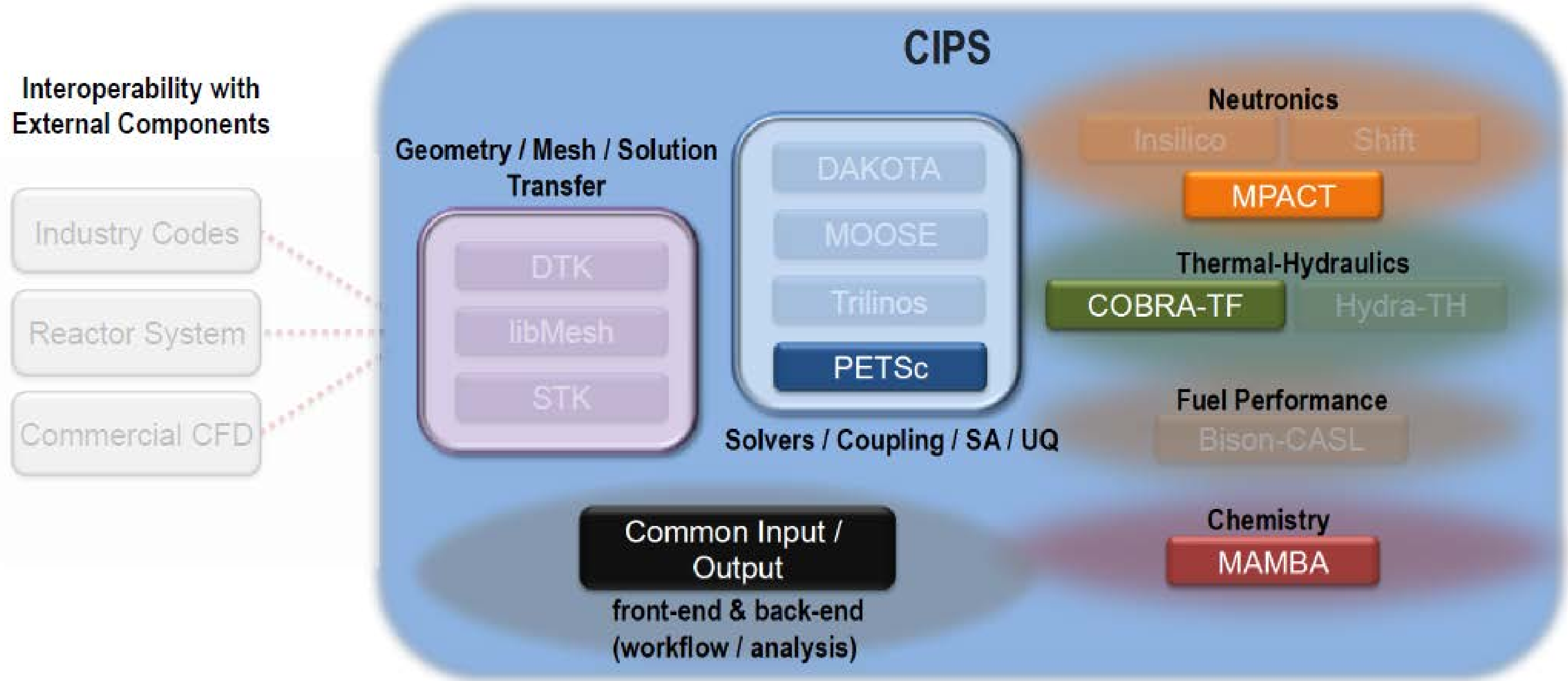
Surrogate

Difference of MC & Surrogate within MC Associated Uncertainty

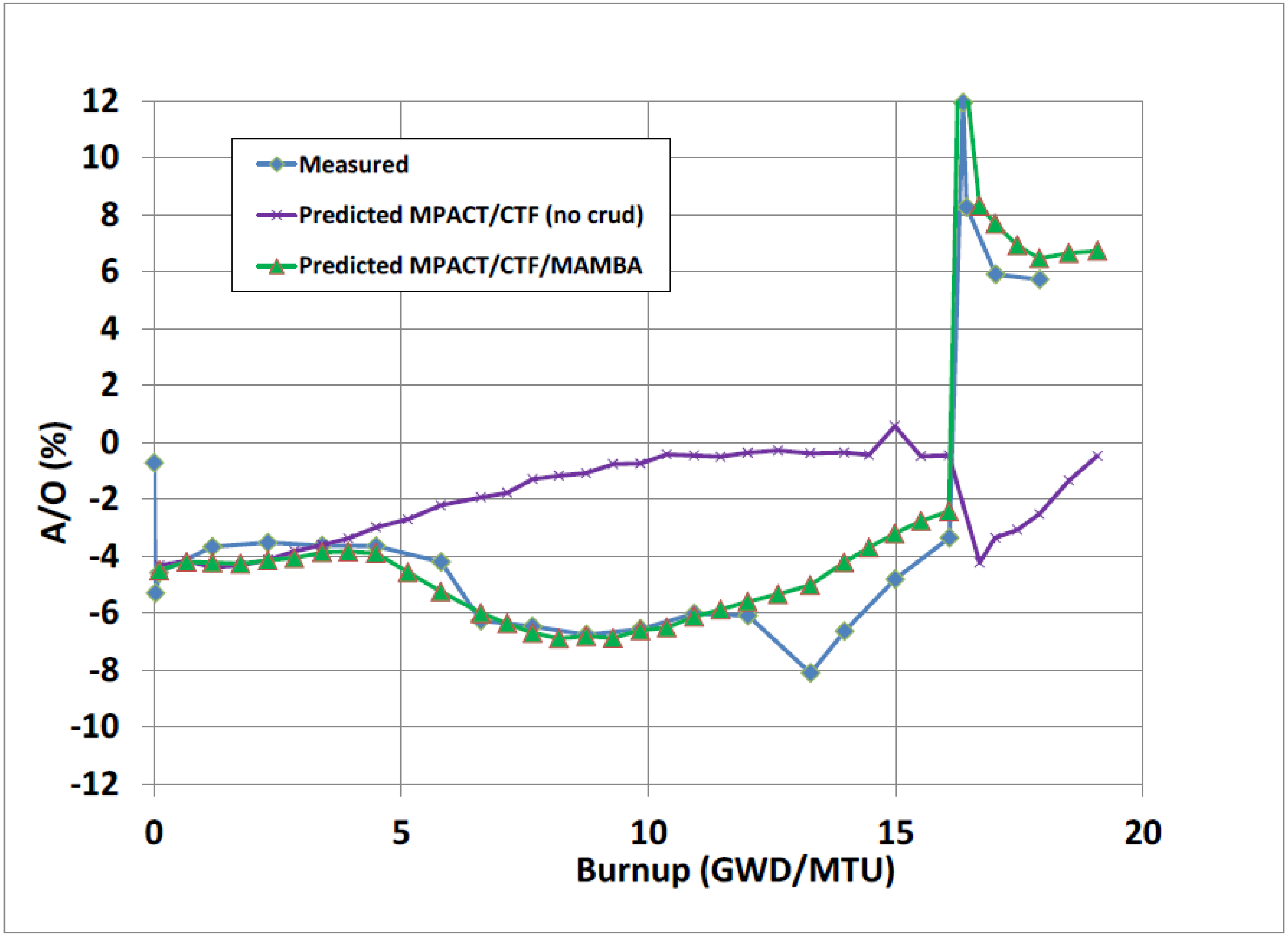
Progress on CRUD Challenge Problem



VERA for CRUD Induced Power Shift Component Coupling



Updated Watts Bar 1 Cycle 7 Measured and Predicted Axial Offset Behavior

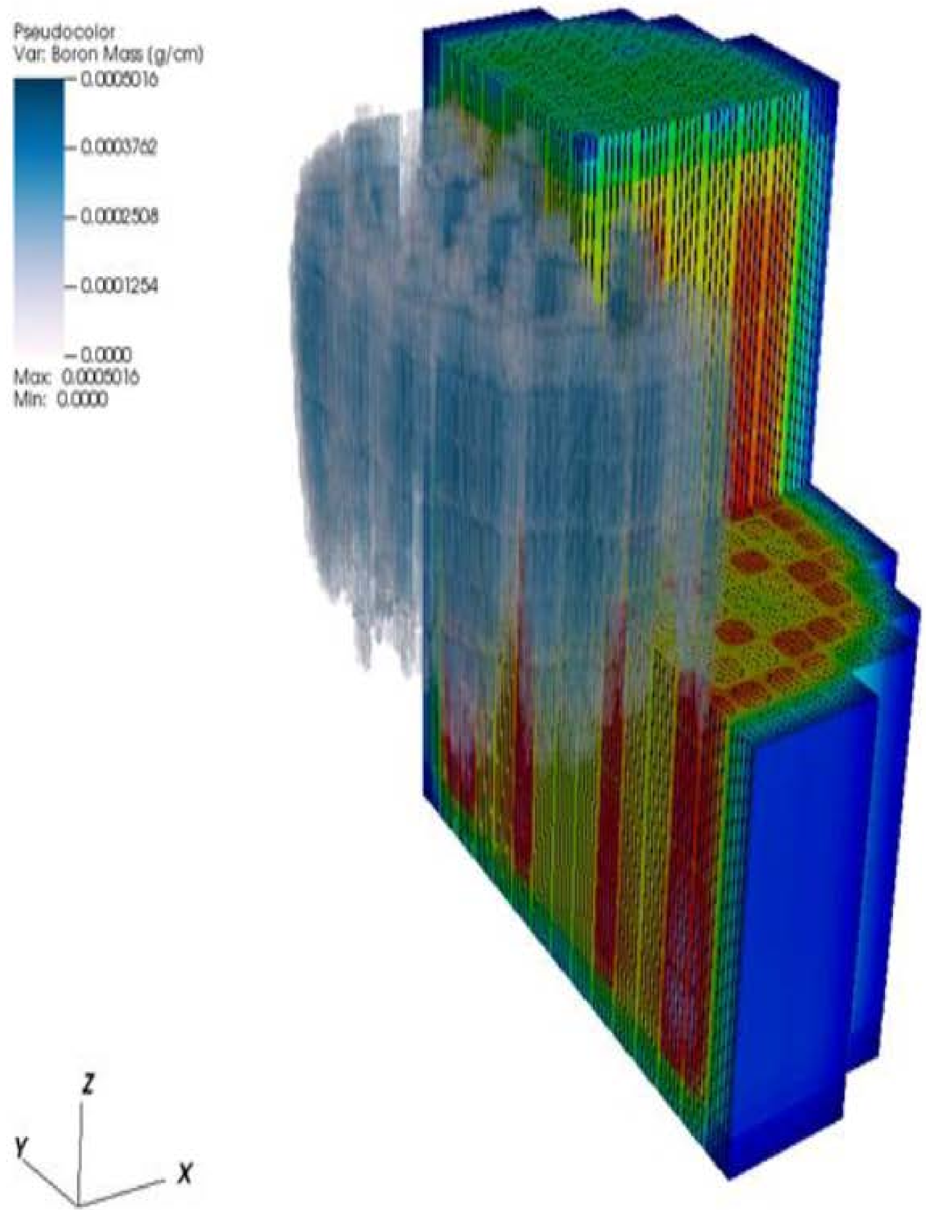


Concentration Threshold For Boron Precipitation Decreased 5X

Fraction of Crud Available For Boron Deposition Increased 3X

Watts Bar 1 Cycle 7 Predicted Boron Distribution

Boron
Distribution
at 16.08
GWD/MTU



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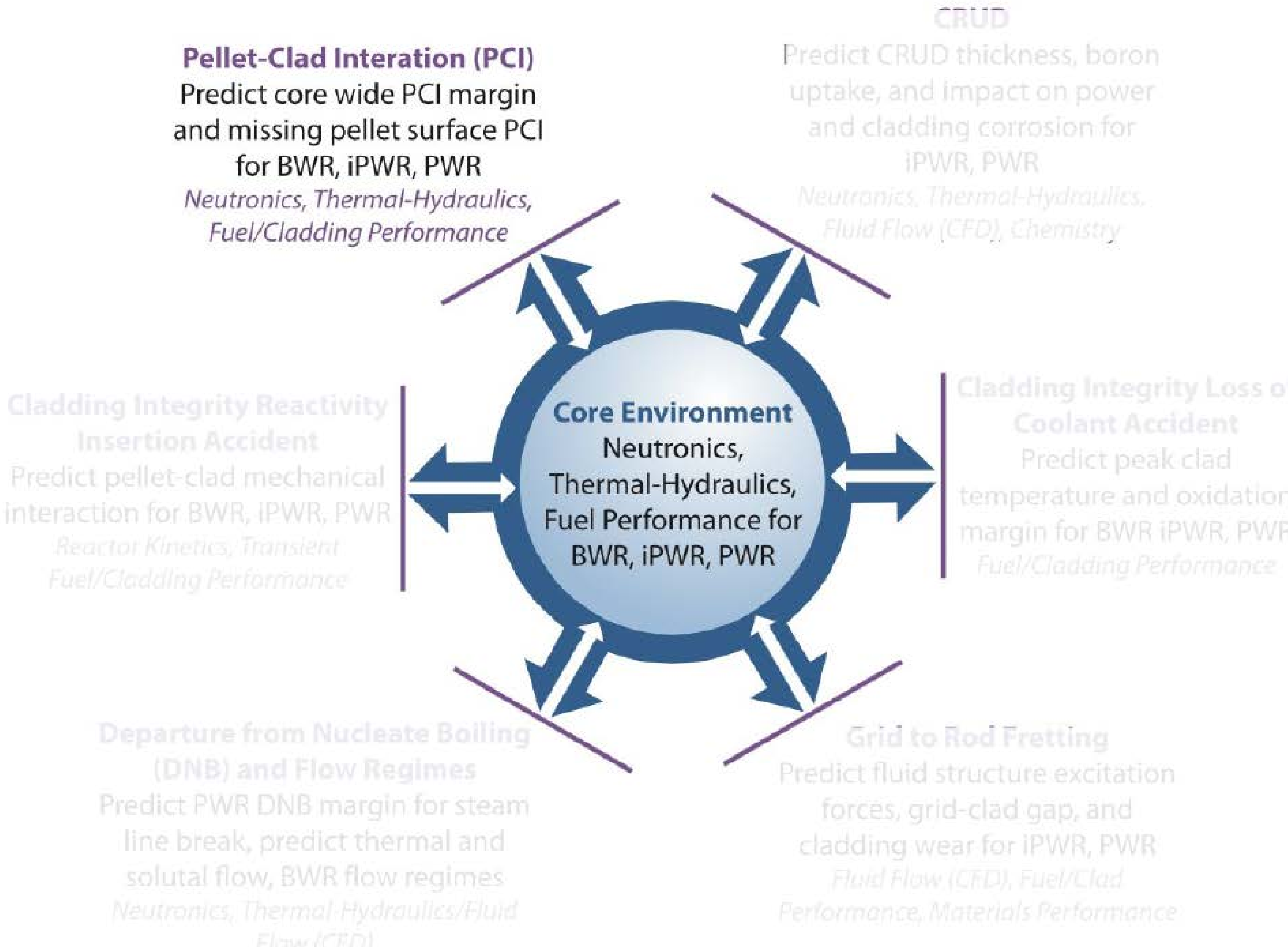
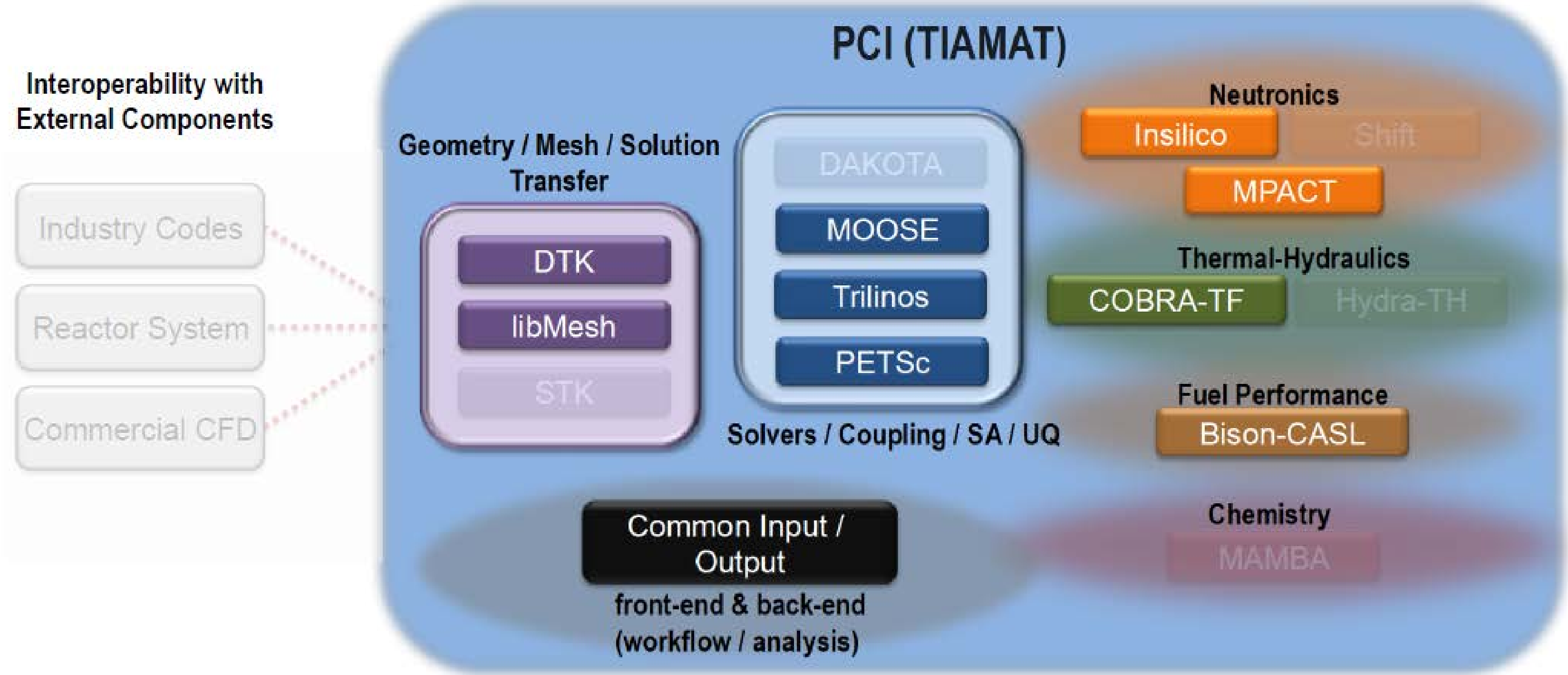
A DOE Energy Innovation Hub

Progress on PCI Challenge Problem



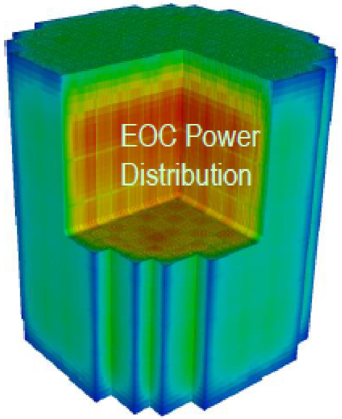
VERA for Pellet Clad Interaction Component Coupling



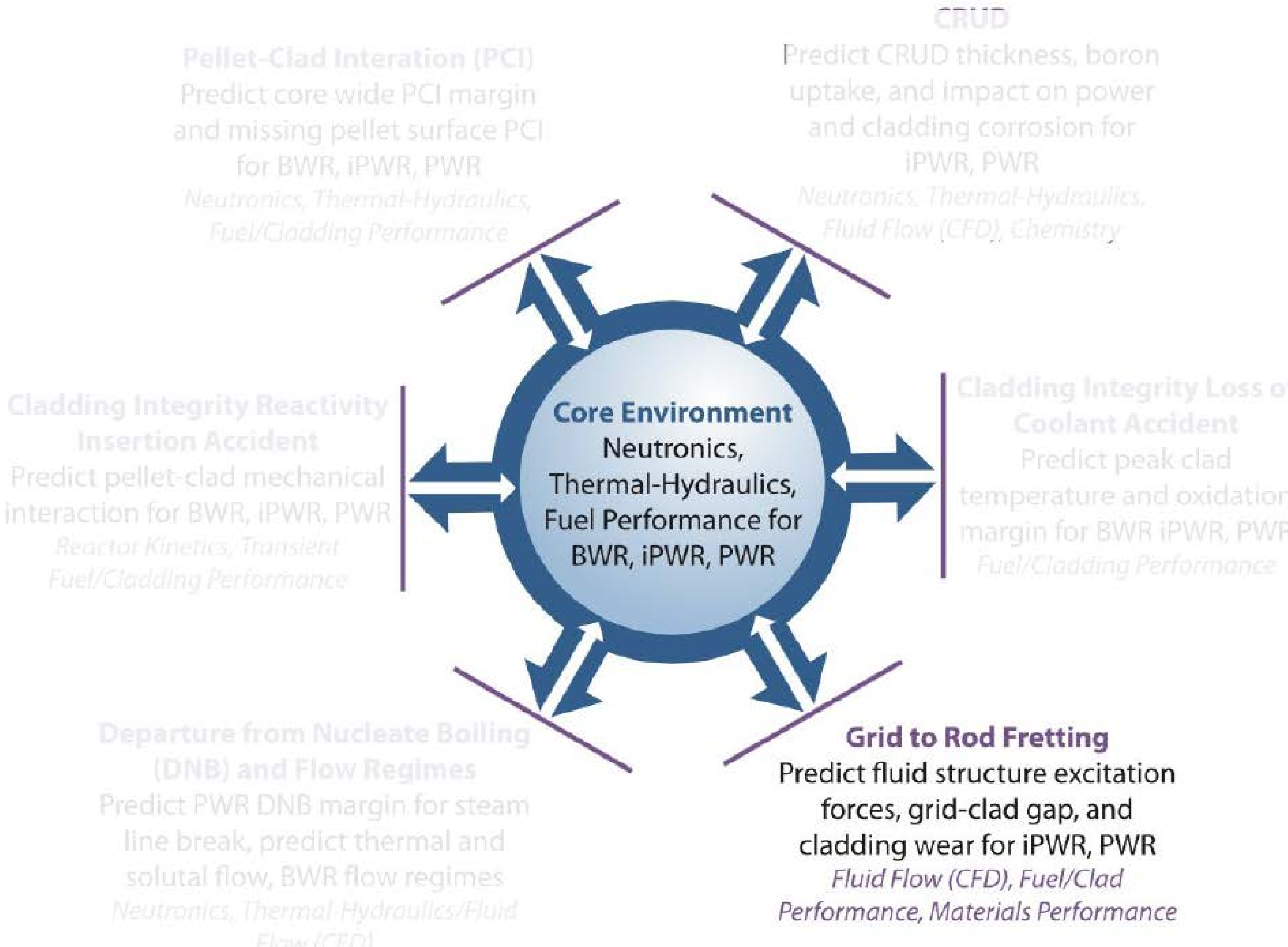
Part 1 Accomplishments

- Development for 2-D and 3-D modeling for both full-length and local effects geometry
- Lower-length scale material modeling of cladding
  - Visco-plastic self consistent model (VPSC) for thermal and irradiation creep and growth
  - Dislocation density crystal plasticity model for Zr-cladding fracture
  - Corrosion and hydriding behavior of Zr-alloys
- Integration into VERA-CS (Tiamat) for multi-rod/multi-assembly simulations
- EPRI Test Stand focus on PCI modeling
  - Initial focus on fuel performance modeling with CASL-BISON

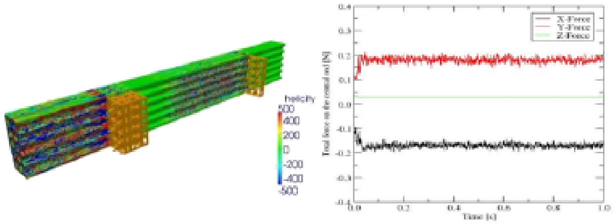
Cladding deformations and stress contour around MPS defect (displacements x20)



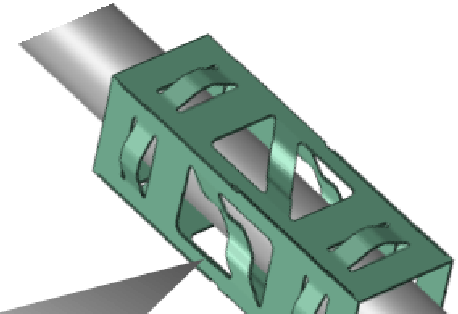
Progress on GTRF Challenge Problem



GTRF Challenge Problem



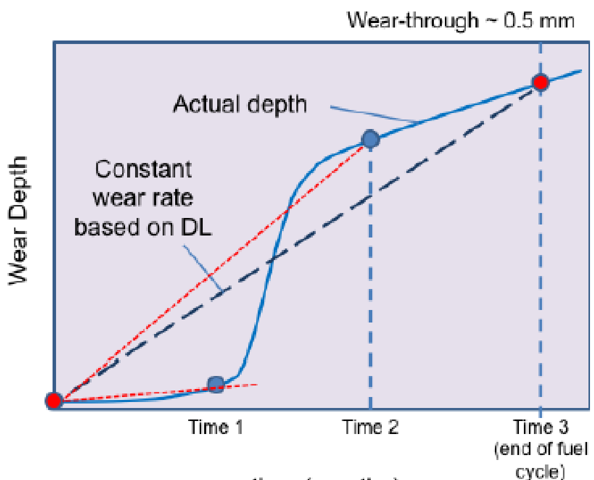
CFD Pressure Load History (Hydra-TH & limited fluid-structure interaction sims)

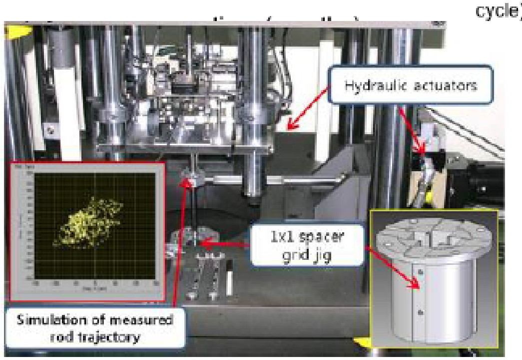


Structural mechanics thru interoperability with ISVs

Wear model

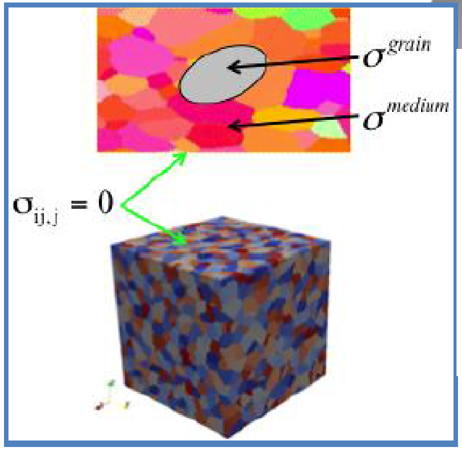
Consisting of incubation, oxide and substrate controlled stages in the wear history.

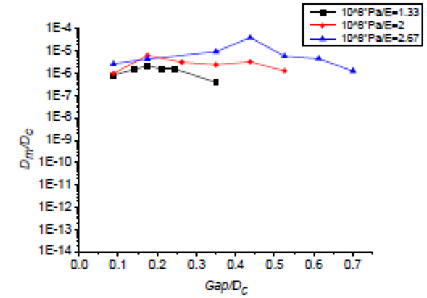




ORNL controlled fretting wear measurements

TEAM: Dave Parks, Ken Kamrin, Michael Demkowicz, Sam Sham, Peter Blau. Jun Qu, Roger Lu, Michael Thouless, Wei Lu,

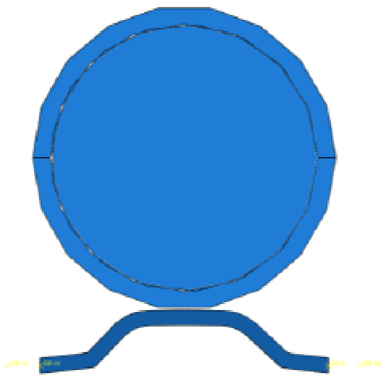


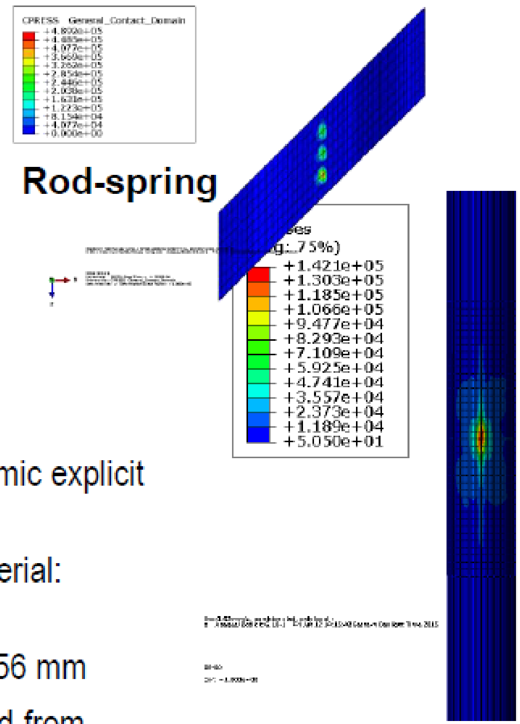


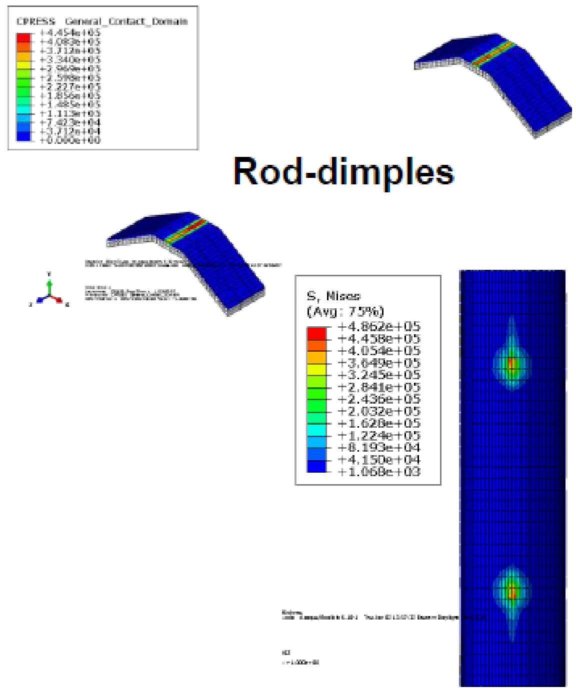
Grid-rod gap evolution, mechanical property evolution & parametric studies of gap size/rod stiffness on wear shapes

Fretting mechanics: recent progress

Finite element modeling used to evaluate and refine design for new fretting tester under procurement







- 3-D FEA model using dynamic explicit code
- Rod and spring/dimple material: Zircaloy-4
- Rod modeled with length 356 mm
- Spring/two dimples modeled from scanned profile
- Contact defined between clad and spring/ dimples surfaces
- Initial velocity of clad upon impacting spring/dimples estimated as 0.25~0.62mm/s

Impact	FEA simulated reaction force (N)
Rod against spring	0.08 ~ 0.16
Rod against dimple	0.17 ~ 0.40

Used to define the specs of contact forces in bench tests.

Summary - Overall Challenge Problem Progress

	Development	Innovation	Validation
Operational			
CRUD-induced power shift (CIPS) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
CRUD-induced localized corrosion (CILC) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Grid-to-rod fretting failure (GTRF) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Pellet-clad interaction (PCI) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Pellet-clad interaction (PCI) - BWR	Significant Progress	Significant Progress	Planning & Scoping
Safety			
Departure from nucleate boiling (DNB) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Cladding integrity during (LOCA) – PWR/iPWR	Good Progress	Planning & Scoping	Not Started
Cladding integrity during (RIA) – PWR/iPWR	Good Progress	Planning & Scoping	Not Started
Predict Thermal & Solutal Flows – iPWR/BWR	Planning & Scoping	Not Started	Not Started
Cladding integrity during (LOCA) – BWR	Planning & Scoping	Not Started	Not Started
Cladding integrity during (RIA) – BWR	Planning & Scoping	Not Started	Not Started

Significant Progress

Planning & Scoping

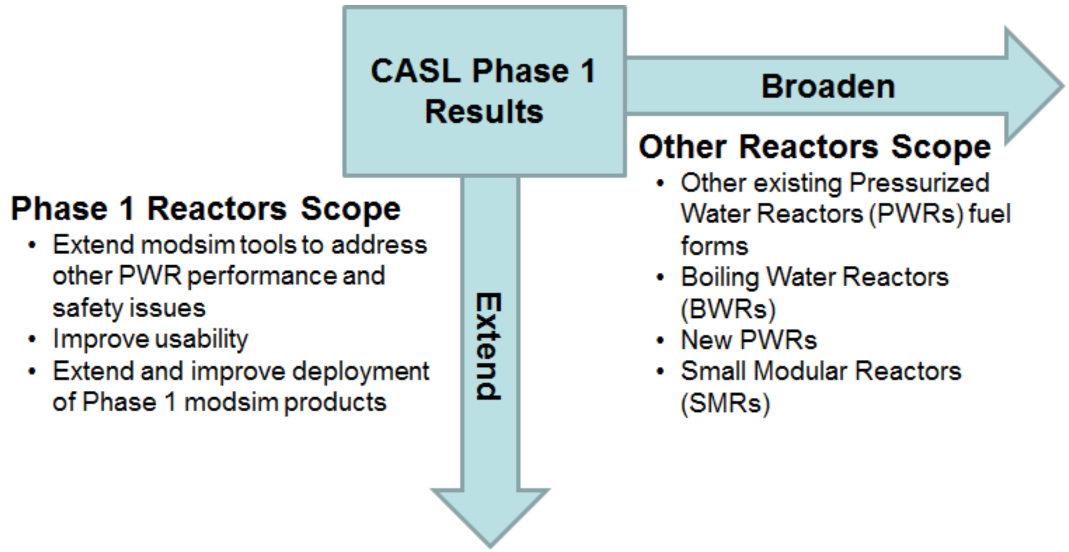
Good Progress

Not Started

Phase 2 Application Process

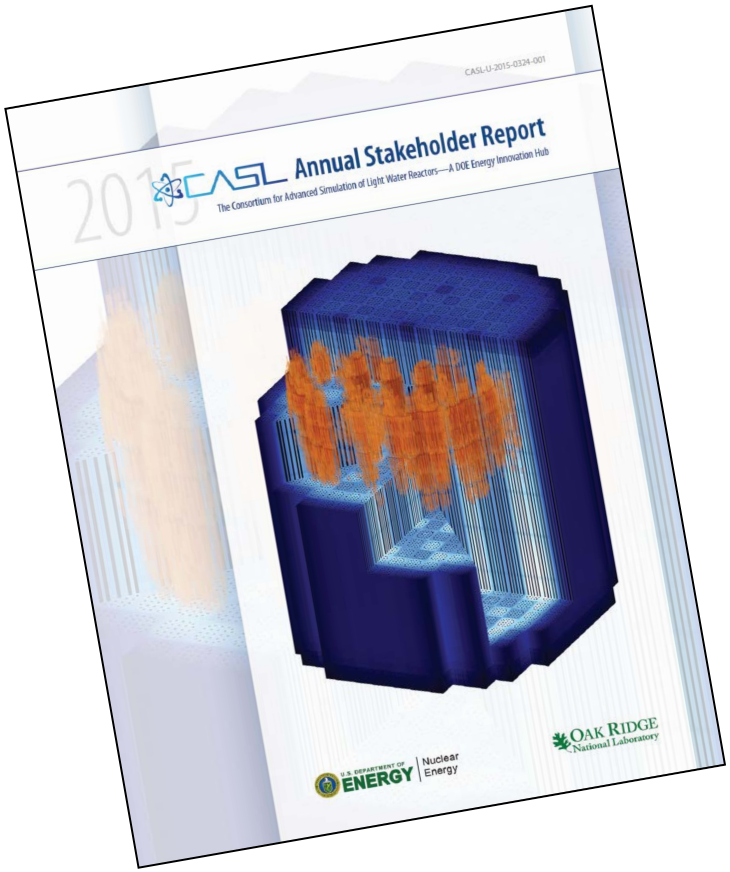
- **Demonstrated CASL Met Criteria to Qualify for Phase 2**
  - **Technical Performance** – Meeting Milestones
  - **Annual Reviews** – Successful Completion
  - **Impact on Science and Engineering** – Publications, Presentations, Students
  - **Technology Deployment** – Demonstrated Success

- **Generated Plans for Phase 2**



  - **Most Importantly** – Phase 2 is not a repeat of Phase 1!

Phase 2 Light Federal Touch Oversight to be Provided by an Annual Stakeholder Report



- **End Nuclear Energy Modeling and Simulation Users**
  - Simulated all 13 fuel cycles of the Watt Bar #1 Reactor with depletion, fuel shuffling and discharge
  - Extended VERA tools to SMRs & BWRs
  - Accurately simulated (pin by pin) simulation of the cycle 7 CRUD induced power shift
- **Science and Engineering**
  - Extensive publications
  - Recognition of CASL with individual research awards and journal special editions
- **Workforce Training and Education**
  - Created VERA-EDU
  - Initiated VERA training, documentation and course curriculum
  - CASL Undergraduate Research Scholars Program
- **Sustaining Taxpayer Investments**
  - Initiated the creation of the VERA-Working Group based on the RELAP5 model to collect funds for code maintenance and ongoing user support.
  - NCSU Business School study of CASL

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CASL is Overcoming the Barriers for Successful Advanced Computing Deployment

■ 2012 Workshop Identified Barriers

- **Technical** – Simulation Tools that are Useful and Usable
  - CASL Responses Includes
    - Focused on industry defined challenge problems
    - Standard input based on industry workflows and standards
    - Improved computational efficiency to allow running simulations on industry class systems
- **Structural** – IP and Legal Agreements
  - CASL Responses Includes
    - Established export control protocols
    - Released Intellectual Property Management Plan
- **Motivation** – Demonstration of the value CASL tools
  - CASL Responses Includes
    - Deployment of VERA Test Stands
    - Return on investment studies
    - Ongoing engagement through the Industry Council