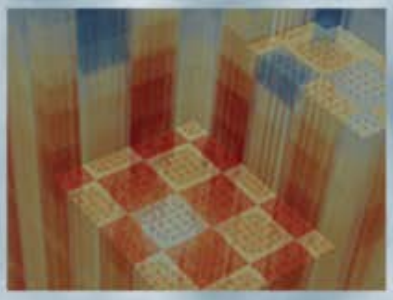
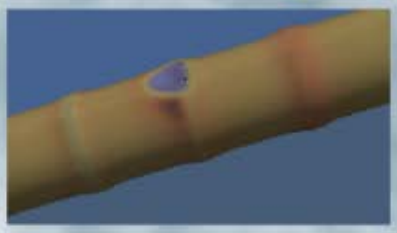
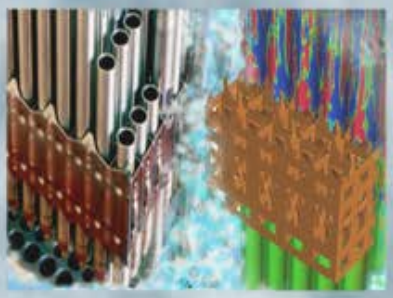
CASL-U-2015-0104-000

CASL: The Consortium for Advanced Simulation of Light Water Reactors A DOE Energy Innovation Hub







Doug Kothe
Oak Ridge National Laboratory

Paul Turinsky
North Carolina State University

July 8-10, 2013

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

CASL-U-2015-0104-000

CASL: The Consortium for Advanced Simulation of Light Water Reactors

A DOE Energy Innovation Hub

Doug Kothe and Paul Turinsky

CASL

A DOE Energy Innovation Hub in the Office of Nuclear Energy

- First Introduced by Energy Secretary Chu in the President's FY2010 Budget

- A Different Approach
  - "Multi-disciplinary, highly collaborative teams ideally working under one roof to solve priority technology challenges" – *Steven Chu*
  - "Create a research atmosphere with a fierce sense of urgency to deliver solutions." – *Kristina Johnson*
  - Characteristics
    - Leadership – Outstanding, independent, scientific leadership
    - Management – "Light" federal touch
    - Focus – Deliver technologies that can change the U.S. "energy game"

Mission

Provide leading edge modeling and simulation capabilities to improve the performance of currently operating Light Water Reactors

Vision

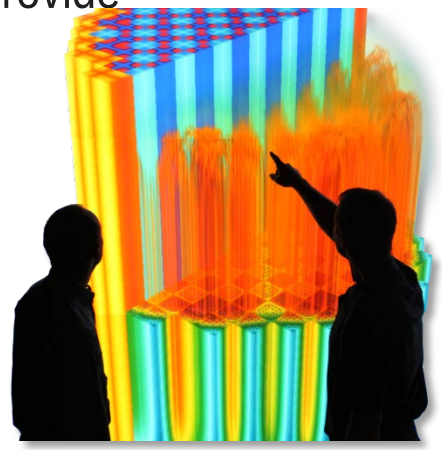
Predict, with confidence, the performance and assured safety of nuclear reactors, through comprehensive, science-based modeling and simulation technology that is deployed and applied broadly within the U.S. nuclear energy industry

Goals

1. Develop and Effectively Apply Modern Virtual Reactor Technology
2. Provide More Understanding of Safety Margins While Addressing Operational and Design Challenges
3. Engage the Nuclear Energy Community Through Modeling and Simulation
4. Deploy New Partnership and Collaboration Paradigms`

CASL is addressing industry needs

- Driven by 3 key issues for nuclear energy:
  - Reducing cost
  - Reducing amount of used nuclear fuel
  - Enhancing safety
- Applying and developing advanced M&S capabilities to create a usable Virtual Reactor environment for predictive simulation of LWRs
- Focused on performance of pressurized water reactor (PWR) core, vessel, and in-vessel components to provide greatest impact within 5 years

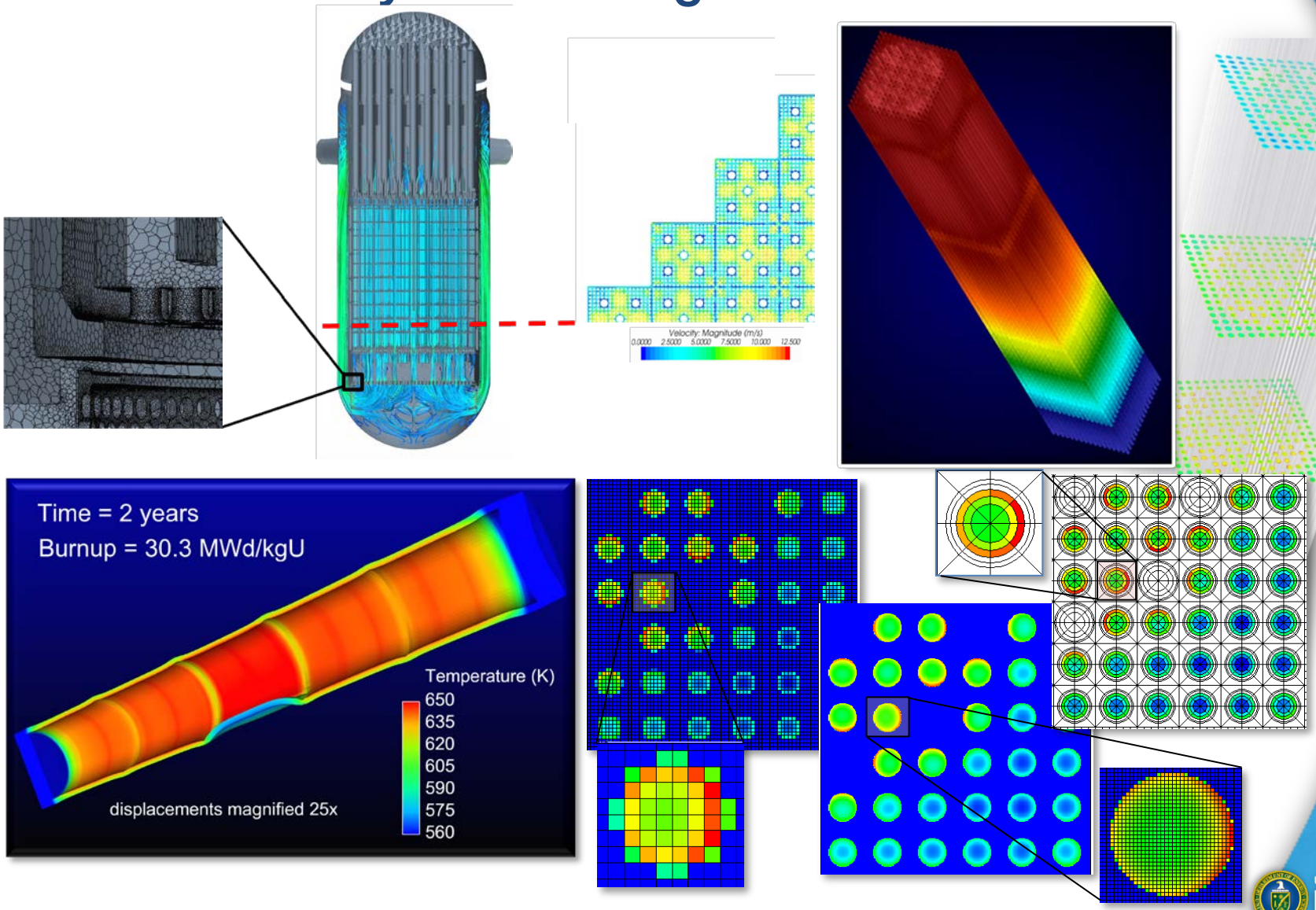


CASL advisory groups

Industry Council *What needs to be addressed?*	• Reviews plans, specifications, and products • Advises on gaps and critical needs • Advises on incremental technology deployment
Science Council *How should we address it?*	• Provides independent assessments of alignment between scientific work, as planned and executed, and overall goals

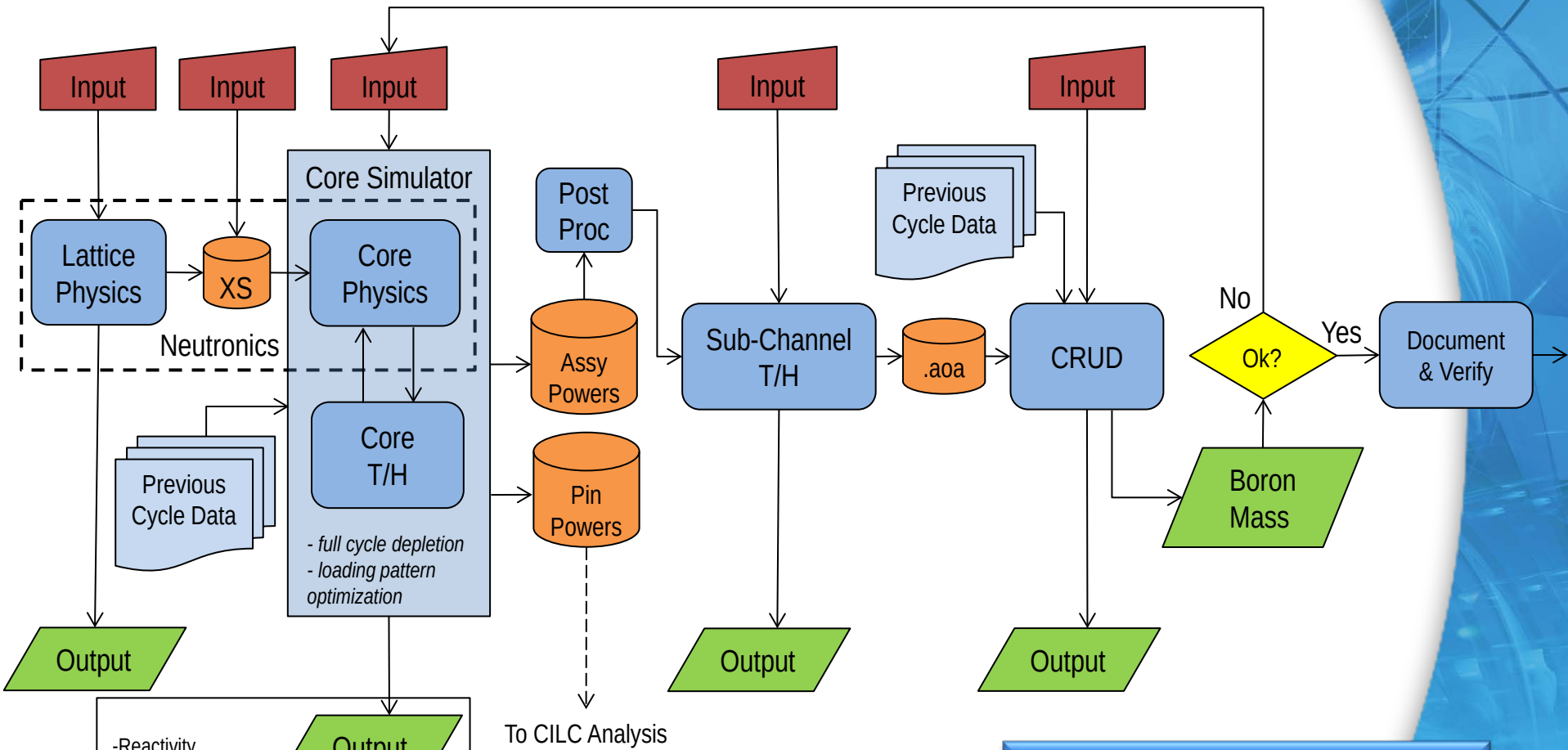
CASL-U-2015-0104-000

CASL Tackles the Multi-Scale Challenge of Predictively Simulating a Reactor Core



From full core to fuel assembly to fuel subassembly to fuel pin/pellet

Complexity Prevails - An Example Nuclear Industry M&S Workflow
Crud Induced Power Shift Risk Evaluation



-Reactivity
-Critical Boron
-Critical Control Rod Positions
-Assembly and Rod Powers
-Assembly and Rod Exposures
-Core Coolant Density Distribution
-Core Axial Offset
-Instrument Response
-Neutron Fluence

Criteria

Compare calculated Boron mass over entire cycle to a 'low risk' threshold = X lbm Boron

Workflow: processes, tools, and technologies used to take a problem to a solution or a concept to a design

CASL Challenge: Navigate Transforming Landscape

Source: Heather Feldman (EPRI)

Flexible Nuclear Plant Operation

- Gray control rods
- Flow induced vibration
- Flow accelerated corrosion

License Extension

- Higher burn up fuel
- Enhanced core design

Accident Tolerant Fuel

- Concept refinement
- Test Planning
- Margins

Power Up-rate

- Fuel modifications
- Safety margin assessment

CASL Test Stand - Potentials

- Peregrine validation
- Inform mods to Falcon
- Technical Challenges

History of Power Uprates

Source: Heather Feldman (EPRI)

- Measurement uncertainty recapture (MUR)
  - Ex: Feed water flow rate (<2%)
- Stretch Power Up-rate (SPU)
  - Ex: Instrument set points (2% to 7%)
- Extended Power Up-rate (EPU) <= ModSim Role
  - Ex: Design changes (7% to 20%)
- Ultra Power Up-rate (UPU) <= ModSim Role
  - Ex: Extensive fuel and BOP changes (> 20%)
  - None have been performed
- Equivalent to ~6 large nuclear power plants (6,440 Mwe) added to the grid thru uprates
  - 143 power up-rates approved since 1977
- About 6,000 MWe remains available for EPU
  - 17 applications currently under review (9 MURs, 8 EPUs)
  - 15 new applications are expected in the next 5 years (8 MURs, 7 EPUs)

Westinghouse Experience

MUR COMPLETED
- 25 Americas PWRs
- 5 European PWRs
- 2 Asian PWRs

SPU COMPLETED
- 10 Americas PWRs
- 0 European PWRs
- 4 Asian PWRs

EPU COMPLETED
- 7 Americas PWRs
- 5 European PWRs
- 0 Asian PWRs
- Completed/planned: 5 of 6 2-loops, 4 of 13 3-loops, 0 of 30 4-loops, 5 of 14 CE Design

Where is NRC's Focus on Up-rates?

- Japan Event Follow-up
- GSI -191 Post-LOCA Debris Effects
- Containment Accident Pressure (CAP)
- Thermal Conductivity Degradation (TCD)
- Boron Precipitation/Long Term Cooling
- Gas Accumulation
- LOCA Analysis
- Spent Fuel Pool Issues
- Digital I&C
- Alternate Source Term
- Steam Dryers
- Steam Generator Issues
- Single Failure Concerns
- High Energy Line Break
- Licensing Amendment Issues
- Licensing Conditions and Commitments

Nearly all items could benefit from ModSim advances

More at: http://www.nrc.gov/reactors/operating/licensing/power-uprates.html

Industries' Hopes and Expectations for CASL

Source: Dan Stout, Rose Montgomery (TVA)

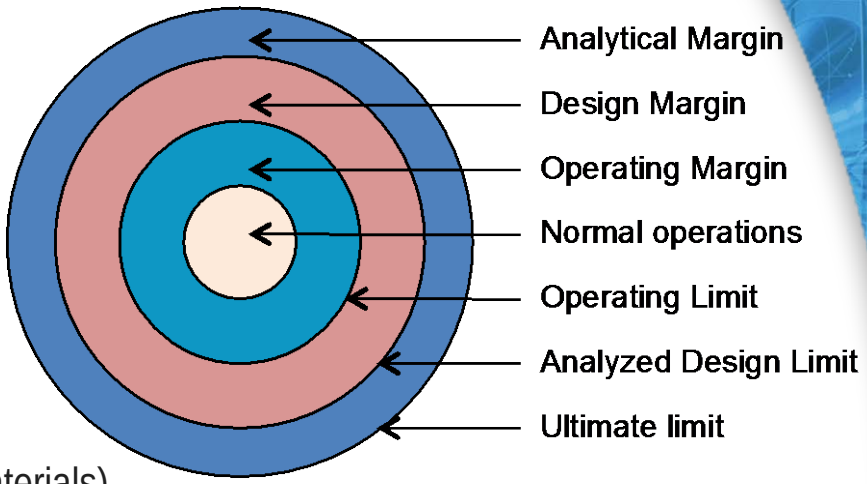
- Advance the state of the art in understanding nuclear concepts and performance
- Produce a rigorous, fully-coupled, first principles simulation code package usable by the full range of domestic fuel vendors and power utilities
  - Ensure key performance models are fully described for industry implementation
  - Provide a flexible path to industry implementation
- Strategically address power-limiting operating scenarios
  - Design Basis Accidents (DBAs), Power Ramp rates
  - Departure from Nucleate Boiling (DNB)
  - Potential for better understanding of beyond design basis events

Phase 1: Insights from CASL enable a utility to realize more aggressive core loading saving on fuel costs with applicability to multiple utilities/reactors;

Phase 2: Insights from CASL result in multiple vendors making code modifications to existing licensed codes that enable utilities to seek license amendments that could add ?? GW(e) of nuclear energy on the grid

Long Term: CASL tools are broadly used to enhance nuclear energy safety and capacity

Margin Management
Source: Sumit Ray (Westinghouse)



- Requires a strategic approach
  - How much is needed? How to allocate?
  - How can margin be transferred from one bucket to another?
- Key considerations
  - Plant operating parameters & assumptions (plant optimization & flexibility, load follow)
  - Fuel hardware (advanced product features & materials)
  - Design software and methodology (advanced technologies)
  - Core monitoring, In-core fuel management
  - Margins for the unknown or uncertain
  - Reload flexibility
  - Regulatory changes
- Margins can be "recovered"
  - Change in design or operation or testing, reduced safety factor
  - Reduced calculational conservatism (possibly employing advanced analytic tools)
  - Changes to design characteristics of a limiting variable
  - Decrease in the margin of one parameter to increase the margin in another
  - Modification of system or component

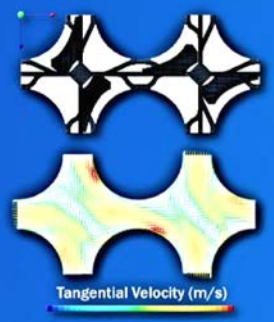
Margin trade-offs and evaluation of risks require involvement of many stakeholders within the Utility (Fuels and Plant Operations) and suppliers (BOP, NSSS, T/G, etc.)

One of the strategic targets for the CASL VERA toolkit is to provide enhanced insights in the area of critical reactor margins

CASL Challenge Problems

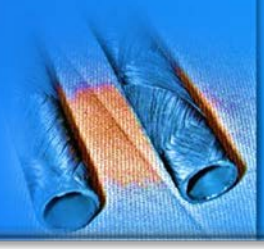
Key safety-relevant reactor phenomena that limit performance

Departure from Nucleate Boiling

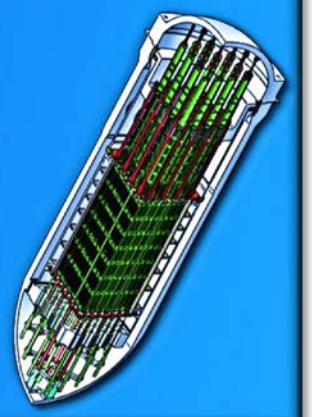


Cladding Integrity

- During LOCA
- During reactivity insertion accidents
- Use of advanced materials to improve cladding performance



Reactor Vessel and Internals Integrity



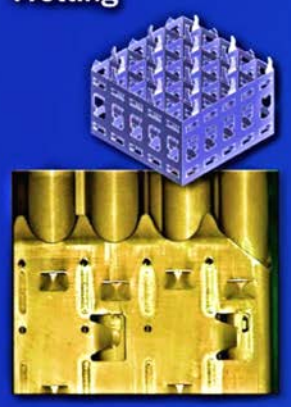
CASL is committed to delivering simulation capabilities for

- Advancing the understanding of key reactor phenomena
- Improving performance in today's commercial power reactors
- Evaluating new fuel designs to further enhance safety margin

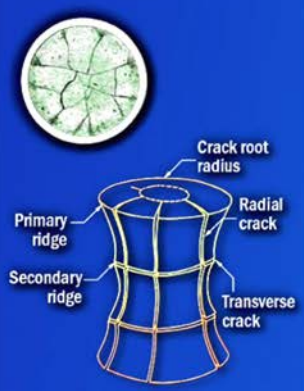
Crud

- Deposition
- Axial offset anomaly
- Hot spots

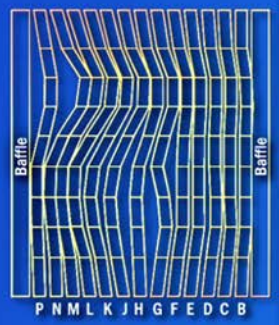
Grid-to-Rod Fretting



Pellet-Clad Interaction



Fuel Assembly Distortion

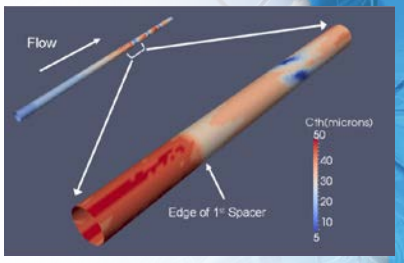


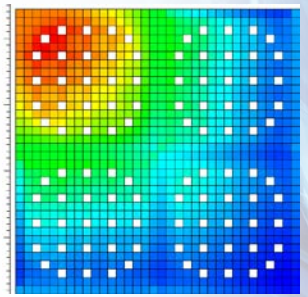
Challenge Problems Directly Support Key Nuclear Industry Drivers

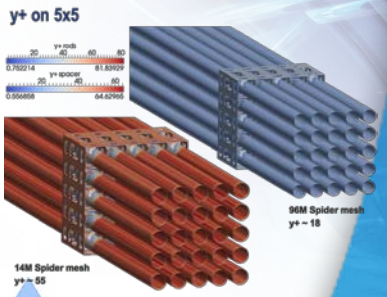
Industry Driver	Industry Driver Performance Measures	Supporting CASL Challenge Problems	Success Metrics for Tangible CASL Support
Power Uprates	• Augment planned U.S. reactor fleet power uprates beyond current value of 2694 MW_e thru 2016 • Increase proportion of stretch (>2%) and extended (>7%) power uprates in U.S reactor fleet	• CRUD, PCI, FAD, GTRF • Cladding Integrity (DNB, LOCA, RIA) • Reactor Integrity (vessel, internals) • Advanced Fuels	• Reduce or eliminate restrictions to uprates associated with current challenge problem • Contribute capability to support one or more license uprate applications
Lifetime Extension	• License remaining ~30% of U.S. reactor fleet to 60 years where appropriate before 2015 • Safely extend lifetimes of U.S. reactor fleet to 80 years where appropriate before 2020	• Reactor Integrity (vessel, internals) • Advanced Fuels	• Provide reliable estimates of reactor environment experienced over lifetime • Contribute capability to support one or more lifetime extension applications
Higher Fuel Burnup	• Increase maximum fuel assembly burnup of 55 GWd/MTU in U.S. reactor fleet • Increase allowable peak fuel rod burnup of 62 GWd/MTU in U.S. reactor fleet	• CRUD, PCI, FAD, DNB, GTRF • Cladding Integrity (LOCA, RIA) • Advanced Fuels	• Provide capability to support increase of average fuel cycle length • Provide capability to support increase NRC fuel burnup limits • Facilitate advanced fuel design
Improved Safety	• Maintain coolable fuel geometry and minimize fuel hydrogen production during/after LOCA • Minimize fuel damage and fission gas release during accidents • Maintain fission product barriers during anticipated accidents	• CRUD, PCI, FAD, DNB, GTRF • Cladding Integrity (LOCA, RIA) • Reactor Integrity (vessel, internals) • Advanced Fuels	• Facilitate advanced fuel design • Improve understanding and quantification of margins

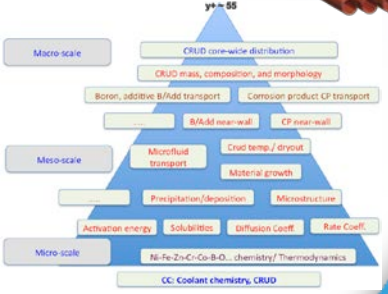
Enabling R&D Objectives

- Materials Performance and Optimization (MPO)
  - Mature 3D fuel performance capability with full assessment against CRUD/PCI/GTRF problems. Validated fuel performance models inform assessments of safety margin (PCI) and best operational practices (CRUD, GTRF). Functional capability and partial assessment for RIA- and LOCA-based transient problems.
- Radiation Transport Methods (RTM)
  - Robust 3D pin-resolved transport and prototype hybrid Monte Carlo transport with modern cross section/shielding treatments and coupling to T-H, fuel, and corrosion chemistry capabilities
- Thermal Hydraulics Methods (THM)
  - Robust 3D steady-state/transient turbulent multi-phase capability with subcooled boiling models, an initial assessment of DNB, and complementary with a modern subchannel capability
- Validation and Uncertainty Quantification (VUQ)
  - Mathematical tools and methodologies integrated and accessible to enable quantifying sensitivities and uncertainties in full-scale multi physics PWR simulations



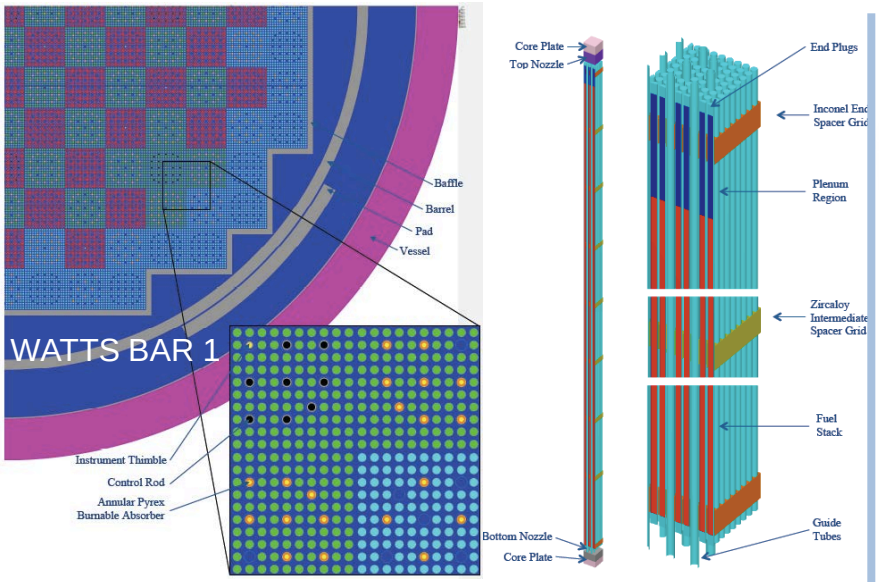




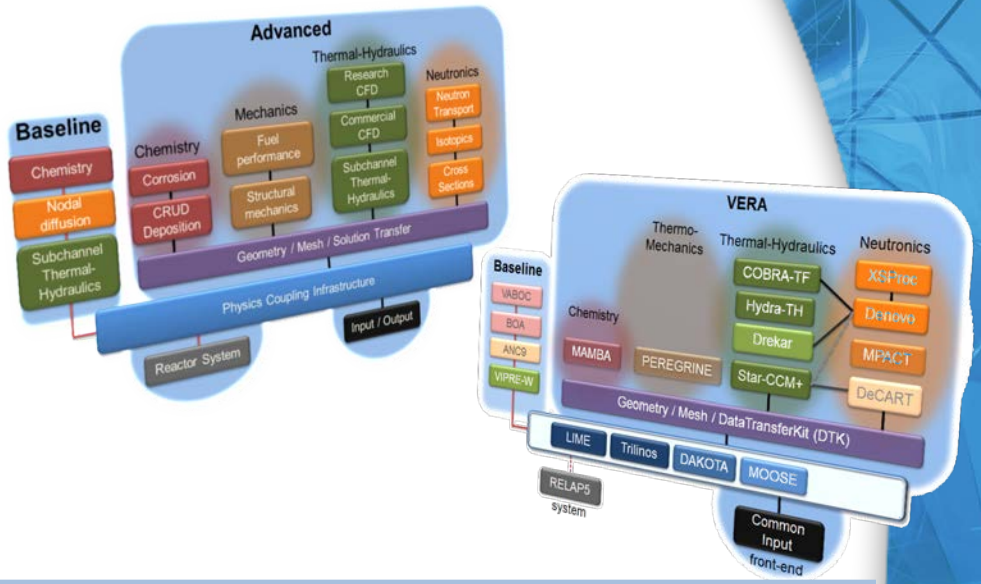


Highlights, Accomplishments, Capabilities

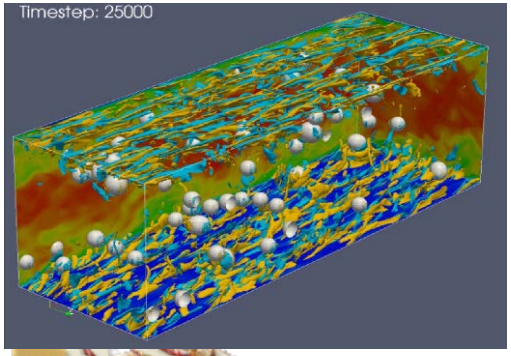
Advanced Modeling Applications

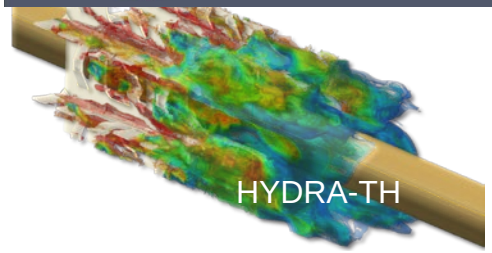


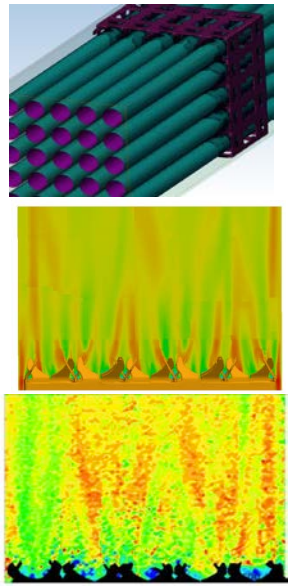
Virtual Reactor Integration



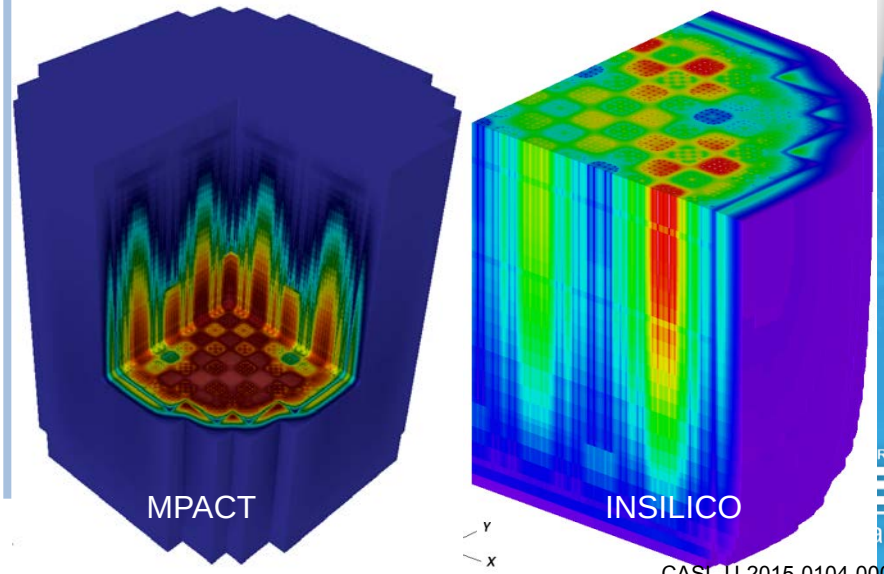
Thermal Hydraulic Methods





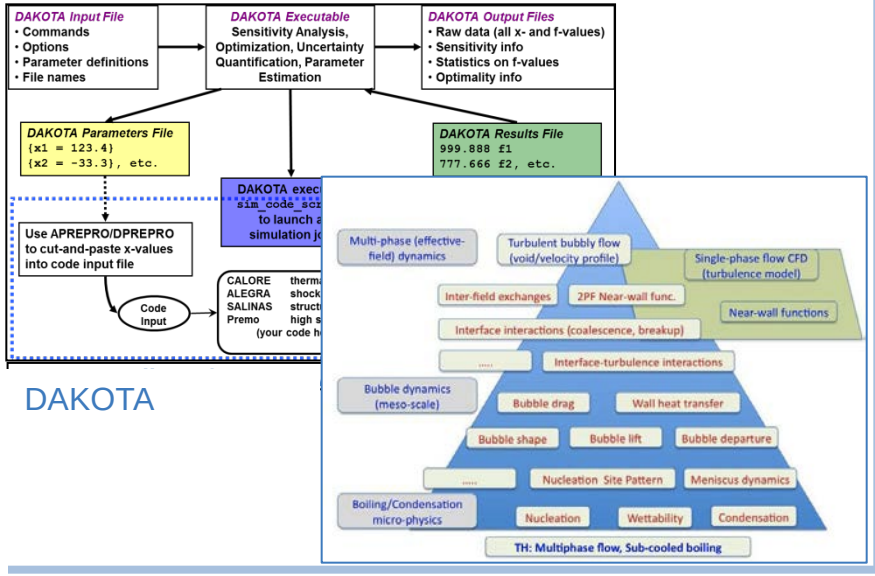


Radiation Transport Methods



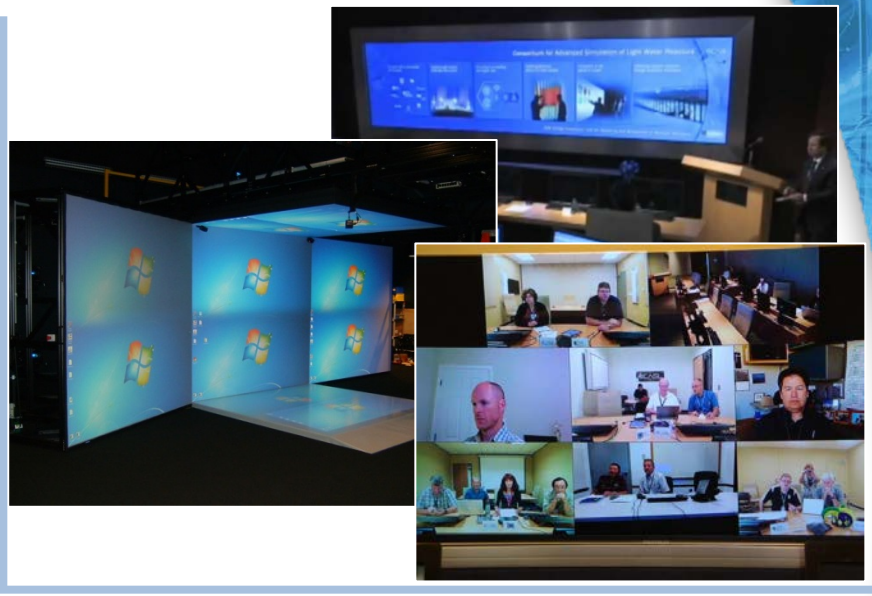
Highlights, Accomplishments, Capabilities

Validation & Uncertainty Quantification

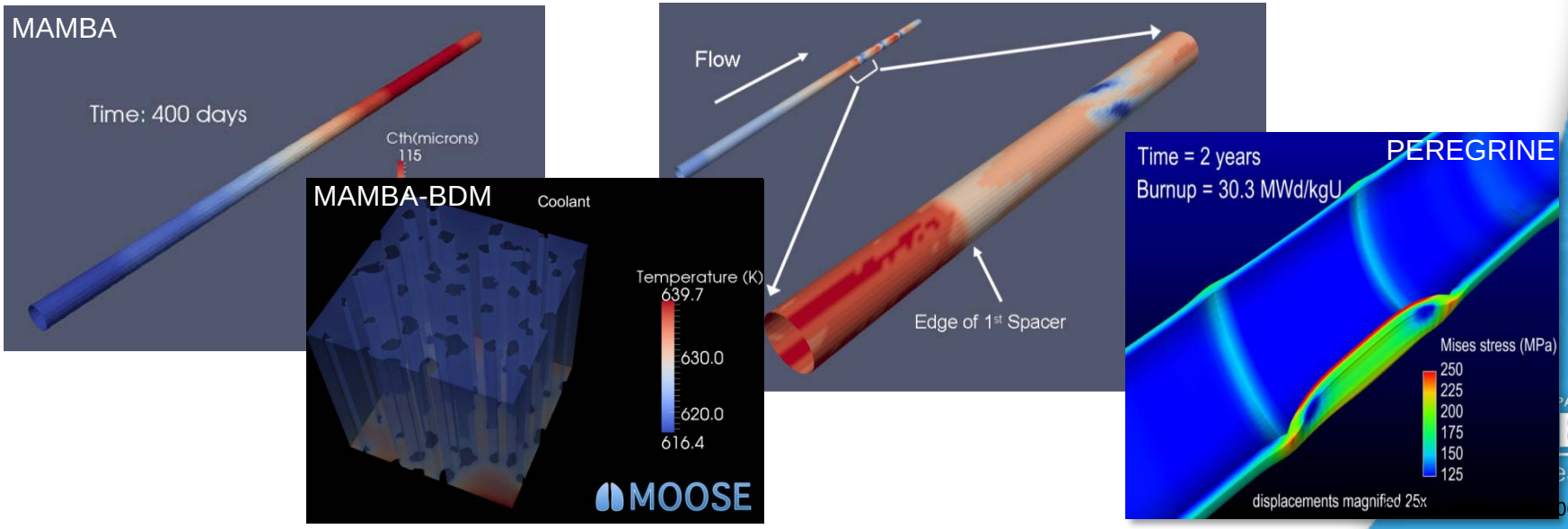


DAKOTA

VOCC

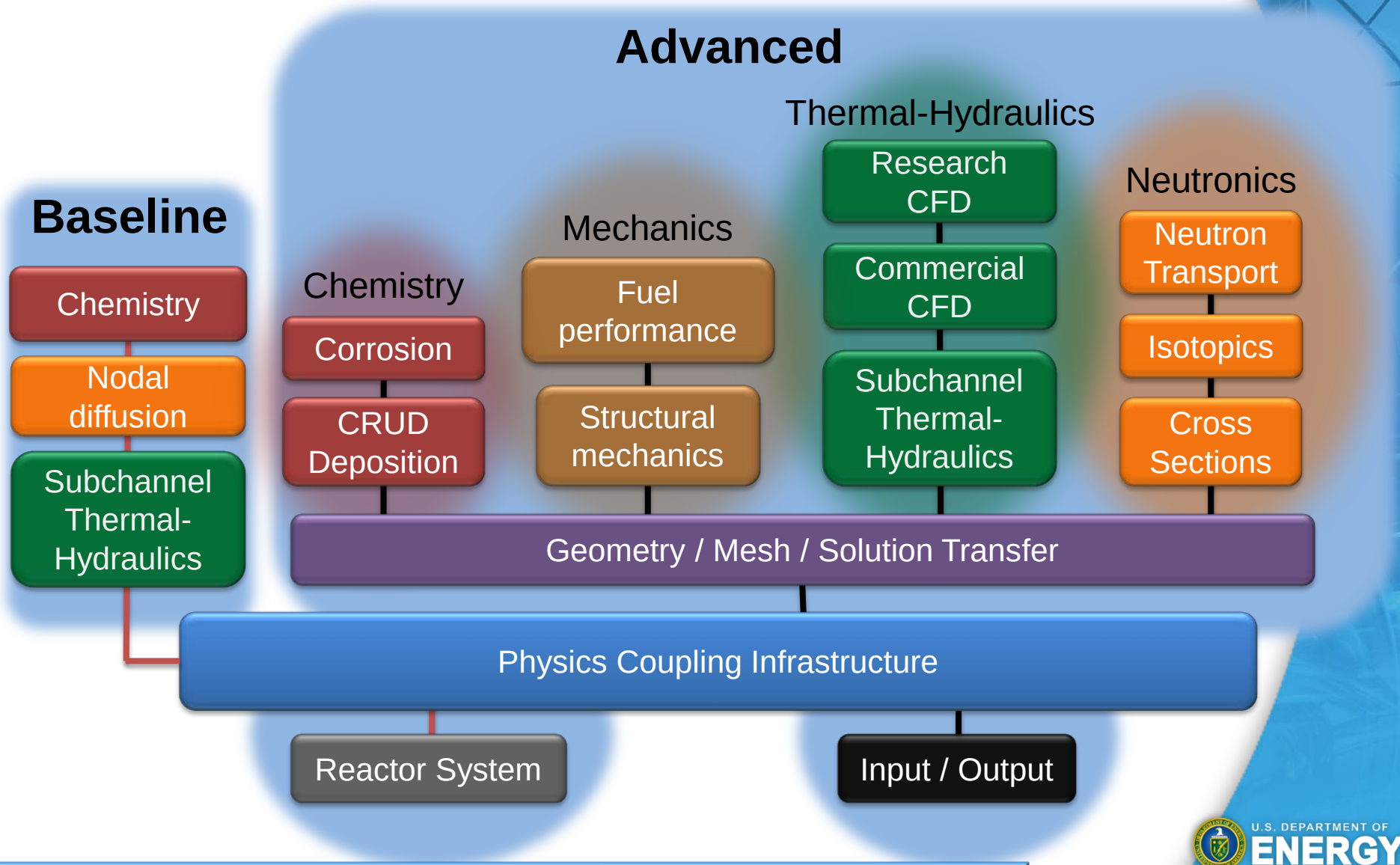


Materials Performance and Optimization



Virtual Environment for Reactor Applications (VERA)

CASL's virtual reactor for in-vessel LWR phenomena



More in the talks today by John Turner and Ross Bartlett

What enhanced capabilities over current practices will CASL capabilities provide?

Predictive capabilities

- Utilization of more science based models
- Utilization of micro and mesa scale models to increase understanding and provide closure relationships

Phase-space resolution

- Space, time, energy and angle
- Pin-resolved detail

VUQ practices

- Verification & validation
- Data assimilation
- Uncertainty quantification

Computational resource utilization

- Hardware: multiprocessor, multicore & GPUs
- Software: object oriented, I/O standards, third-party software (modern solvers)

High level differences of current versus CASL capabilities

Fluids (HYDRA-TH)

- Current Practices: Closed channel HEM, limited sub-channel &limited CFD
- CASL Practices: Sub-channel, CFD & MCFD
- Why not utilize commercial CFD/MCFD code?
  - Need to access source code for multiphase/multifield closure model implementation & testing
  - Desired high utilization of evolving HPC architectures

Radiation Transport (MPACT & INSILICO)

- Current Practice: MG Lattice Physics (2D MOC Transport)=>FG Core-wide Physics (3D Nodal Diffusion)=>Pin-wise power/flux (reconstruction)
- CASL Practice: MG Core-wide Physics (2D MOC Transport)/Axial Leakage (1D or 3D SPN)
- Why not Sn or Monte Carlo?
  - Computational burden *currently* to great

High level differences of current versus CASL capabilities

Fuel Performance (PEREGRINE)

- Current Practice: 2D with experimentally derived closure models
- CASL Practice: 2D and 3D with experimentally derived and micro/meso scale modeling derived closure models

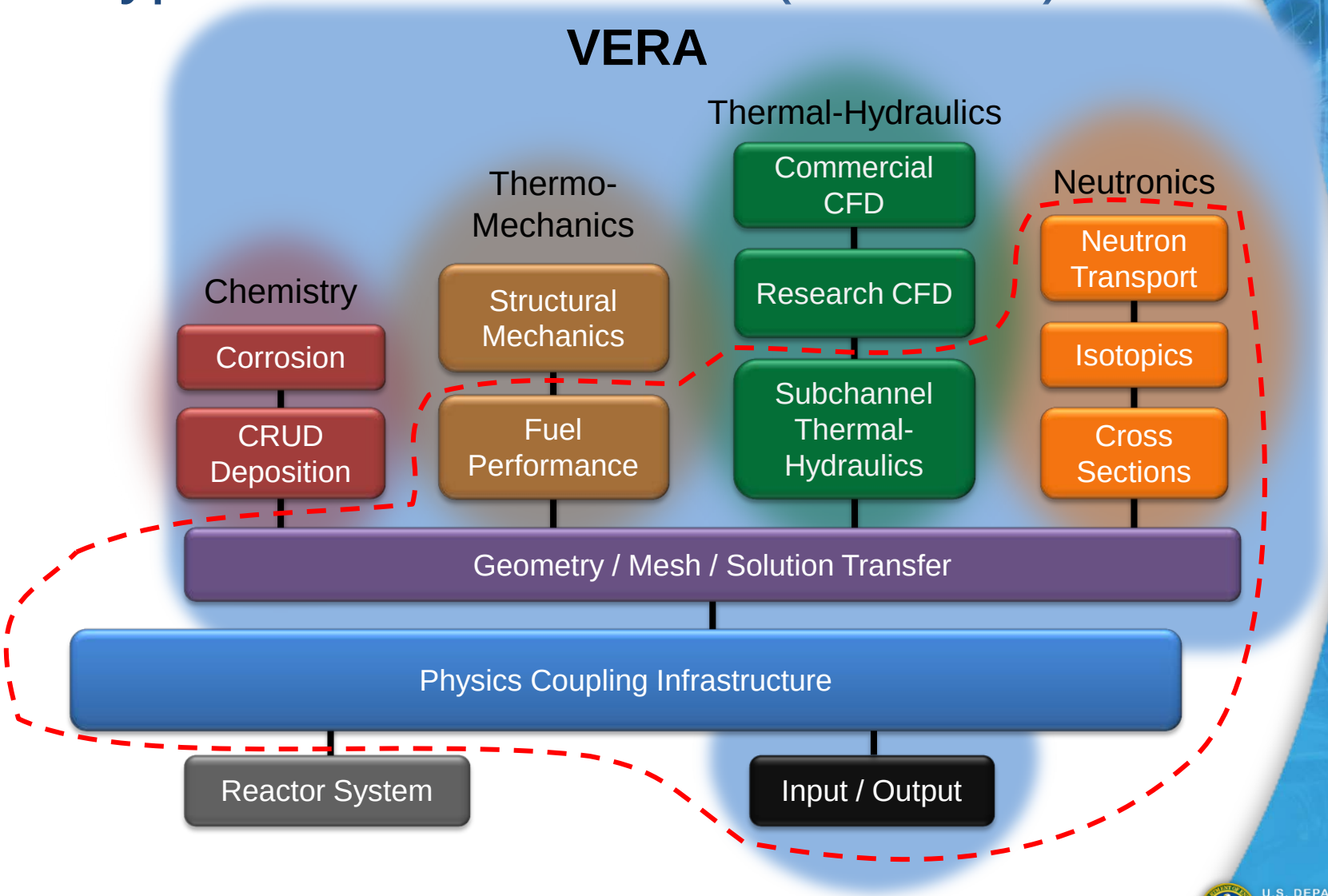
Crud Chemistry (MAMBA & MAMBA-BDM)

- Current Practice: 2D with limited chemical species & experimentally derived models' parameters
- CASL Practice: 2D and 3D with expanded chemical species, experimentally & micro modeling derived models' parameters, and enhanced mass/energy transport

Multiphysics (VERA)

- Current Practice: Lower fidelity single-physics modeling coupling via one-way sweep or iterative sweep
- CASL Practice: Appropriate fidelity single-physics modeling coupling via appropriate loose to tight (e.g. JFNK) or total removal of required coupling (e.g. no lattice physics)

Some of our VERA components comprise a new type of "Core Simulator" (VERA-CS)

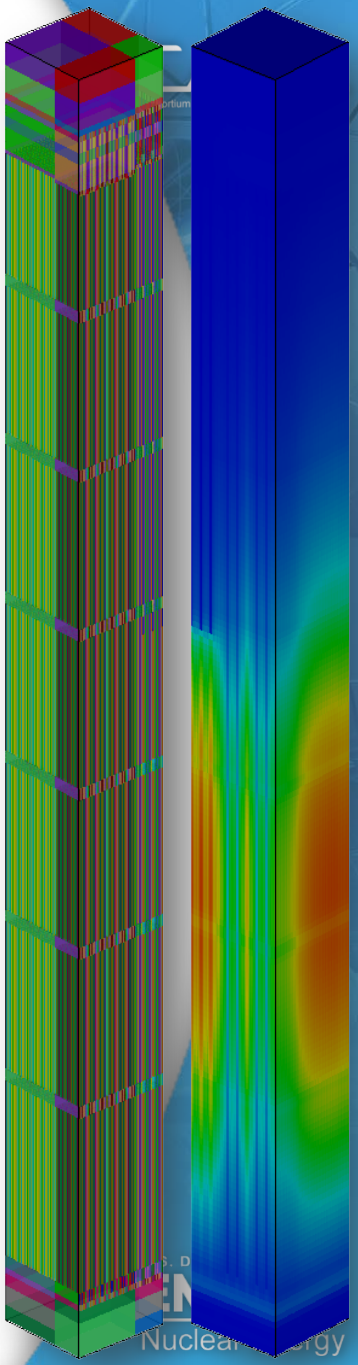


More in the talk today by Scott Palmtag

Industry Core vs. VERA-CS Simulators

Physics Model	Industry Practice	VERA-CS
Neutron Transport	3-D diffusion (core) 2 energy groups (core) 2-D transport on single assy	3-D transport 23+ energy groups
Power Distribution	nodal average with pin-power reconstruction methods	explicit pin-by-pin(*)
Thermal-Hydraulics	1-D assembly-averaged	subchannel (w/crossflow)
Fuel Temperatures	nodal average	pin-by-pin(*) 2-D or 3-D
Xenon/Samarium	nodal average w/correction	pin-by-pin(*)
Depletion	infinite-medium cross sections quadratic burnup correction history corrections spectral corrections reconstructed pin exposures	pin-by-pin(*) with actual core conditions
Reflector Models	1-D cross section models	actual 3-D geometry
Target Platforms	workstation (single-core)	1,000 – 300,000 cores

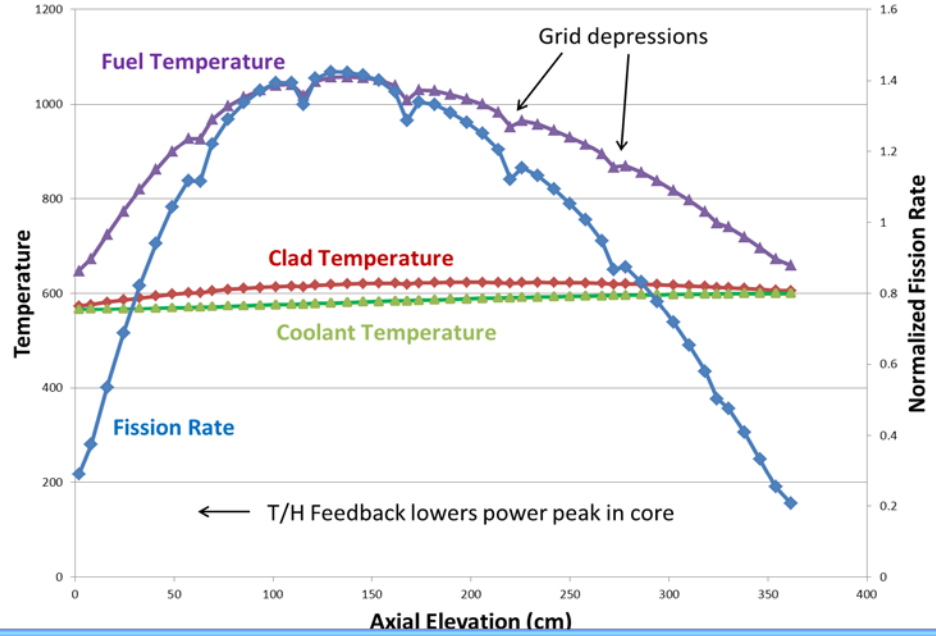
(*) pin-homogenized or pin-resolved depending on application

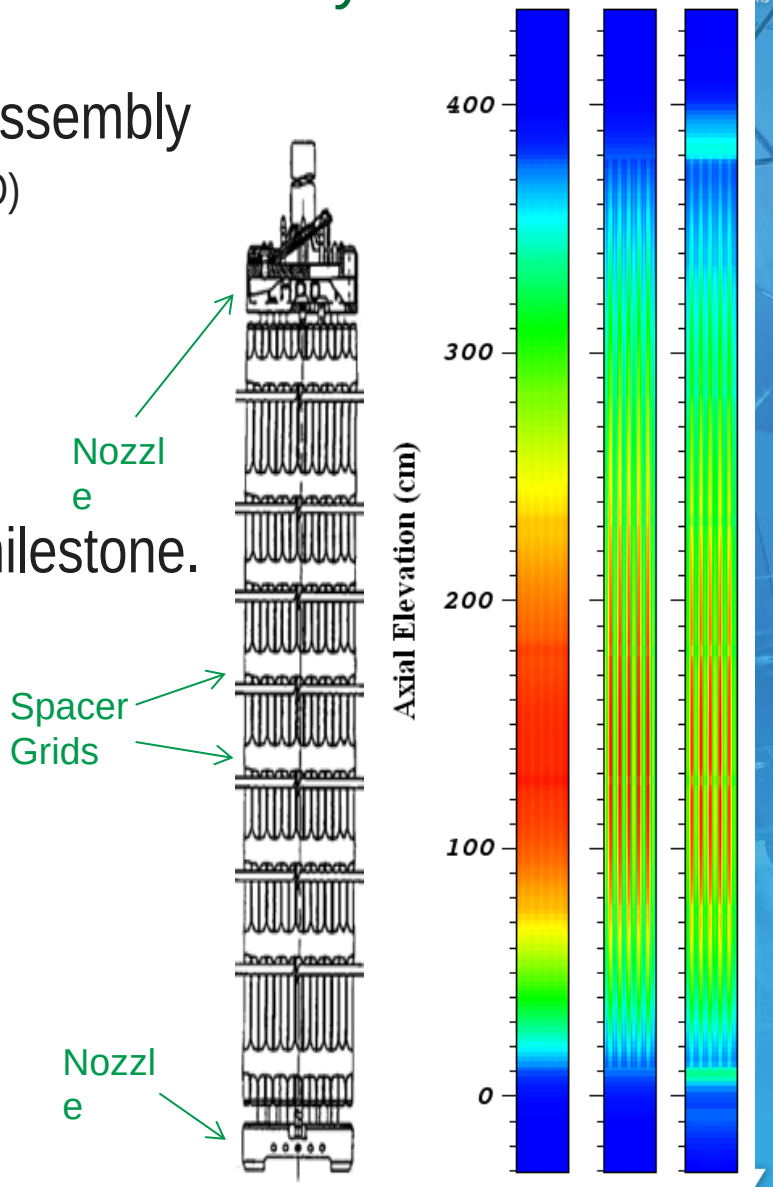


More in the talk today by Scott Palmtag

Successfully Completed High Fidelity Multiphysics Model of PWR Fuel Assembly

- Coupled Multiphysics Model of PWR Fuel Assembly
  - Neutron transport to calculate power distribution (DENOVO)
  - Thermal-Hydraulics in coolant (COBRA-TF)
  - Heat conduction in fuel rods (COBRA-TF)
  - Neutron cross sections as function of temperature and density (SCALE)
- Currently scaling up to a 1/4 reactor core simulation in support of a DOE reportable milestone.





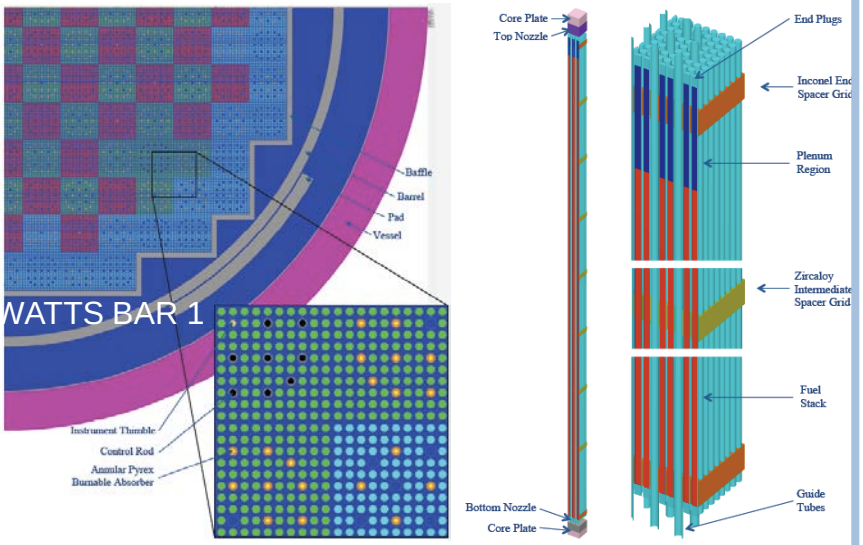
Fast, Epithermal, and Thermal Flux Profiles

More in the talks and demos today by Scott Palmtag, Andrew Godfrey, and Roger Pawlowski

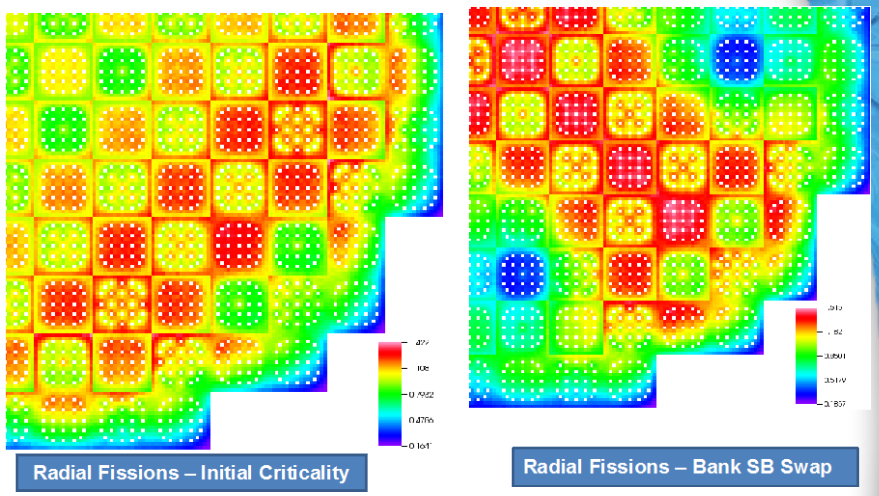
CASL Modeling Comparisons

First results against Watts Bar Nuclear Unit 1 measured data

3D Core/Vessel Neutronics Model



Fission Distribution Configurations



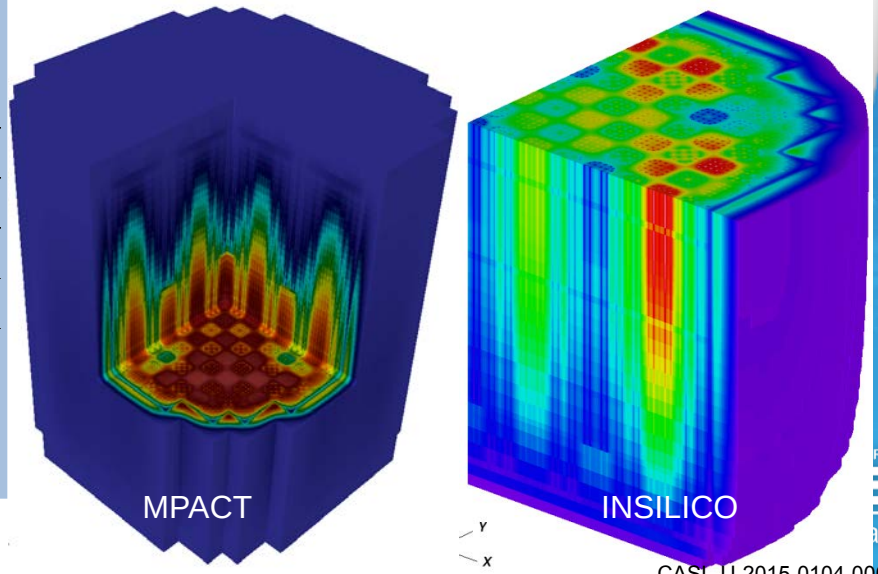
Excellent Match with Plant Conditions

Critical Configuration	VERA k-eff	Difference
Initial	1.00122	122
ARO	1.00157	157
Bank D In	1.00084	84
Bank C In	1.00094	94
Bank B In	1.00081	81
Bank A In	1.00092	92
Bank SD In*	1.00073	73
Bank SC In*	1.00071	71
Bank SB In	1.00100	100
Bank SA In	1.00070	70
Average	1.00094	94
St. Deviation	0.00027	27

Control Rod Bank Locations

	H	G	F	E	D	C	B	A
8	D		A		D		C	
9						SB		
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								

Neutron Transport Methods Utilized



VERA Usage for Challenge Problems

Challenge Problem	Time Scale (Seconds, Minutes, Hours, Days, Years)	Spatial Scale of Phenomina	Code Coupling
Crud-CIPS	Y (*always implies COBRA-CS depletion*)	Core-wide	MPACT- COBRA - MAMBA (light)
Crud-CILC	Y	Few pin-wide	MPACT/Insilico – Hydra – Peregrine – MAMBA
GTRF	Y + 50 Hz	Few pin-wide	MPACT - Hydra – Peregrine –STK
PCI	Y + M to H	Few pin-wide	MPACT/Insilico - Hydra - Peregrine
DNB	Y + S to M	System to assembly-wide	MPACT – COBRA/Hydra – Peregrine - RELAP
LOCA	Y + S to M	Pin-wide	Peregrine (B.C. from WEC)
RIA	Y + S	Few pin-wide	MPACT – Hydra – Peregrine

CASL Results to Date

- Developed and released Virtual Environment for Reactor Applications (VERA) to CASL core partners through ORNL's Radiation Safety Information Computational Center
- Established baseline industry capability and advanced R&D capability in VERA for neutronics, thermal hydraulics, and corrosion chemistry
- Applied selected aspects of VERA to operational PWR core scenarios with conditions relevant to corrosion buildup ("crud"), pellet-clad interaction, and grid-to-rod fretting
- Integrated within VERA a state-of-the-art sensitivity and optimization capability to support uncertainty analysis of reactor operational and safety scenarios
- Demonstrating that newly established single-physics simulation capabilities can exceed industry capabilities in physics modeling

Scientific output

- 261 publications
- 30+ invited talks
- 247 milestone deliverables in CASL database

Questions?

www.casl.gov or *info@casl.gov*