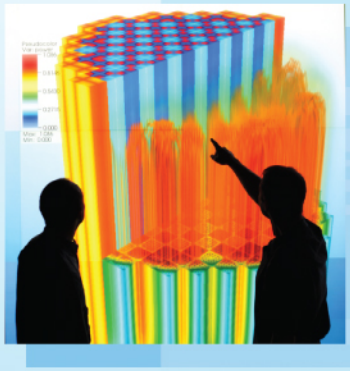
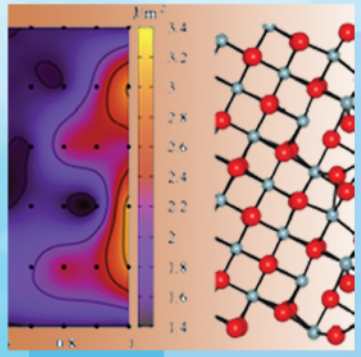
CASL-U-2013-0330-000

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

CASL/WEC Industry Fellows Forum Presentation

Fausto Franceschini
Westinghouse Electric Company

October 8, 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

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CASL: The Consortium for Advanced Simulation of Light Water Reactors

A DOE Energy Innovation Hub

Fausto Franceschini
Fellow Engineer

Westinghouse Electric Company LLC
Research and Technology

Outline

- Background
- Typical approach to nuclear reactors modeling and simulation
- Drive for advanced simulation capabilities
- CASL: the Consortium of Advanced Simulation for Light Water Reactors
- Development Status
- Industrial Applications
- Conclusions

Westinghouse Non-Proprietary Class 3

Who we are and what we do

- Westinghouse helped birth of nuclear power generation
  - Designed and built reactors for USS Nautilus and USS Enterprise the world's first nuclear-powered submarine and aircraft carrier
  - Designed, built and operated the first commercial nuclear power plant in Shippingport, PA in 1957
  - >50% of today's reactors based on Westinghouse's design
- Westinghouse is a global nuclear company
  - Design, build, service and fuel reactors worldwide
  - Deploying the AP1000™ PWR (passive safety)
  - Designing the Westinghouse Small Modular Reactor
  - Developing new "Accident Tolerant" fuel materials

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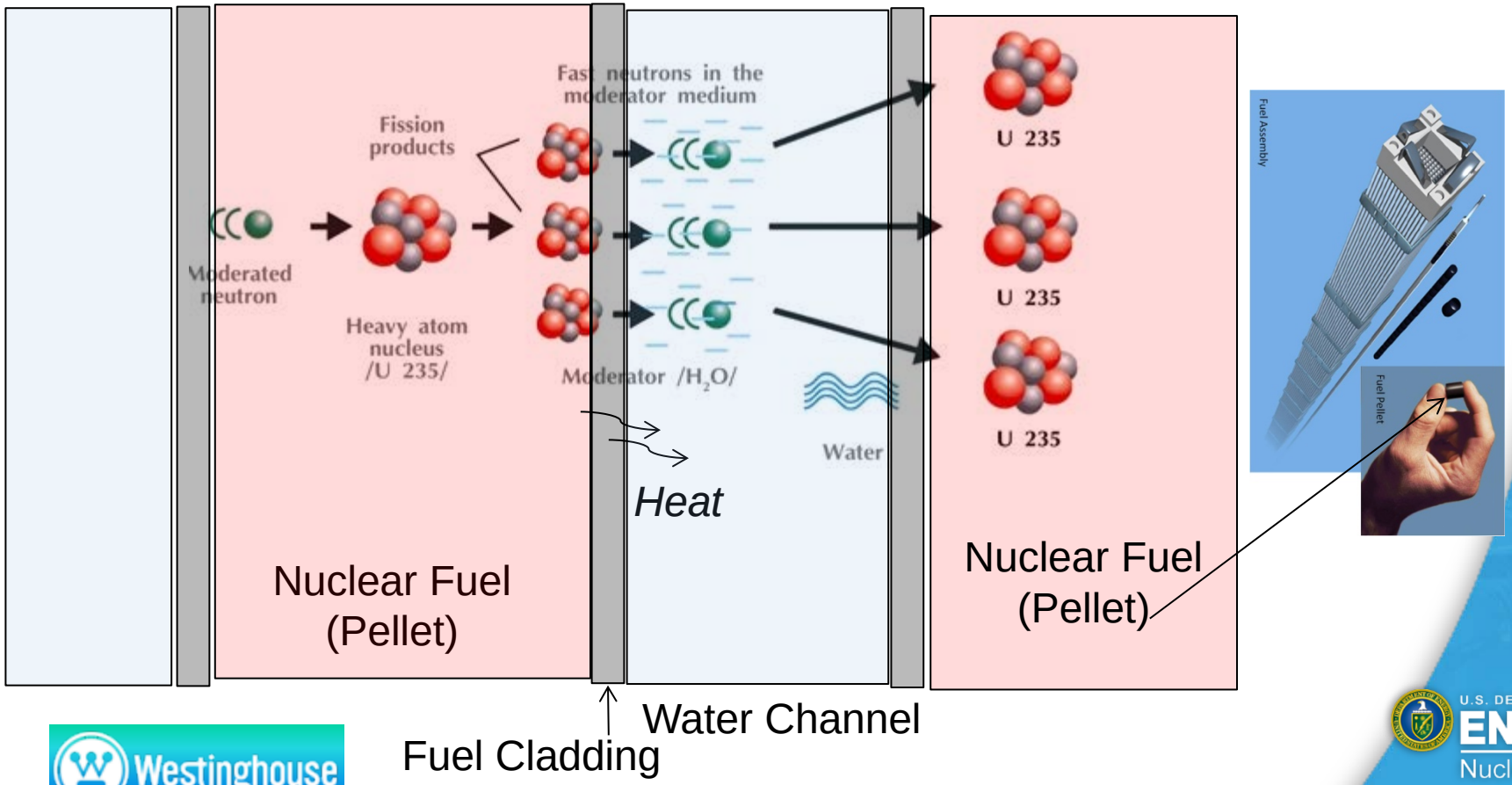
Nuclear Reactors in a Nutshell

- Fissile material (UO2 enriched in U-235) bombarded by neutrons generates fission products and neutrons
- Fission products slowdown generates heat in the nuclear fuel matrix (pellet). Neutrons sustain chain reaction
- Heat is transferred to the water through the cladding (Zr), eventually generating steam which is fed to a turbine



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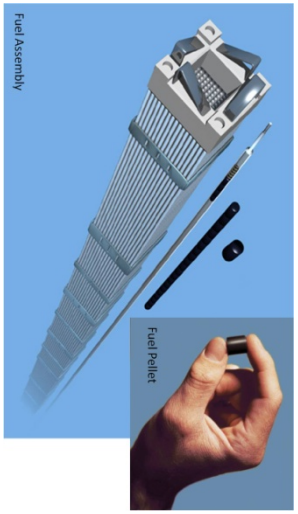
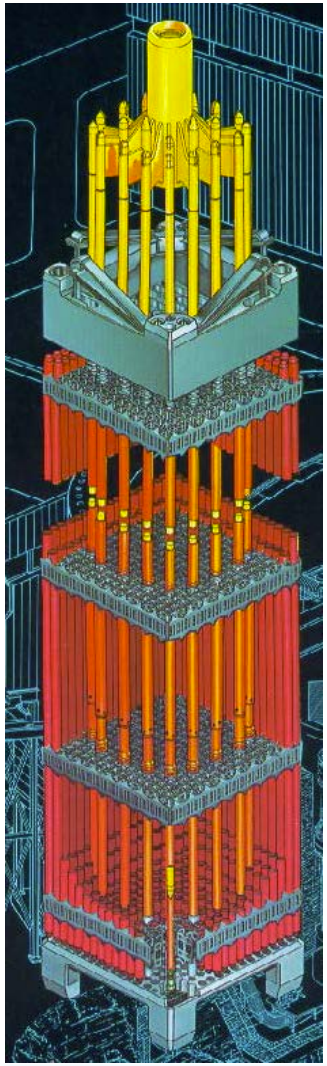
Anatomy of a Nuclear Reactor – Fuel Assembly

Example: Westinghouse 17x17 Pressurized Water Reactor (PWR) Fuel





17x17 fuel assembly

Fuel Assemblies

- 17x17 pin lattice
- 264 fuel pins plus 24 Guide Thimbles and one Instrumentation Tube
- 12-14 ft high

Fuel Pins

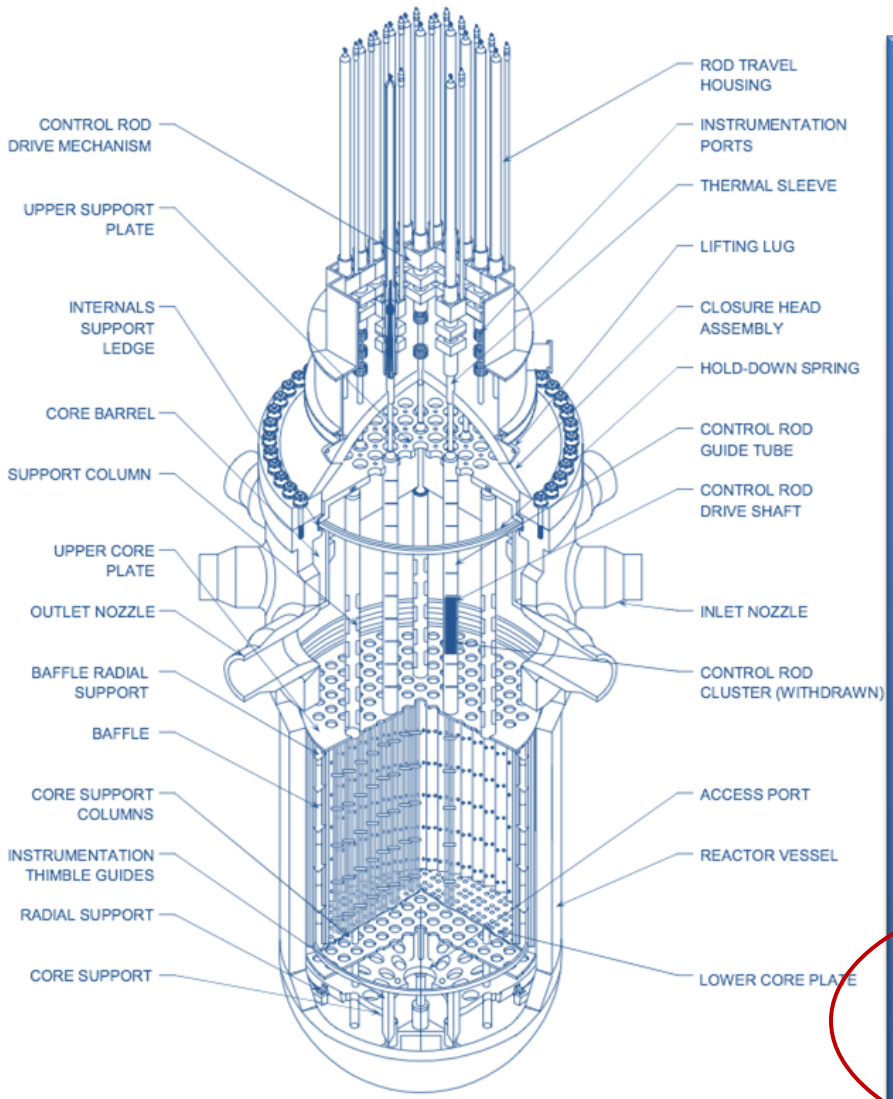
- ~300-400 pellets stacked within 12' high x 0.61 mm thick Zr-4 cladding tube

Fuel Pellets

- ~1 cm diameter x ~1 cm high

Anatomy of a Nuclear Reactor – Vessel

Example: Westinghouse 4-Loop Pressurized Water Reactor (PWR)



Core

- 11.1' diameter x 12' high
- 193 fuel assemblies
- ~110 tons of UO_2

Fuel Assemblies

- 17x17 pin lattice
- 264 fuel pins plus 24 Guide Thimbles and one Instrumentation Tube

Fuel Pins

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

Fuel Pellets

- ~1 cm diameter x ~1 cm high

>50,000 fuel pins and 16M fuel pellets in the core of a PWR!

reactor vessel and internals

Role of Modeling and Simulation

- Modeling and Simulation has a critical role in NPP:
  - ensure safe and economic operation of NPPs
  - assess behavior during transient and accidental conditions
  - evaluate design and core reload options
  - perform product development (tests are expensive and lengthy)
- Several disciplines are involved when modeling nuclear reactors:
  - Neutronics (Boltzmann equation) for heat source distribution
  - Fuel rod performance tools for heat transfer inside the fuel and to the cladding
  - Thermal-hydraulic (Navier-Stokes equations) for heat transfer to the water
  - Chemistry to evaluate deposits on the clad
  - Mechanical analysis to evaluate structural effects
- Physics is coupled to varying extent and temporal scales
  - Nuclear properties affected by the environment (temperatures, water density) which affects the chain reaction, which feedbacks to the environment
  - E.g. neutronics <-> fuel rod performance <-> thermal-hydraulics

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What Would it Take to Track "All" the Physics

- 16M fuel pellets in a core with 24 flat source regions
  -> ~400M meshes only for the neutronics!
- *Coupling with thermal-hydraulics:*
  - Sub-channel core: ~50,000 meshes
  - CFD ~500M meshes
- *Couple with fuel rod behavior*
  - New physics comes into play –
- *Additional physics*
  - E.g.: chemistry for corrosion, mechanical/vibration analysis for wear etc.
- *Need to track various quantities*
  - Cross-sections, fluxes etc.
  - Energy dependence
  - Fuel depletion with a~5 year simulation span

Prohibitive for the computational capabilities typically deployed at a nuclear industry

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Current Industry Analytical Tools

- Resort to significant physics simplifications
  - Evolutionary changes built over time
  - Born in an era of low computer power
  - Most of the solvers are serial or unwieldy to parallelization
  - Need to cope with small compute clusters/large number of users/large number of calculations/quick turnaround required for safety analyses supporting core reloads
  - Generally loose or no coupling between codes and physics
- With few exceptions, tools are developed in-house
  - Little influx of external developments due to proprietary concerns
  - Safety is ensured by large margins allocated and err on the side of caution
- Codes are safe, proven, fast and licensed
  - Current codes have been licensed by the Nuclear Regulators (e.g. US NRC)
  - Lengthy and costly licensing process for the new codes is a barrier
- Where is the driving force ($ case) for a change?
  - Beside improved computational capabilities

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Trends in Reactor Operation and Fuel Use

- Very high capacity factors, thanks to better operational knowledge, products development and improvements in analytical tools
  - From 60% in the ‘80s to 80% in the ‘90s to >90% in 2000
  - Reliable and cost-effective base-load with some load-following capability
- Reactor power uprates with respect to nominal power
  - yielded ~6.5 Gwe since 1977 , equivalent to ~6 large nuclear power plants
  - additional ~6 GWe in the working
- Life extension
  - Licenses extended from 40 years to 60 years for many plants
- Longer cycles and better nuclear fuel utilization
  - 18 up to 24-month intervals between refueling
  - >30% improvement in fuel use compared to the ‘90s

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Operational Consequences

- Longer cycles and higher powers make nuclear energy more profitable for our customers
  - Reduction in cost of electricity
  - A key discriminator in a deregulated market
- Higher fuel duty leads to operational challenges
  - Relatively new phenomena
  - Complex interplay of different disciplines
  - More details later
- Capacity to anticipate or mitigate these challenges relies on the capacity to properly simulate them
  - Current simulation tools unwieldy to implement the physics to model these phenomena, or provide high-fidelity data to downstream dedicated codes

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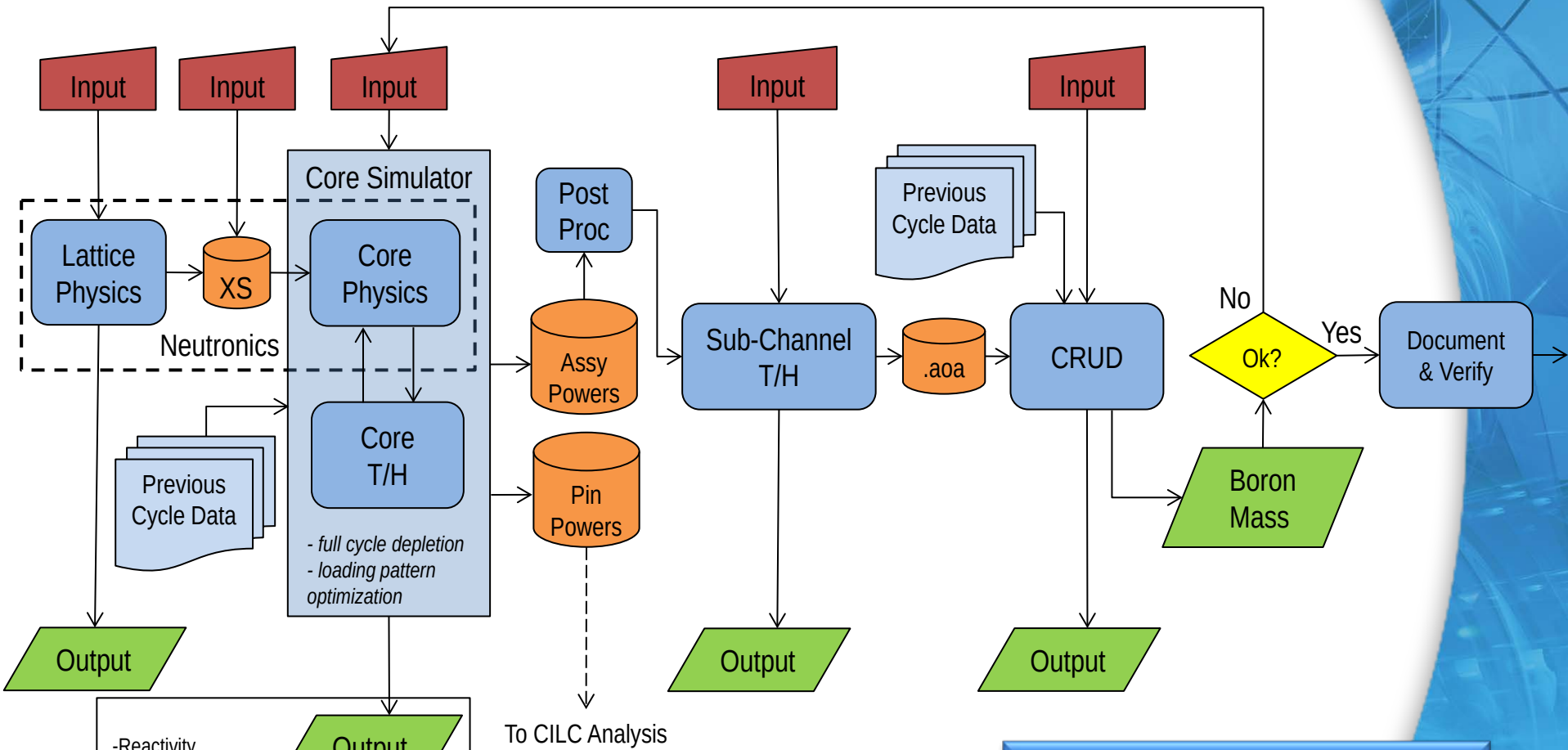
Benefits of Advanced Simulation Capabilities

- Prevent or mitigate issues affecting plant performance
  - Increase reliance on first principle methods
  - Improve understanding phenomena leading to operational issues
  - Favor Implementation of an effective mitigation strategy (e.g. fuel or core design change)
- Support to power uprates
  - As part of margin recovery strategy
- Core design and operational flexibility
  - Core design constrained as a result of operating the plant closer to the tech spec limits
  - Advanced tools can be used to recover additional margin to relax those constraints and
- Product development
  - Current reliance on semi-empirical correlations limit range of validity of some tools
  - Use of testing to assess a new product's performance is expensive
- Optimize and simplify analytical workflow
  - Currently a burdensome process with multiple codes and sequential flow of information
  - Would greatly benefit by coupling the codes and using a common input/interface

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

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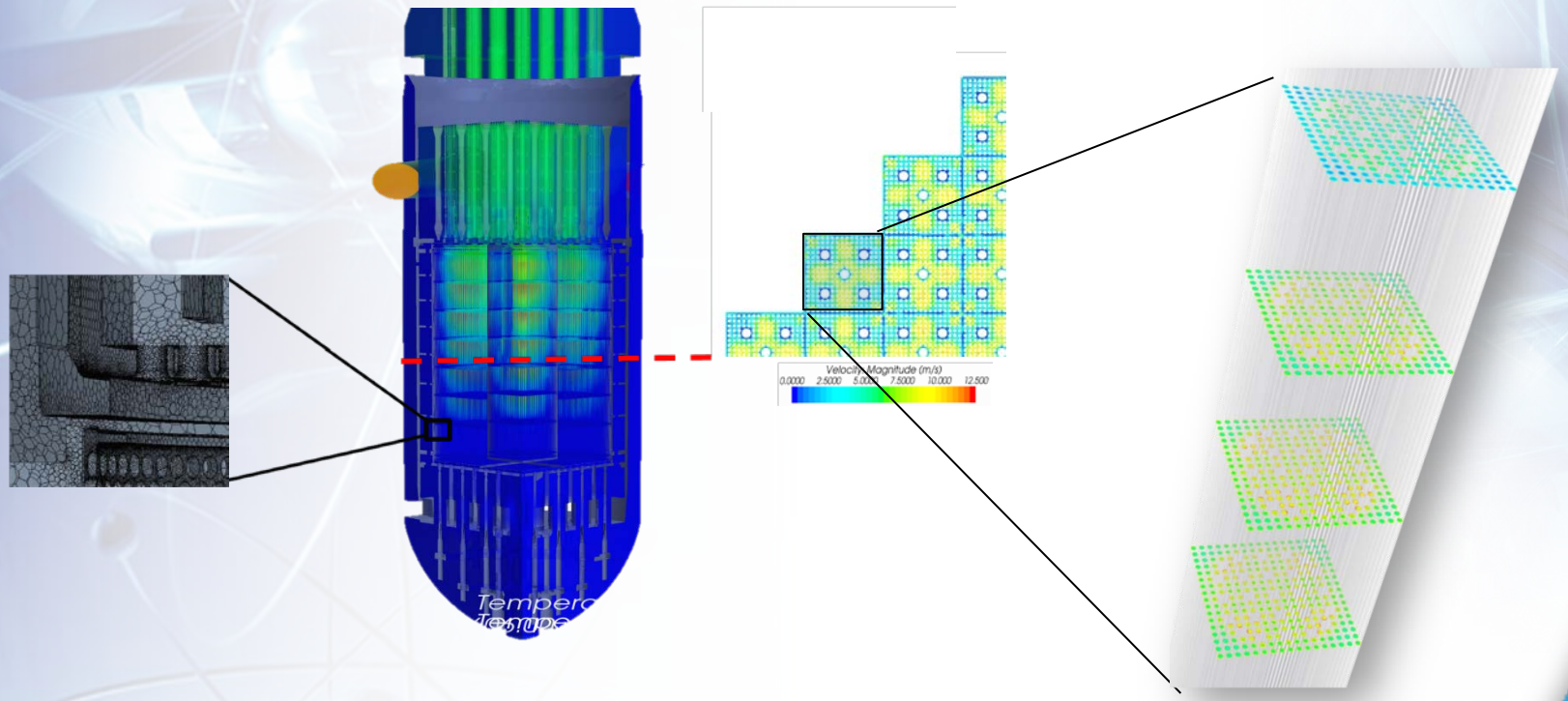
CASL: The Consortium for Advanced Simulation of Light Water Reactors



CASL - The Consortium for Advanced Simulation of Light Water Reactors

CASL is an Energy Innovation Hub funded by the Department of Energy:

- Large, highly integrated & collaborative teams working to solve problems in areas presenting the most critical barriers to achieving national climate & energy goals

Mission: Provide leading edge modeling and simulation capabilities to deploy within the U.S. nuclear energy industry to improve LWR operational performance

CASL is an Industry/National Labs/University Consortium

- *US National Labs:* ORNL (lead) , INL, LANL, SNL
- *Universities*: MIT, NCSU, UM
- *Industry*: Westinghouse, TVA, EPRI

CASL is Addressing Key Industry Needs

- CASL is developing and deploying the Virtual Environment for Nuclear Reactor Analysis (VERA)
  - Environment and tools to perform high-fidelity multi-physics simulations of nuclear reactors
  - Improving prediction capabilities of key phenomena limiting reactor performance

- VERA capabilities are driven by three key issues for nuclear energy:
  - Reducing costs (power uprates, lifetime extension)
  - Reducing waste generation (high burnup)
  - Enhancing safety

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CASL Challenge Problems

	Power uprate	High burnup	Life extension
Operational			
CRUD-induced power shift (CIPS)	✕	✕	
CRUD-induced localized corrosion (CILC)	✕	✕	
Grid-to-rod fretting failure (GTRF)		✕	
Pellet-clad interaction (PCI)	✕	✕	
Fuel assembly distortion (FAD)	✕	✕	
Safety			
Departure from nucleate boiling (DNB)	✕		
Cladding integrity during (LOCA)	✕	✕	
Cladding integrity during (RIA)	✕	✕	
Reactor vessel integrity	✕		✕
Reactor internals integrity	✕		✕

CASL Development Focused on Solving Actual Issues of Operating PWRs

CRUD-induced power shift (CIPS) and CRUD-induced localized Corrosion (CILC)

Problem Definition

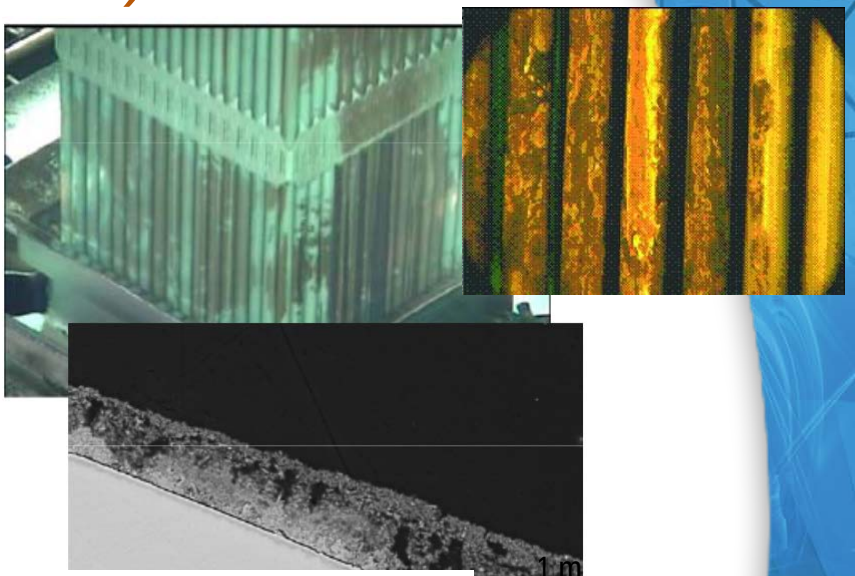
- Reactor internals corrode, releasing products into coolant
- Sub-cooled boiling creates porous deposits
- Boric acid in coolant hides out in CRUD pores
- CRUD-Induced Power Shift (CIPS) due to boron
- CRUD-Induced Localized Corrosion (CILC) due to degraded heat transfer
- *High uncertainty in predicting CIPS due to uncertainty in crud source and boiling surface area*
- High uncertainty affects fuel management and thermal margin in many plants

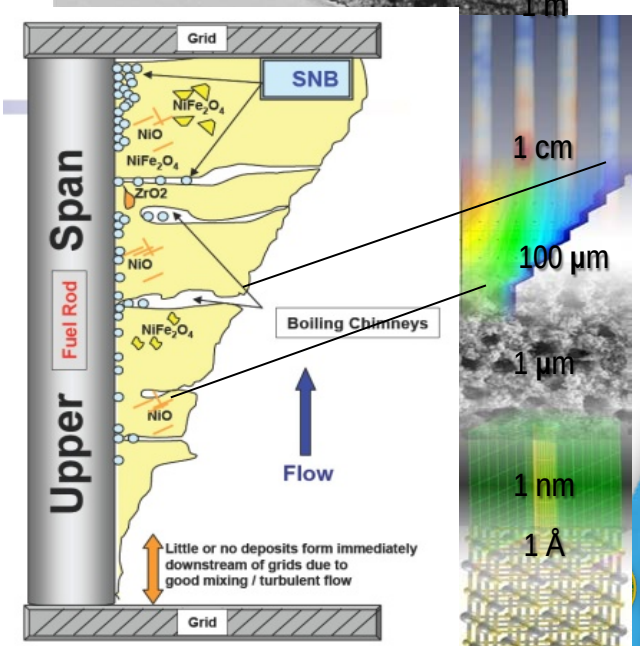
Need for Advanced Simulation

- Current tools do not account for crud impact on neutronics and more accurate models needed to evaluate boiling surface area and crud deposits

CASL Approach

- Advanced Materials/Boron Analyzer Tool Developed
  - Reduce CIPS prediction uncertainty
  - Provide capability to increase flexibility in incore fuel management

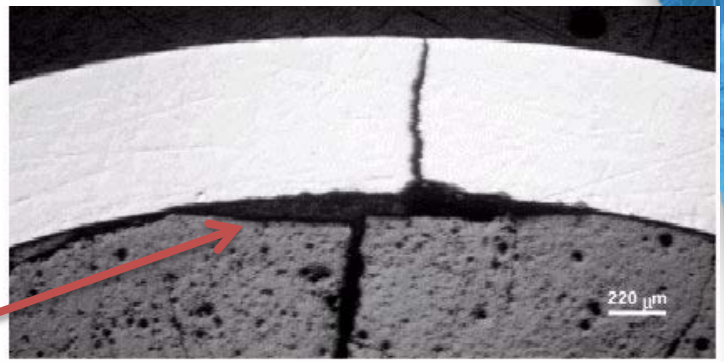




Pellet Clad Interaction (PCI)

Definition of Problem

- Cladding "creeps down" onto pellets after about one cycle of operation. During power maneuvers, pellet expands and creates stresses against cladding.
- Pellet imperfections such as Missing Pellet Surface (MPS) increase local stresses resulting in clad failure.
  - Missing pellet surface induces localized clad stresses, causing cracks
  - Iodine stress corrosion cracking (SCC) of clad
  - Clad can form brittle hydrides under temperature gradients

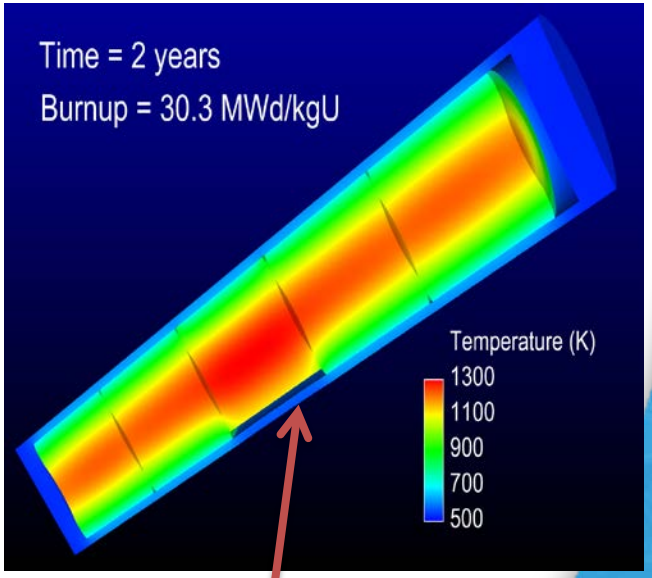


Need for Advanced Simulation

- Current fuel rod performance tools do not model fuel rod in sufficient detail and are not linked to neutronics and thermal-hydraulic

CASL Approach

- Develop advanced fuel rod tool to properly model PCI
- Couple fuel rod tool to neutronics & TH and apply for core wide analyses to evaluate PCI margin
- Provide capability to increase flexibility of power maneuvering of the plant



Localized T increase from missing pellet surface

Grid To Rod Fretting (GTRF)

Problem Definition

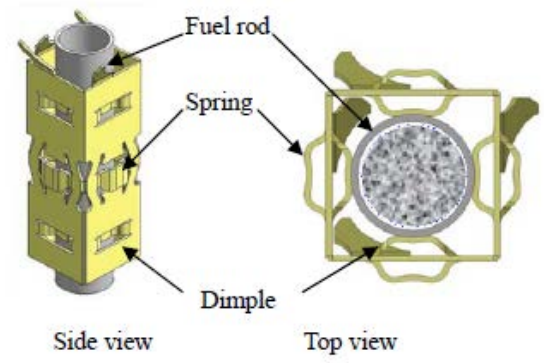
- Clad failure can occur as a result or rod growth changes, flow induced vibration, irradiation-induced grid growth and spring relaxation
- Power uprates increase potential for grid to rod fretting

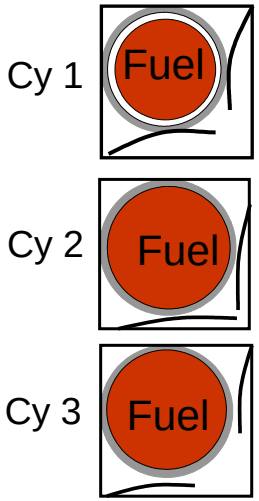
Need for Advanced Simulation

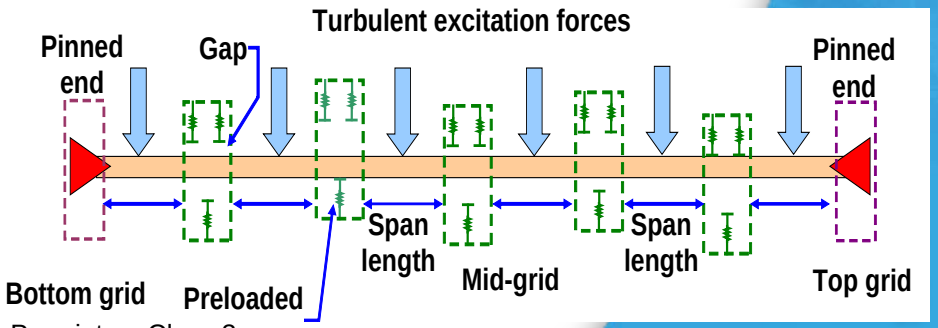
- Current tools do not predict rod wear margin in core
  - Predict grid to rod gap
  - Predict turbulent flow excitation rod vibration & wear at any location in core

CASL Approach

- Develop capability to predict rod wear for any rod in core
- Provide capability to evaluate impact of spacer grid design features effect on GTRF
- Methodology still evolving
- Coupling of Neutronics- CFD– Fuel Rod Performance







Departure from Nucleate Boiling (DNB)

Definition of Problem

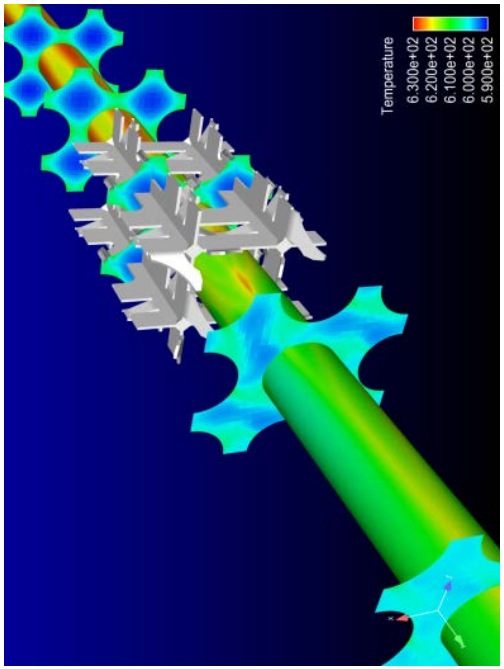
- Local clad surface dryout causes dramatic reduction in heat transfer during transients (e.g., overpower and loss of coolant flow) leading to high cladding temperatures
- Detailed flow patterns and mixing not explicitly modeled in single & two-phase flow downstream of spacer grids
- Simplified models and steady-state correlations typically used resulting in loss of DNB margin during transients
- Power uprates require improved quantification and increased margins for DNB

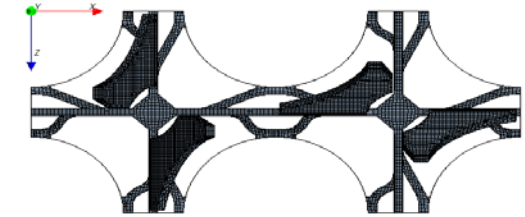
Need for Advanced Simulation

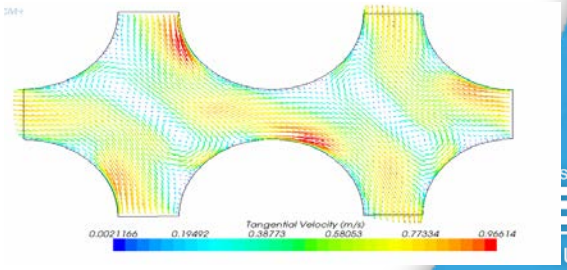
- Current tools do not model detailed flow patterns and mixing downstream of mixing grids and simplified models used in DNB transients

CASL Approach

- Develop capability to predict DNB utilizing more advanced methods to reduce margin and enhance understanding
- Develop detailed coupled pin-resolved radiation transport models for application to DNB transients
- Provide capability to evaluate impact of spacer grid design features effect on DNB







Current versus CASL capabilities

Radiation Transport (MPACT and INSILICO)

- Current Practice: 2-step process Lattice to Core-wide Physics with decreasing accuracy and detail
- CASL: 1-step process with detailed and accurate Core-wide Physics

Fluids (COBRA and HYDRA)

- Current Practices: Closed channel HEM, limited sub-channel &limited CFD
- CASL: Sub-channel, CFD & MCFD

Fuel Performance (PEREGRINE)

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

Crud Chemistry (MAMBA)

- 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

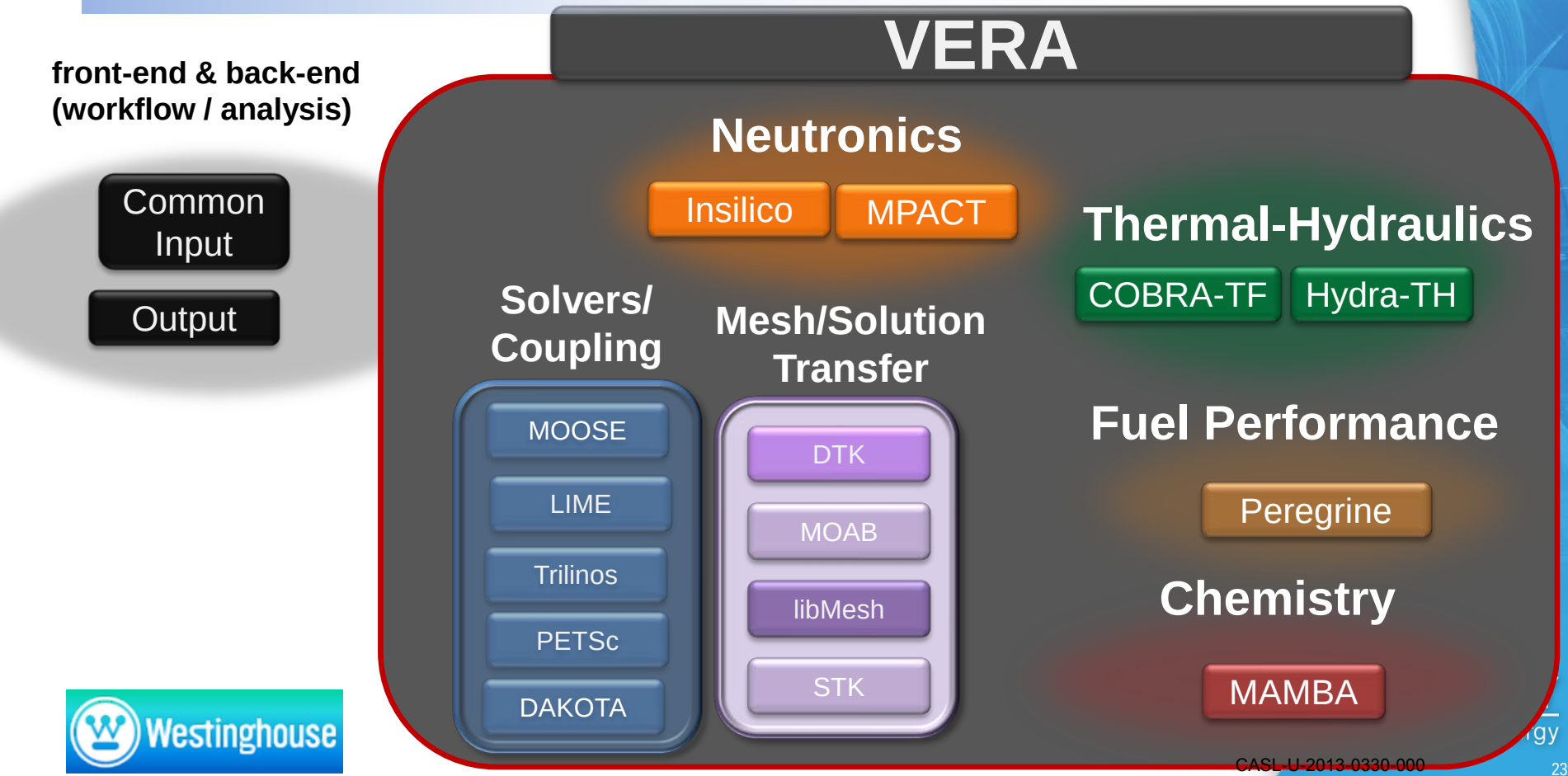
Multiphysics (VERA)

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

Virtual Environment for Reactor Analysis (VERA)

CASL's virtual reactor for in-vessel LWR phenomena

Schematic of CASL Virtual Reactor Environment : disciplines and code names with infrastructure to perform coupling, meshing and solvers



VERA Computational Requirements

- VERA codes have massively parallel architecture
- Allocation on Large Computing Facilities resources - e.g. Oak Ridge LCF
- Acquisition & operation of centralized location (CASL only) under consideration
- Lower cores option for portability to industrial medium-size cluster (~1,000 cores)

	Current CASL Need		10 Years	
	Geometry	Number of Cores	Geometry	Number of Cores
Neutronics	Quarter Core	1,000 – 10,000	Full Core	1,000 – 200,000
Thermal Hydraulics	Quarter Core	100 – 1,000	Full Core	100 – 10,000
CFD	Assembly	1,000 – 50,000	Quarter Core	50,000 – 200,000
Fuel Performance	3D Pin	1,000 – 5,000	Multiple Pins	5,000 – 50,000
Chemistry	Assembly Section	1,000 – 10,000	Assembly	10,000 – 50,000
Structural	Assembly	1,000 – 10,000	Quarter Core	10,000 – 100,000

CASL Use of Oak Ridge Leadership Computing Facility (OLCF) Platforms

Jaguar / Titan usage

- CASL usage (core-hours): Total – ~65M (2 year period)
  - 2011 – 14.8M; 2012 – 50.7M
  - Majority (72%) of use consumes 30% or less of full system (< 90K cores)
  - Over half of use (57%) consumes 10% or less of full system (< 30K cores)

Leadership Computing Facility resources are key to CASL's execution and success.

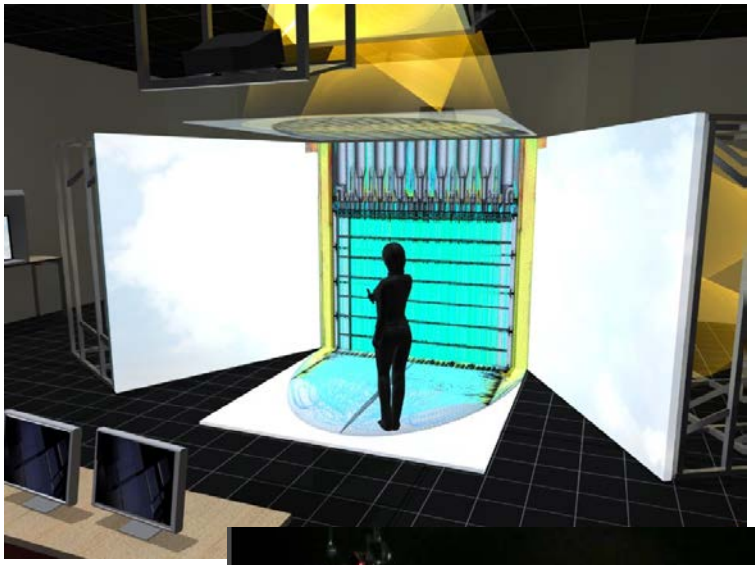
CASL Virtual Office, Community and Computing - VOCC

- The VOCC Laboratory is a state-of-the-art collaboration space
  - provides physical and virtual connectivity to geographically distributed groups of energy science researchers.
- Relies on human centric, immersive, and visually analytic design techniques to build a physical work space for the purpose of virtually unifying computational scientists, high performance Computing (HPC) resources, and modeling & simulation instruments and applications.

Data Visualization in VOCC's Facilities

Virtual Office, Community, and Computing

Innovation at the speed of Insight



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Data Visualization

- Facilities and capabilities for data visualization established
  - 3D plotting venues created at the ORNL site
  - Various software packages added to each 3D venue for local, remote, and/or remote parallel rendering

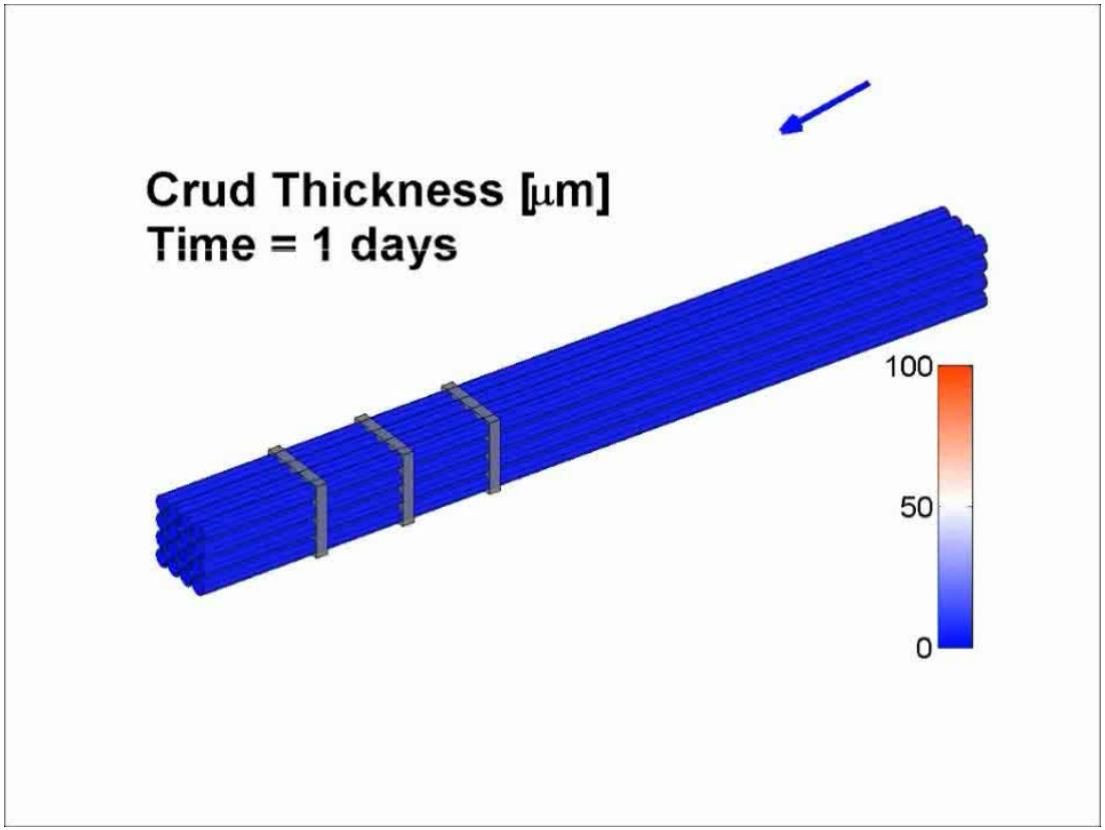
WALDO	F-5	Immersion Room	PI
Conduit for VisIt 2.5.2, Google Earth, and SketchUp	Conduit for VisIt 2.5.2, Google Earth, and SketchUp	ParaView (older version)	Conduit for VisIt 2.5.2, Google Earth, and SketchUp
ParaView	ParaView	Solid Works	
Stereoscopic Player	Stereoscopic Player	Stereoscopic Player	
Ensight Viewer 10.0	Ensight DR	Ensight Viewer 10.0	
		Eon Reality (limited)	

Some Results: CRUD Analysis

Simulation of CRUD deposition on nuclear fuel

–Crud accumulates with fuel irradiation time

–Crud accumulation in regions with higher sub-cooled boiling



Some Results: In-Vessel Flow Patterns

- iff\Movies\Movies\Vessel Animation.pptx
- Full Vessel CFD model - includes all details of vessel, internal structures (down comer, flow skirt, lower core plate, control rod drives, etc), fuel.
- This model allows detailed analysis of flow through all structures in the vessel
- Can be used to support analysis of fluid structure interactions (flow induced vibration)
- Can be used to support analysis of flow blockages including alternative flow paths.
- ~1.3B cells!

VERA Deployment Status

- VERA is being released for alpha-testing at various CASL organizations
- Westinghouse is paving the way with first deployment
  - VERA deployed on Westinghouse clusters on June 28 2013
  - Take advantage of CASL high-fidelity multi-physics tools to drive development and troubleshoot mispredictions and operational issues
  - Initial application focused on core physics analysis of Westinghouse AP1000® PWR
  - Simulations run on dedicated Westinghouse compute cluster (~1,000 cores)
  - Optional access to supercomputers as needed

Challenges

- Complete VERA development
- Make it lighter
  - Industries typically don't have access to supercomputers
  - Need to build dedicated cluster at the industry's site
- Validate results
  - Compare to plants operational data and higher-order numerical experiments
- Support to the Users
- License with the regulator

Conclusions

- While the CASL tools are still under development, their initial application matches the promises and shows the benefits for the US nuclear industry
- VERA tools currently being deployed for initial testing at CASL partners organizations
  - First industrial deployment of VERA at Westinghouse
- CASL confirms the value of a result-driven and collaborative engagement between the industry and the scientific community
- CASL can pave the way for a momentous change in simulation of nuclear reactors
  - Multi-physics, taking full advantage of new computing capabilities