Thermal Hydraulics R&D Plans and Efforts within CASL: The Consortium for Advanced Simulation of Light Water Reactors

CASL is a DOE Energy Innovation Hub for Modeling and Simulation of Nuclear Reactors

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CASL Charter

Mission

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

Vision

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

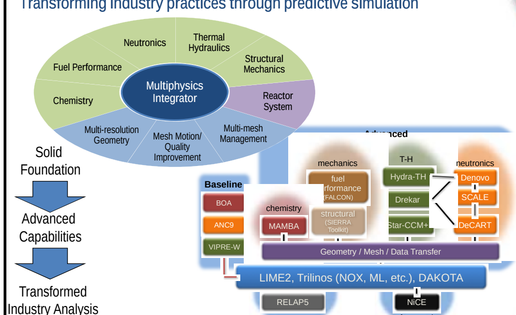
Goals

1. *Develop and Effectively Apply Modern Virtual Reactor Technology*
2. *Assure Nuclear Safety and Address Operational and Design Challenges*
3. *Engage the Nuclear Energy Community Through Modeling and Simulation*
4. *Deploy New Partnership and Collaboration Paradigms*

CASL became the first DOE Energy Innovation Hub upon receiving a 5-year, $122M award in July 2010

Virtual Environment for Reactor Applications (VERA)

Transforming industry practices through predictive simulation



Tightly coupled, multi-physics, high-fidelity simulations
Validated tools, quantified uncertainties
Combining existing tools from industry partners

CASL Challenge Problems

CASL Challenge Problems	Power uprate	High burnup	Life extension	Safety Relevance
Operational "Challenge Problems"				
CRUD-Induced Power Shift (CIPS)	×	×		CRUD influences both mechanical and reactivity behavior of the fuel, impacting operational performance and reactor safety response
CRUD-Induced Localized Corrosion (CILC)	×	×		
Grid-to-Rod Fretting Failure (GTRF)		×		Degraded fuel/clad mechanical integrity due to flow-induced vibrations during normal operations affect accident response
Pellet Clad Interaction (PCI)	×	×		PCI, a fuel failure mechanism during normal operations, can also occur during accident transients causing a local power increase
Fuel Assembly Distortion (FAD)	×	×		Distortion of fuel rods and fuel assemblies has the potential to inhibit control rod insertion, preventing timely reactor shutdown
Safety "Challenge Problems"	Full Scope-Current Focus		Full Scope-Future Focus	Partial Scope-Future Focus
Departure from Nucleate Boiling (DNB)	×			Quantify and prevent local vapor-induced clad surface overheating during certain accident scenarios
Cladding Integrity during Loss of Coolant Accidents (LOCA)	×	×		Predicting fuel response during a LOCA facilitates developing advanced fuel designs that minimize hydrogen production and maintain a coolable geometry
Cladding Integrity during Reactivity Insertion Accidents (RIA)	×	×		Predicting fuel response during an RIA-induced power excursion facilitates advanced fuel designs that minimize failures and fission product release
Reactor Vessel Integrity	×		×	Reactor vessel integrity is essential during normal operation and accident situations. Improved prediction (and models) of vessel irradiation and performance assure adequate fuel cooling
Reactor Internals Integrity	×		×	Operational condition of core internal components prior to an accident-induced transient impacts likelihood of safe shutdown

The CASL Thermal Hydraulic Methods (THM) Focus Area

Lead: Rob Lowrie (LANL); Deputy Lead: Rich Martineau (INL)

- Our primary product is VERA-CFD, a 3-D thermal hydraulics simulation capability:
  - Scalable, non-proprietary, verified and validated
  - Interfaces to couple with other physics under VERA
  - Interfaces for UQ support (possibly intrusive)
- Two projects within THM
- Computational Fluid Dynamics (CFD) Project
  - Development of VERA-CFD: Engineering scale 3-D CFD simulation code
  - Development of multiphase models for PWR applications
  - Subchannel support and develop a "coarse-grid" CFD approach
- Interface Tracking Methods (ITM) Project
  - DNS/ITM simulations, to provide closure parameters for CFD methods
  - 2 Laboratory experimental facilities (Texas A&M; MIT), for both closure parameters and validation

All activities have a direct path to improving VERA-CFD

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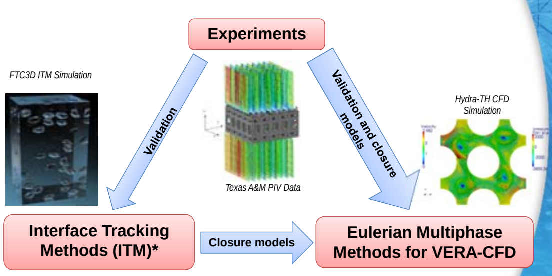
We use experiments and ITM simulations to improve multiphase models in VERA-CFD



*ITM simulations track each vapor bubble

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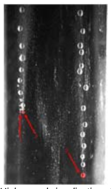
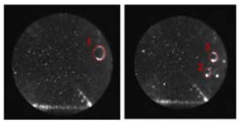
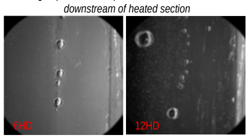
Preliminary images, Texas A&M experiment



High-speed visualization of nucleation sites



High-speed boroscope visualization of bubbles downstream of heated section



Zoom images of nucleation sites

In future, 5x5 bundle experiment, with grid spacer and heated rod, under subcooled boiling conditions

Detailed flow measurements will provide validation and modeling data

Requirements Overview for VERA-CFD

- Single- and multi-phase turbulent flow capability
- Boiling models; in particular, subcooled boiling
- Couple with conjugate heat transfer (CHT), non-conformal mesh interface
  - CHT handled *externally*, to couple tightly with MAMBA, Peregrin, ...
- Couple with thermo/solid mechanics (Sierra), non-conformal
- Couple with neutronics (via CHT), non-conformal
- Ability to freeze velocity field and only update energy equation.
- Couple with system-level codes (Relap)
- Coarse-grid CFD "as good as subchannel"
- Parallel-scalable to 10^{11} cells (surpass "32 bit issue"), on thousands of processors
- Quantification of uncertainties (provide feedback to CFD analyst)
- Verified and validated, with automated confirmation
- Archival of input sufficient to regenerate results quickly
- Follow VERA software development guidelines

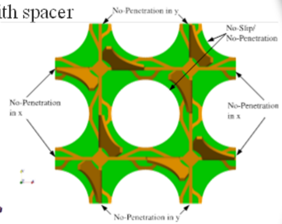
Comparison of *Drekar* and *Hydra-TH*

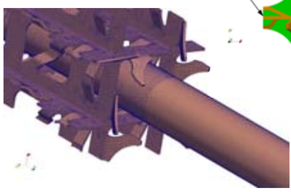
	Drekar	Hydra-TH
Summary of current capabilities	Single phase, incompressible to full compressible. Support for multiple momentum, continuity and energy eqns. General multicomponent transport/reaction. Stability and bifurcation analysis; arbitrary precision (currently, just for assembly)	Optimized single-phase incompressible/low-Mach, multimaterial compressible, heat transfer. Hybrid finite element / finite volume discretization support for general systems of equations. Moving-mesh capability.
Near-term Development Focus	Intrusive UQ, interfaces to other physics, turbulence modeling	Fast problem turn-around (including time-to-mesh), multiphase implementation, turbulence modeling
Turbulence Models	RANS, URANS, LES, DNS	RANS, URANS, LES, DES, DNS
Space Discretization	Stabilized finite elements 2nd order (up to 10th order)	Hybrid finite element/finite volume with high-resolution advection. Explicit advection designed for volume-of-fluid interface tracking.
Time Discretization	Fully-implicit BDF (to order 5), predictor-corrector. Developing adjoint capability for error control.	Implicit (up to 2nd order), semi-implict with explicit advection (up to 2nd order).
UQ Support	Automatic differentiation, Jacobian and sensitivities, black box	Black box
Mesh Topologies	Unstructured, currently either all-hexahedral or all-tetrahedral cells	Unstructured, allows different cell types in the same mesh (hexahedral, tetrahedral, pyramid, and prism).
Leveraged Funding	DOE Office of Science / ASCR	DOE NNSA / ASC

Both codes offer unique capabilities and diversity in numerical methods, but also share much common software infrastructure

Hydra-TH and Drekar codes used to analyze GTRF model problem

- 3x3 rod bundle test case, with spacer
- Fluid properties:
  - Density: 942.0 kg/m^3
  - Viscosity: 2.32x10^{-4} kg/m/s
  - Inlet Velocity: 5 m/s
  - Re_D=4.01x10^5





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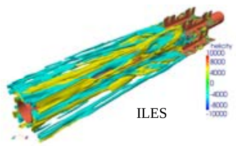
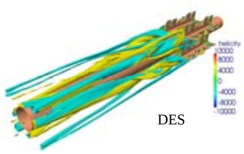
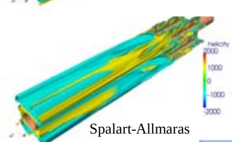
Hydra T-H code compared vortex structures using various models for GTRF



ILES



DES



Spalart-Allmaras

<u>Helicity isosurfaces</u>
- All models capture some level $(v\cdot\omega)$ of detail in the longitudinal vortical structures
- SA eddies appear more damped, rotation around rod is smeared

Ultimate goal is accurate turbulent excitation forces to predict rod vibration and wear

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VERA-CFD Multiphase Plan

- Initial implementation of multiphase model into Hydra-TH (FY12)
  - Start with "standard" 6-equation, two-fluid model
- Use other codes (NPHASE, PHASTA, …) to
  - Prototype new physics models for deployment into VERA-CFD
  - Transfer experience on solution algorithms into VERA-CFD
  - Generate DNS/ITM results to be upscaled
- Small effort at INL on Berry/Saurel 7-equation model development
  - Long-term development for VERA-CFD
  - Basis for Relap-7; need for coupling to Relap-7
  - Fully compressible; very well suited for accident scenerios

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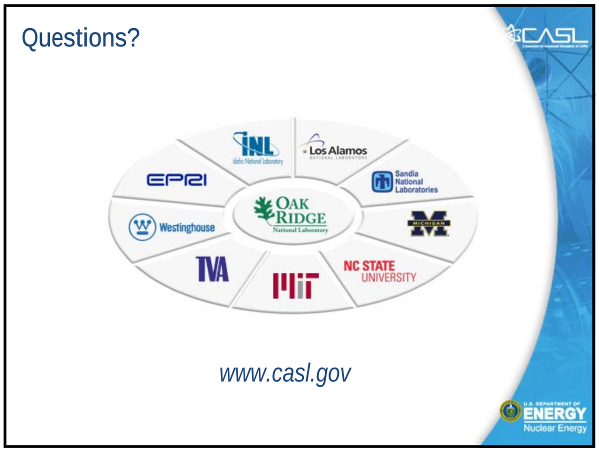
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