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System Analysis Module (SAM)

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GAIN-EPRI Advanced Reactor M&S Workshop #2
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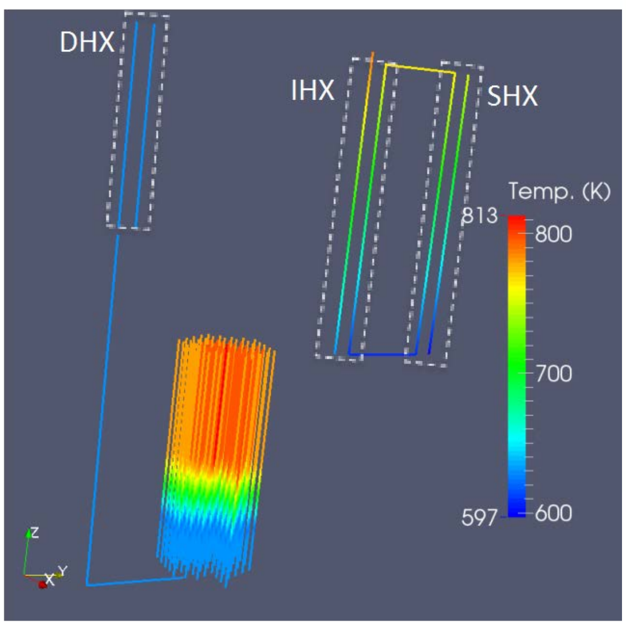
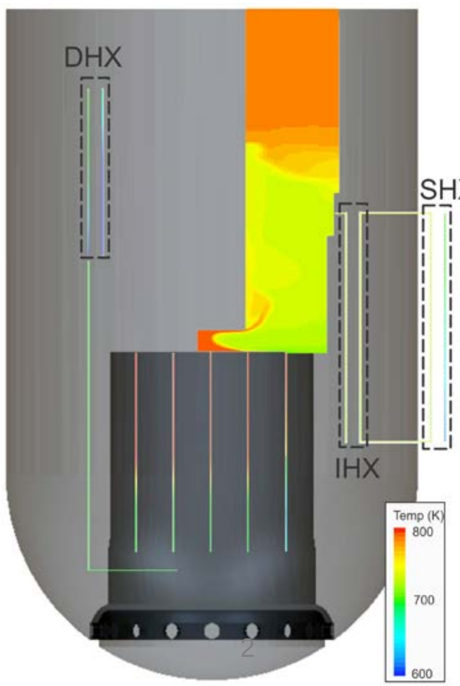
NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

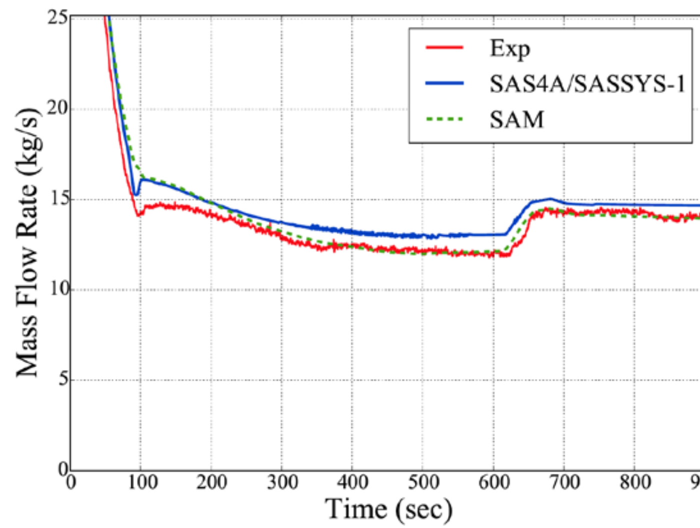
Overview

- A practical plant-level system analysis tool for advanced reactors (SFR, LFR, MSR/FHR);
- Advances in software environments and design, numerical methods, and physical models;
- Flexible multi-scale multi-physics integration with other high-fidelity tools.





Simulation of ABTR PLOF



EBR-II SHRT-45R Benchmark

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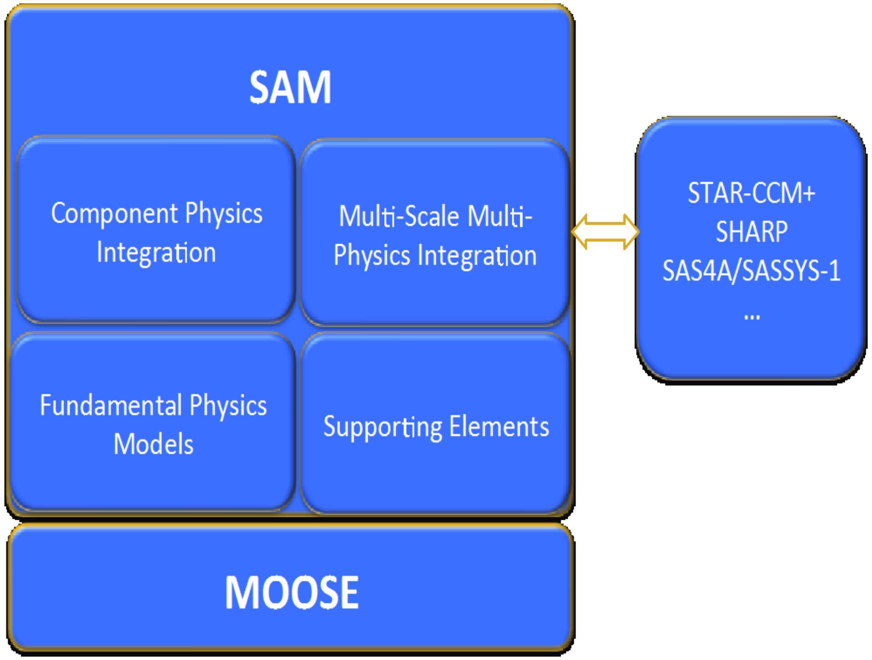
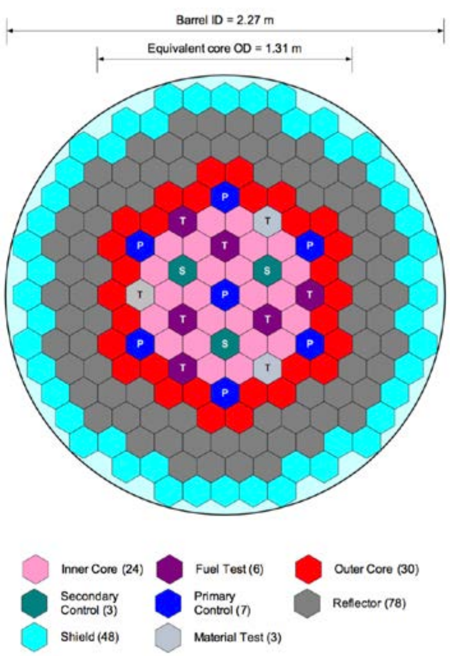
Development Approach

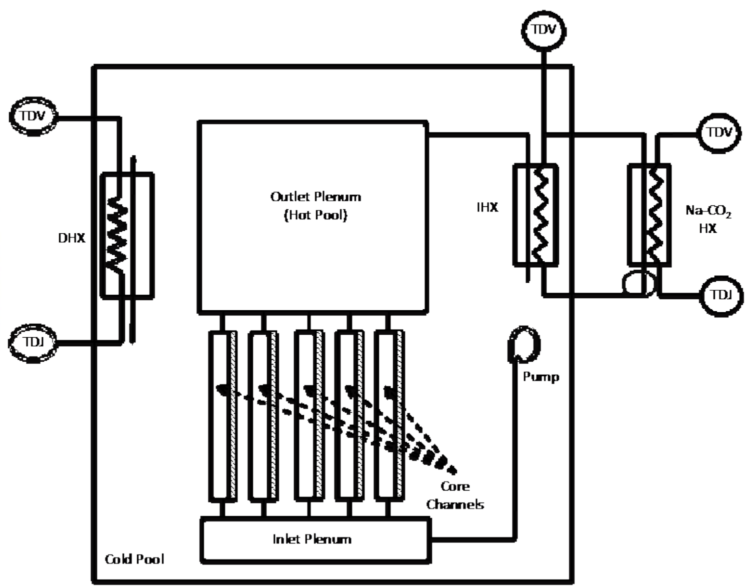
- Built-on MOOSE framework and other modern software libraries
  - Advanced solution methods
- Modern code development practice
  - Object-oriented C++ code
  - Modular, easy to develop and incorporate new capabilities
  - Designed for easy code reuse and code maintenance;
- Component based development
  - User friendliness
- Flexible for coupling with other M&S tools for multi-scale multi-physics modeling.

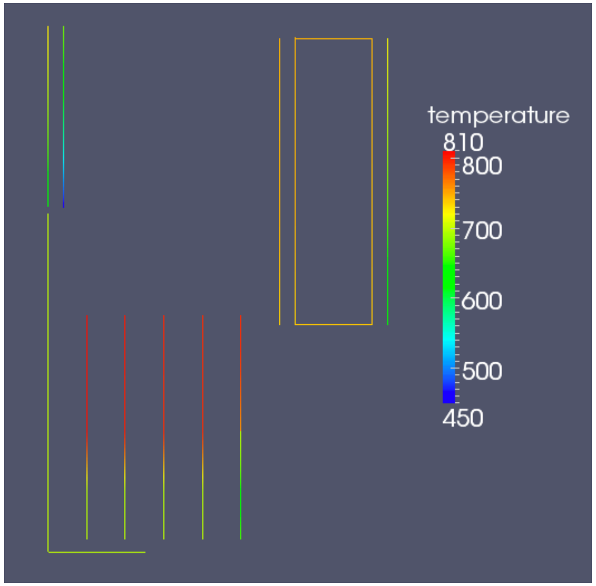


System Thermal-Hydraulics Modeling

- Robust and high-order FEM model of single-phase fluid flow and heat transfer has been developed and verified;
- Component-based code development and system modeling;
- Flexible coupling capability between fluid and solid components enables a wide range of engineering applications;
- Closure Model Enhancements.







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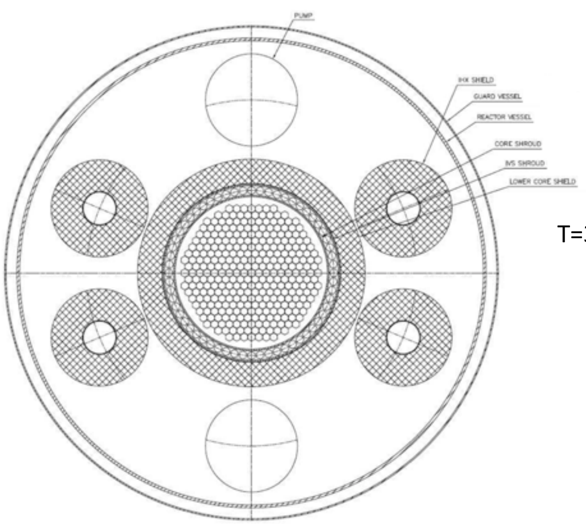
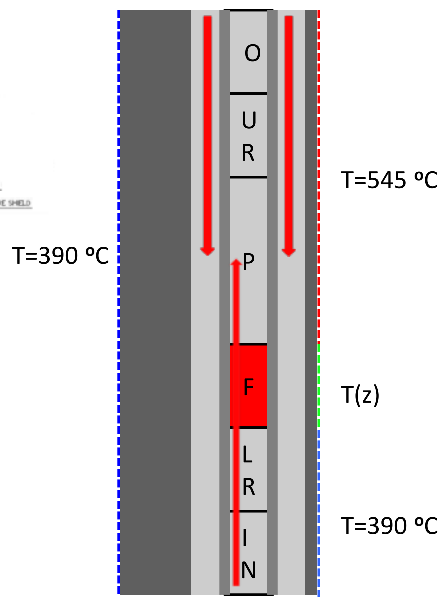
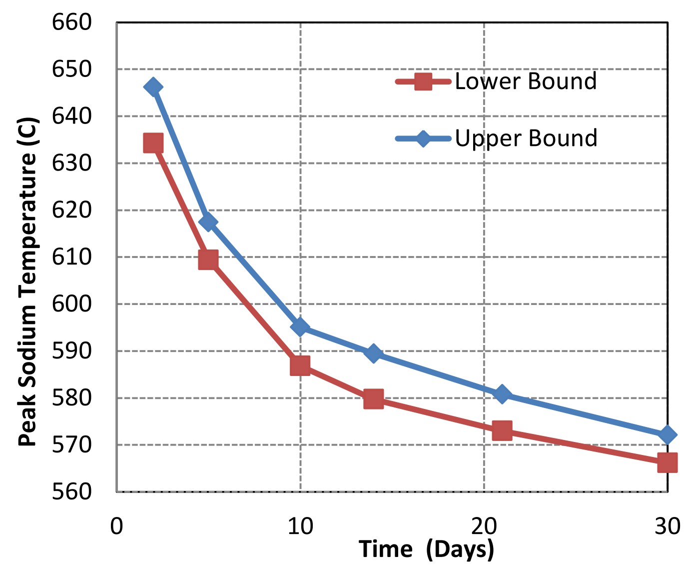
Application to an SFR IVS Cooling Analysis

- In-Vessel Spent Fuel Storage design relies on natural convection and conduction to remove the decay heat in the spent fuel assemblies.
- SAM is uniquely suitable due to its flexibilities, accuracies and efficiency for modeling the conjugate heat transfer and natural circulation.
- Heat transfer to all major solid structures must be modeled, including the assembly duct wall, the core barrel, the IVS shroud, and the core shielding.
- Timely analysis assured the safety of the spent fuel storage, also avoided the potential design changes of the IVS.







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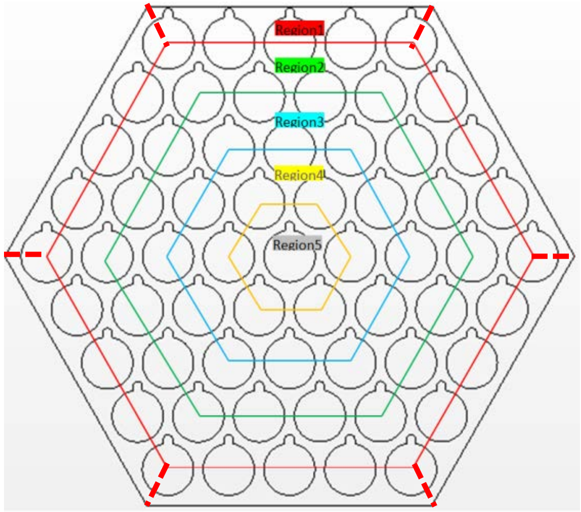
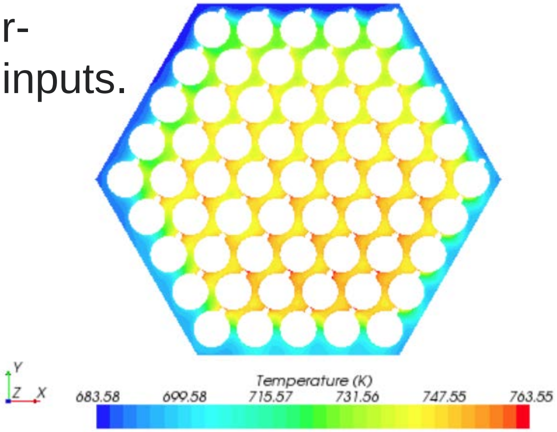
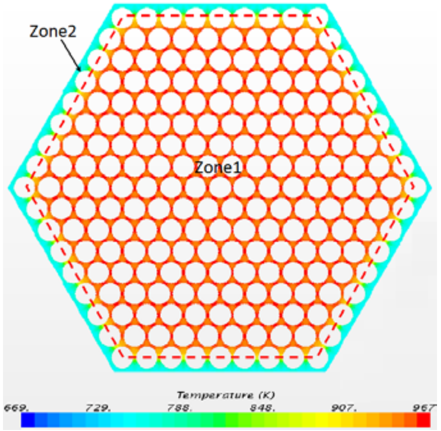
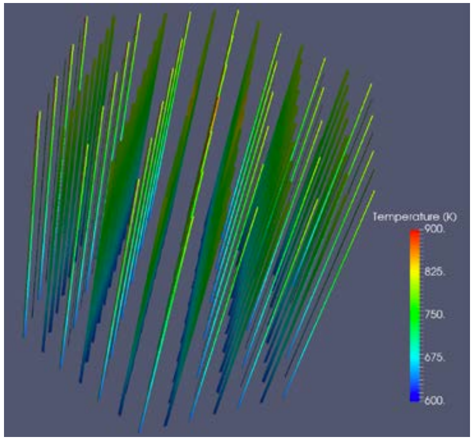
SAM Core Modeling Options

- Single-Channel Modeling
- Multi-Channel Modeling
  – Enabled by flexible fluid-solid CHT model in SAM;
- Flexible Full Core Modeling
  – HexLatticeCore component developed for SFR core modeling;
  – Automatically generate the core lattice (Multi-Channel or Single-Channel), and inter-assembly structures based on simple inputs.









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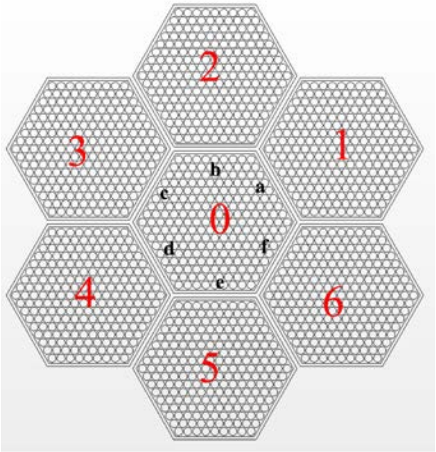
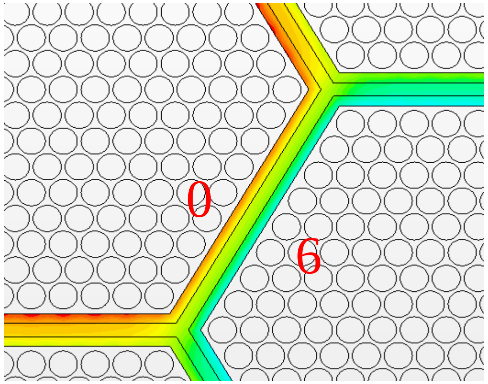
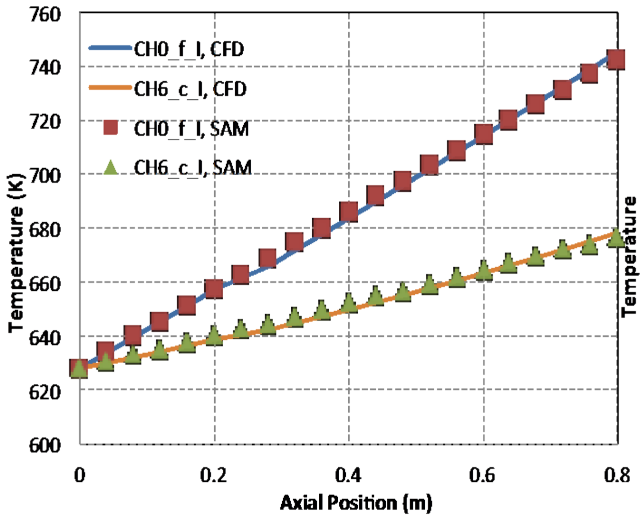
Virtual 3D Full-Core Conjugate Heat Transfer Modeling

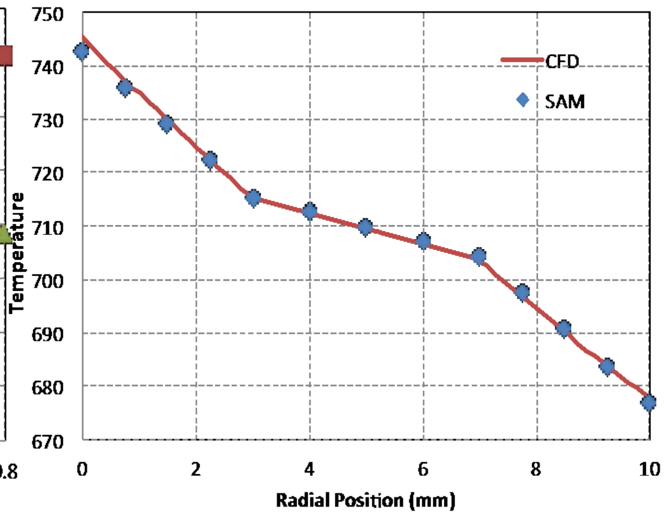
- 7-Assembly demonstration problem with high power Assembly 0, and low power Assembly 6
  - The six sides of the hexagon duct wall of one assembly are modeled separately;
  - Multi-channel assembly model is used;
  - Very good agreement with CFD results, while the computational cost is reduced by 5-6 orders of magnitude.





CFD results of duct wall temperature distributions





Average axial and radial wall temperature distributions

Computationally Efficient Multi-Dimensional Flow Model

Objectives: Model the multi-dimensional flow and thermal stratification phenomena in large enclosures (outlet plena) for reactor safety analysis.

- Multi-dimensional conversation equations on a coarse mesh;
- No turbulence modeling;
- Developing closure models for inter-cell interaction and wall frictions;
- Additional diffusive term in the energy equation to account for the turbulence effects and the use of coarse mesh.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \rho \vec{f}$$

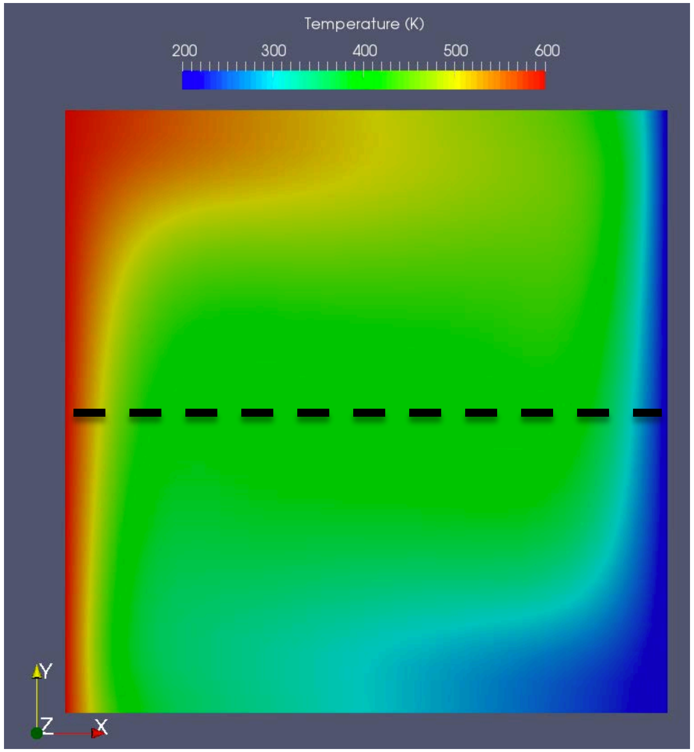
$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \vec{v}) = \nabla \left(k_{eff} \nabla T \right) + q_v'''$$

$$\rho = \rho(p, T)$$

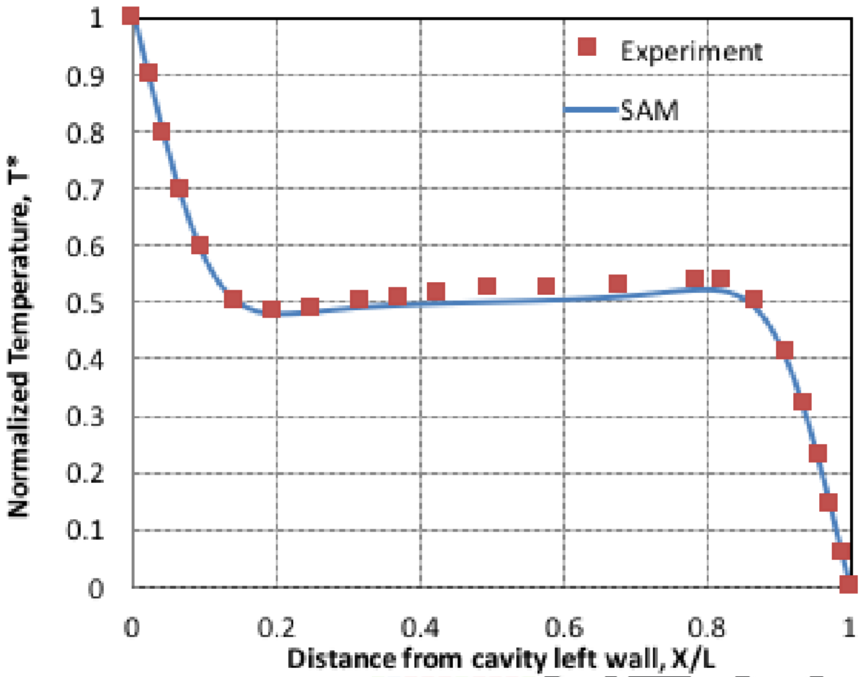
Preliminary Results from Verification Tests

- Test Problem: natural convection in a square cavity
  - Fixed temperatures on left and right walls; adiabatic top and bottom walls;

$Ra = 1.0 \times 10^5$



Normalized temperature distributions,
$Ra = 1.89 \times 10^5$, $Y/L = 0.5$



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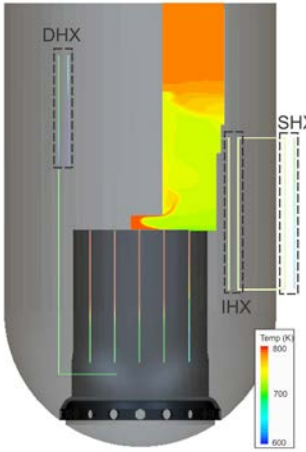
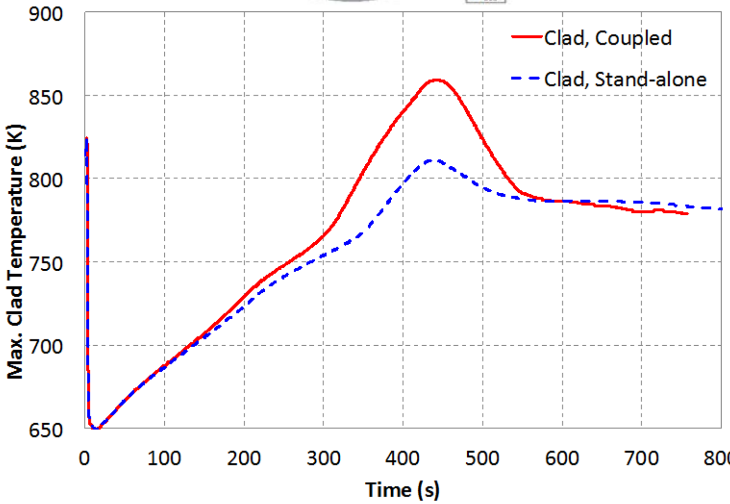
Multi-Physics Multi-Scale Integration

- Flexible multi-scale multi-physics integration through coupling with other M&S tools
- Coupling with CFD codes
  - STAR-CCM+
  - Nek5000 (under development)
- Integration with SAS4A/SASSYS-1
  - Joint collaboration between DOE-NE's ART and NEAMS programs
- Planned Additional Coupling
  - PROTEUS
  - SHARP/SAM/Bison/Workbench

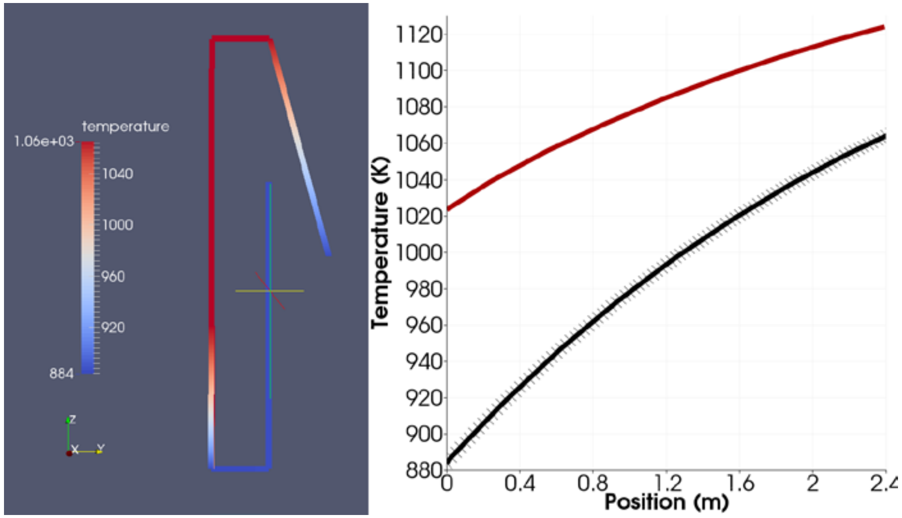




Enhancements for for MSR/FHR modeling

- Engagements with FHR IRPs under DOE-NE's NEUP program
  - FHR system T/H modeling
  - Code benchmarks
- NEUP project on salt freezing modeling
  - 1D freezing module in SAM
- Argonne LDRD project on MSR modeling
  - Radiation heat transfer
  - Liquid fuel transport in the primary loop
  - Additional closure models for salt fluid

SAM Model of PB-FHR DRACS



(Work performed by K. Ahmed (UWM) under the support of NEUP fellowship)

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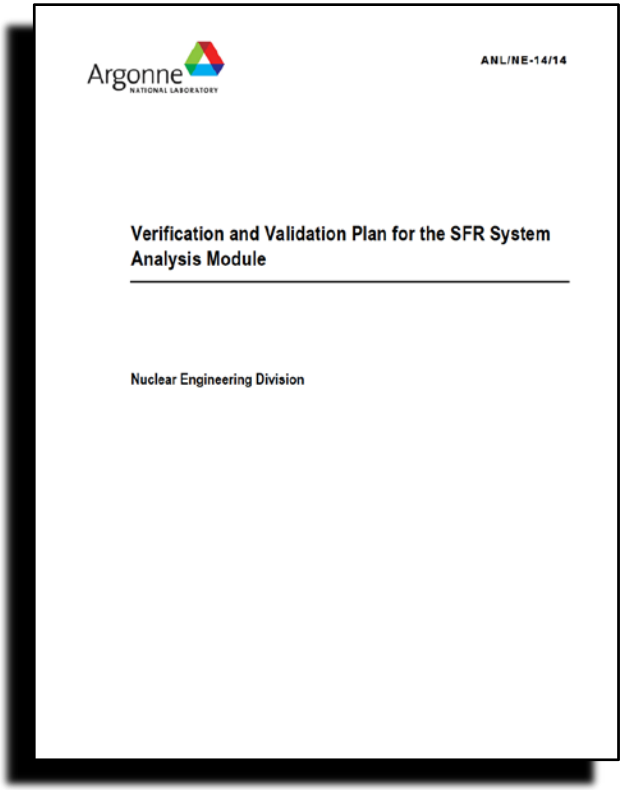
SQA and V&V

- Following QA and verification approaches used by MOOSE and MOOSE-based applications.
  - Continuous development with version control
  - Unit testing
  - Line coverage
- Over 150 test problems have been developed and included in the regression test suite
- Software Verification
  - Regression, Benchmark Tests, and Bug Reporting
  - Documentation
  - Verification with Analytical Benchmarks
  - Verification with Code-to-Code Comparison
- Software Validation
  - Unit, Component, Subsystem, System, Integral tests
  - Validation Matrix and Gaps
  - EBR-II, FFTF, CIET, etc.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Verification and Validation Plan for the SFR System Analysis Module

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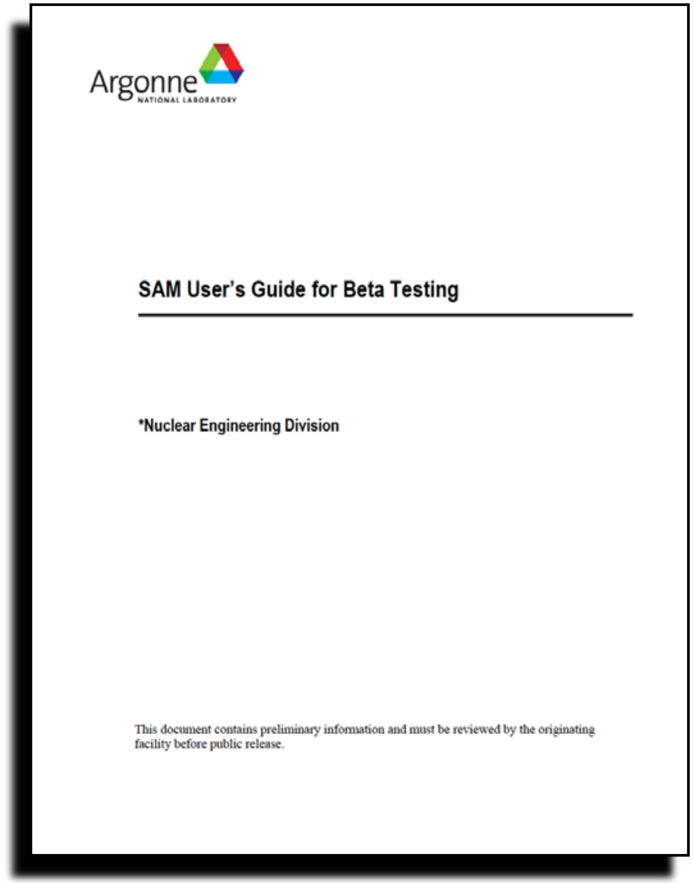
SAM User Engagements

- Usage
  - Availability/Computational resource
  - Input syntax/GUI
- Limited distribution only
  - Non-Disclosure Agreement
  - Special agreement with universities;
  - Users: UWM, OSU/UM, ORNL/PSU, Oklo Inc. etc.
- Free open-source license planned for STH (pipe-network) simulation capabilities
- Training/Tutorial
- Internal use at Argonne
  - KAERI SPP on PGSFR design
  - DOE programs: ART, AFC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SAM User's Guide for Beta Testing

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This document contains preliminary information and must be reviewed by the originating facility before public release.

Ongoing and Future Work

- Reduced-order model for thermal-stratification
- Enhancements for MSR/FHR modeling
  - NEUP project on salt freezing modeling
  - LDRD project on MSR modeling
- Continued capability enhancements and V&V
  - Additional Component models
  - User experience (usability)
  - Benchmark with FFTF and other IET tests
- Multi-scale multi-physics coupling with other M&S tools
  - SAM/SAS
  - SAM-Nek5000, SAM-PROTEUS
  - SHARP/SAM/Bison/Workbench

References:

1. Rui Hu, "A fully-implicit high-order system thermal-hydraulics model for advanced non-LWR safety analyses," *Annals of Nuclear Energy*, Vol. 101, 174–181, (2017).
2. R. Hu and Y. Yu, "A Computationally Efficient Method for Full-Core Conjugate Heat Transfer Modeling of Sodium Fast Reactors," *Nuclear Engineering and Design*, Vol. 308, 182-193, (2016).
3. R. Hu and T. Sumner, "Benchmark Simulations of the Thermal-Hydraulic Responses during EBR-II Inherent Safety Tests using SAM", *Proceedings of ICAPP'16*, San Francisco CA, April 17-20, 2016.
4. T.H. Fanning and R. Hu, "Coupling the System Analysis Module with SAS4A/SASSYS-1", ANL/NE-16/22, ANL-ART-74, Argonne National Laboratory, September 2016.
5. R. Hu, T.H. Fanning, T. Sumner, Y. Yu, "Status Report on NEAMS System Analysis Module Development," ANL/NE-15/41, Argonne National Laboratory, December 2015.

Thank you for your attention!
&
Questions?

BACKUP SLIDES: Glance of Input File – Tool Usability

[Components]
…
[./core]
type = HexLattice
position = '0 0 0'
orientation = '0 0
n_side = 2
assem_pitch = 0.
assem_Dft = 0.13

assem_layout = 'I
F1
F
radial_power_pea

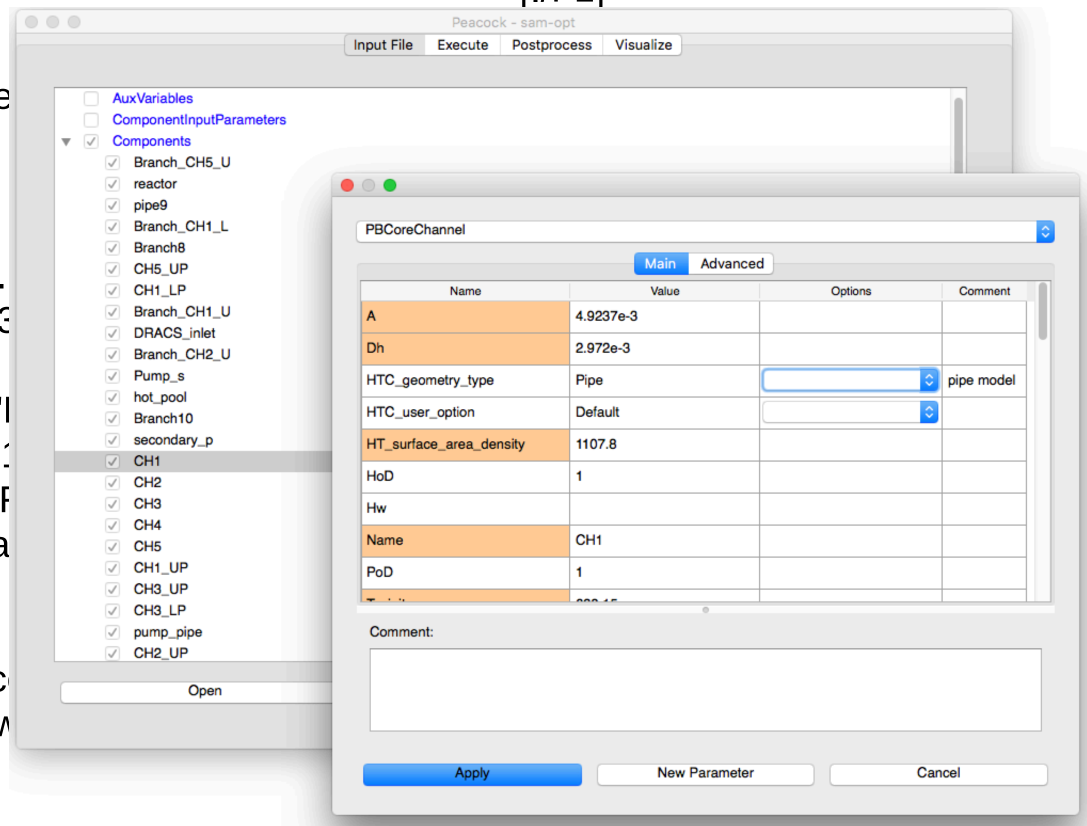
ref_hs = referenc
ref_duct = duct_w
[../]
[ ]

[ComponentInputParameters]
[./F1]
arameters

5 0.00052'

lad-mat'
l

beta = 0.01
[../]
…
[ ]



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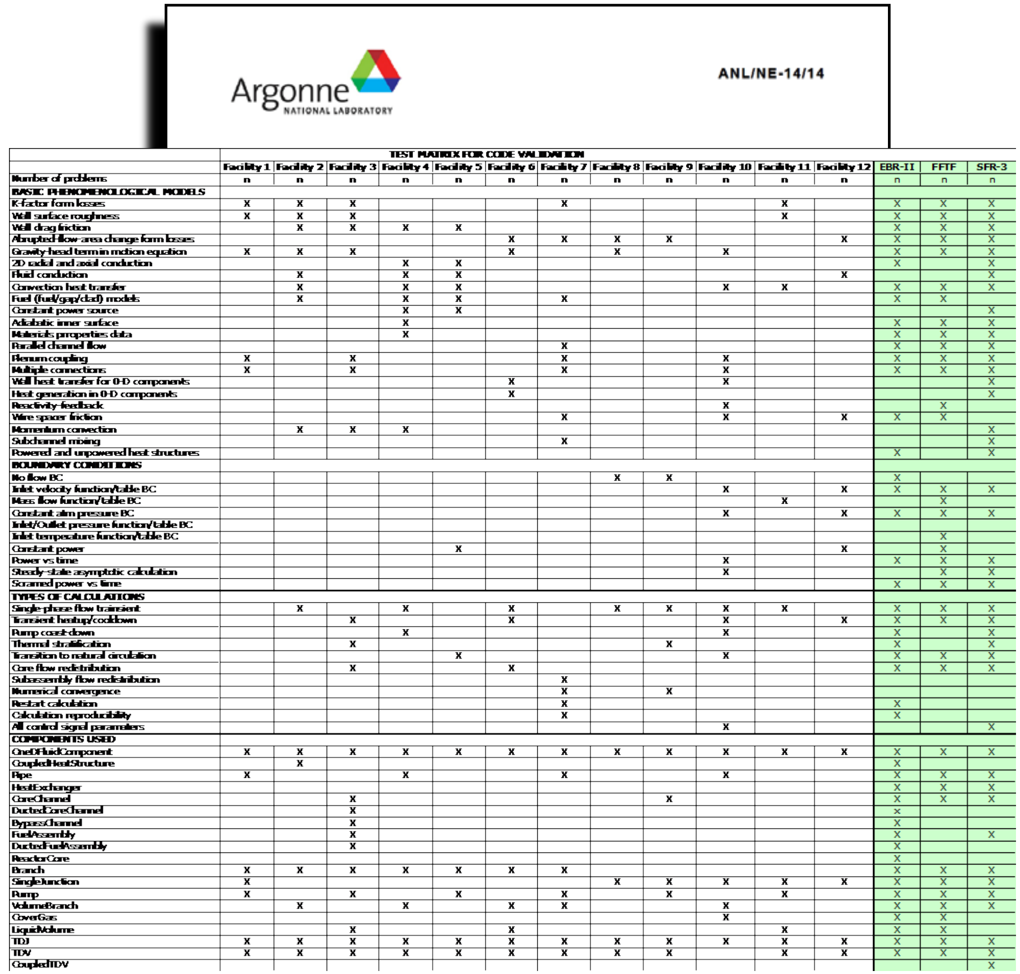
Closure Model Enhancements

- Review, select, and implement a set of thermal-hydraulic closure models
  - Focused on heat transfer and friction correlations
  - Sodium, simple fluoride salt and air EOS models
- Interactions with IAEA NAPRO Coordinated Research Project
- Selection criteria and points of consideration:
  - Fluid type (sodium) and flow geometry examined
  - Applicable flow regime and geometric ranges
  - Uncertainty of correlation
  - Model complexity / user-accessibility
  - Popularity amongst system code users
  - State-of-the-art investigation
- Verified with unit test problems
- Initial study on the effects of closure models in SFR safety analysis

SAM V&V Plan

- Phenomena Identification
- Software Verification
  - Regression, Benchmark Tests, and Bug Reporting
  - Documentation
  - Verification with Analytical Benchmarks
  - Verification with Code-to-Code Comparison
- Software Validation
  - Unit, Component, Subsystem, System, Integral tests
  - Validation Matrix and Gaps
  - Schedule and Priorities



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TEST MATRIX FOR CODE VALIDATION															
	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5	Facility 6	Facility 7	Facility 8	Facility 9	Facility 10	Facility 11	Facility 12	EBR-II	FFTF	SFR-3
Number of problems	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
BASIC PHENOMENOLOGICAL MODELS															
K-factor form losses	X	X	X				X				X		X	X	X
Wall surface roughness	X	X	X								X		X	X	X
Wall drag friction		X	X	X	X								X	X	X
Abrupted-flow-area change form losses						X	X	X	X			X	X	X	X
Gravity-head term in motion equation	X	X	X			X		X		X			X	X	X
2D radial and axial conduction				X	X								X		X
Fluid conduction		X		X	X							X			X
Convection heat transfer		X		X	X					X	X		X	X	X
Fuel (fuel/gap/clad) models		X		X	X		X						X	X	
Constant power source				X	X										X
Adiabatic inner surface				X									X	X	X
Materials properties data				X									X	X	X
Parallel channel flow							X						X	X	X
Plenum coupling	X		X				X			X			X	X	X
Multiple connections	X		X				X			X			X	X	X
Wall heat transfer for 0-D components						X				X					X
Heat generation in 0-D components						X									X
Reactivity-feedback										X				X	
Wire spacer friction							X			X		X	X	X	
Momentum convection		X	X	X											X
Subchannel mixing							X								X
Powered and unpowered heat structures													X		X
BOUNDARY CONDITIONS															
No flow BC								X	X				X		
Inlet velocity function/table BC										X		X	X	X	X
Mass flow function/table BC											X			X	
Constant atm pressure BC										X		X	X	X	X
Inlet/Outlet pressure function/table BC															
Inlet temperature function/table BC														X	
Constant power					X							X		X	
Power vs time										X			X	X	X
Steady-state asymptotic calculation										X				X	X
Scramed power vs time													X	X	X
TYPES OF CALCULATIONS															
Single-phase flow trainsient		X		X		X		X	X	X	X		X	X	X
Transient heatup/cooldown			X			X				X		X	X	X	X
Pump coast-down				X						X			X		X
Thermal stratification			X						X				X		X
Transition to natural circulation					X					X			X	X	X
Core flow redistribution			X			X							X	X	X
Subassembly flow redistribution							X								
Numerical convergence							X		X						
Restart calculation							X						X		
Calculation reproducibility							X						X		
All control signal parameters										X					X
COMPONENTS USED															
OneDFluidComponent	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
CoupledHeatStructure		X											X		
Pipe	X			X			X			X			X	X	X
HeatExchanger													X	X	X
CoreChannel			X						X				X	X	X
DuctedCoreChannel			X										x		
BypassChannel			X										X		
FuelAssembly			X										X		X
DuctedFuelAssembly			X										X		
ReactorCore													X		
Branch	X	X	X	X	X	X	X						X	X	X
SingleJunction	X							X	X	X	X	X	X	X	X
Pump	X		X		X		X		X		X		X	X	X
VolumeBranch		X		X		X	X			X			X	X	X
CoverGas										X			X	X	
LiquidVolume			X			X					X		X	X	
TDJ	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
TDV	X	X	X	X	X	X	X	X	X		X	X	X	X	X
CoupledTDV															X

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Demonstration of SAS/SAM Coupling

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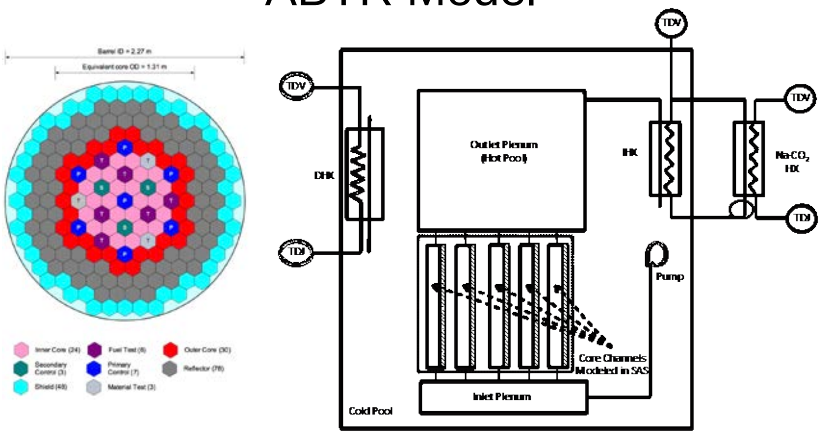
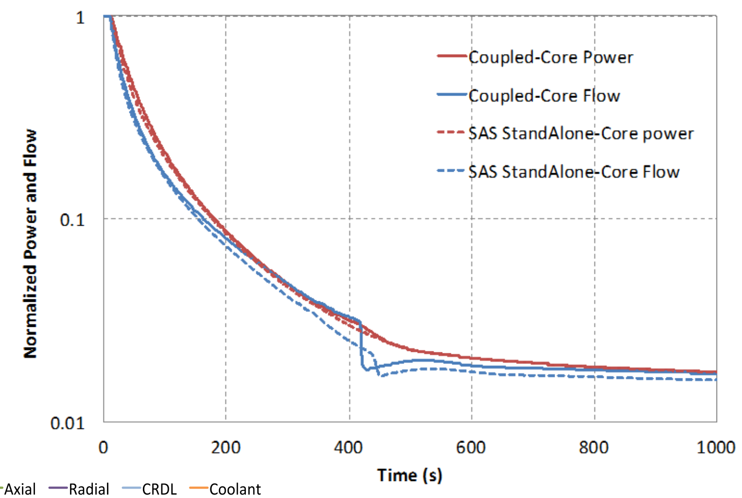
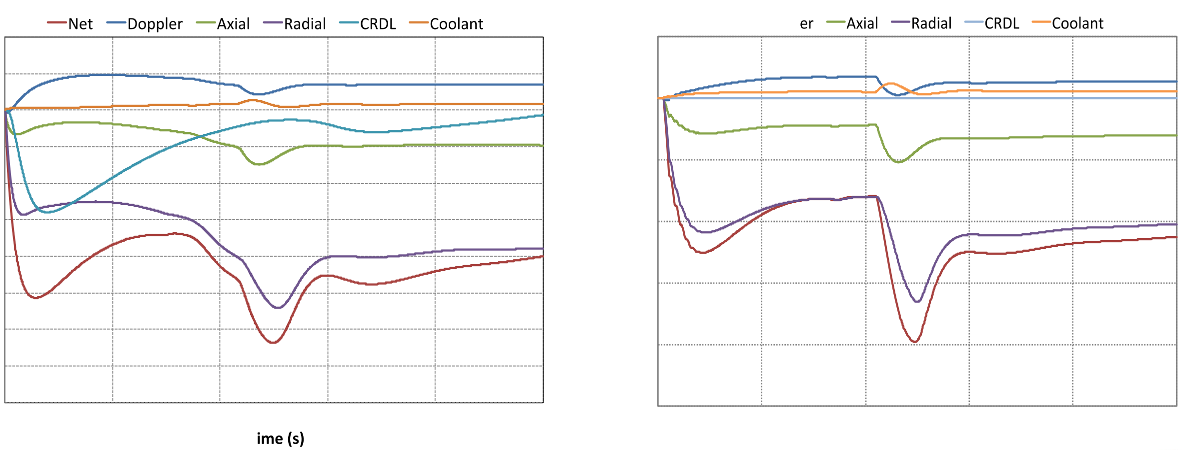
ABTR Model



Power and Flow during ABTR ULOF





Reactivity Feedback Effects

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