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# SHARP Multiphysics


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# Interrelated Phenomena over a range of Length and Time Scales

- Among all of reactor technologies being pursued by industry and DOE-NE R&D programs, modeling & simulation needs vary

- Reactor design and safety performance requires analysis of a wide range of length and time scales of interrelated physics
  - Reactivity response to minor geometric changes during transients in SFRs
  - Analysis of inherent safety and passive decay heat removal for large pebble bed or prismatic block HTGRs
  - Intrinsic connection between neutronics and flow field in liquid fueled MSRs

- Need for a mission-agile toolkit for reactor core analysis
  - Multiphysics, multiresolution, multiscale

# SHARP Multiphysics Interface: SIGMA

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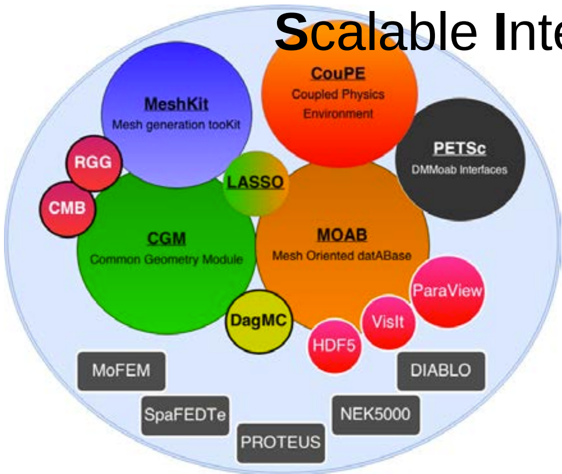
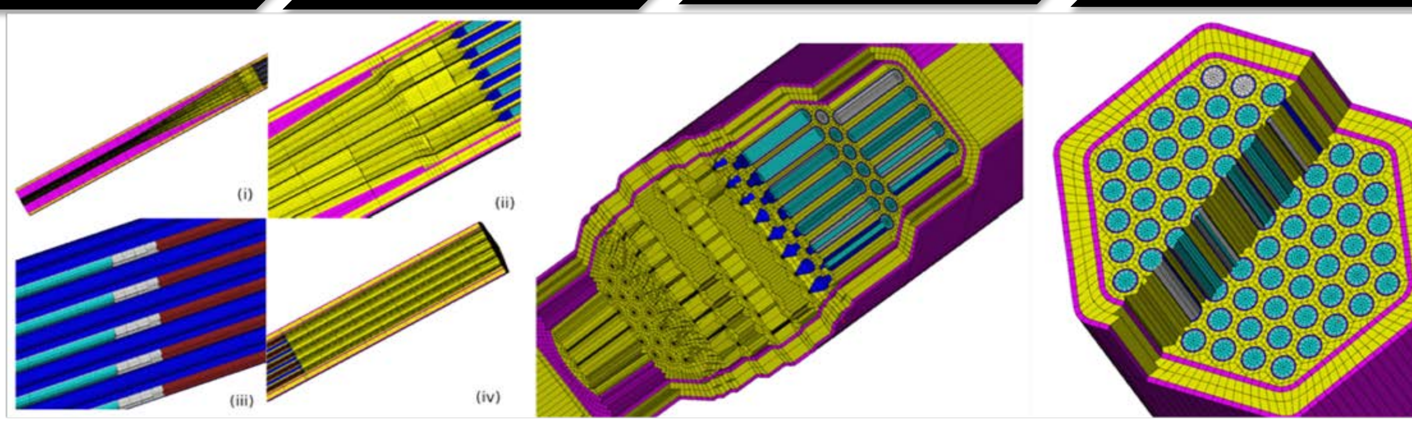
**S**calable **I**nterfaces **for G**eometry **and M**esh-based **A**pplications



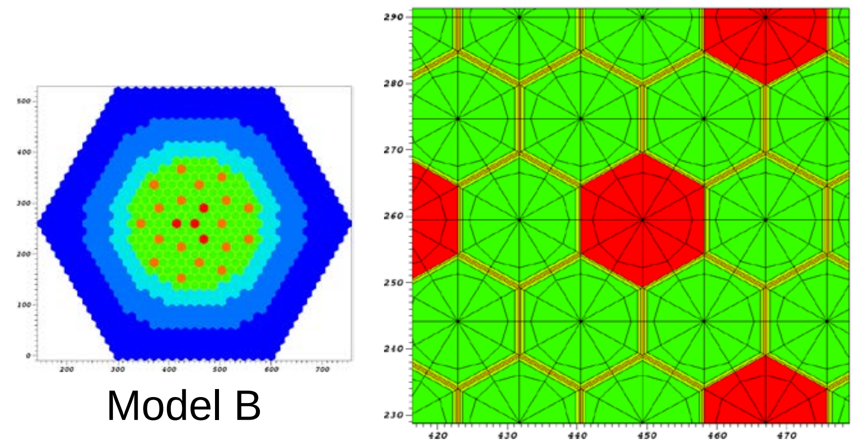

- CGM: ACIS and OCC geometry models
- MeshKit: Optimal mesh for complex geometries with extensions to use Cubit/Tetgen/Netgen
- MOAB: Scalable array based for access and storage of mesh data on entities
- CouPE: Coupled physics global nonlinear solvers based on PETSc for multiphysics solutions

Define Geometry (**CGM**) → Generate Mesh (**MeshKit**) → Discrete Mesh (**MOAB**) → Coupled Physics (**CouPE**)

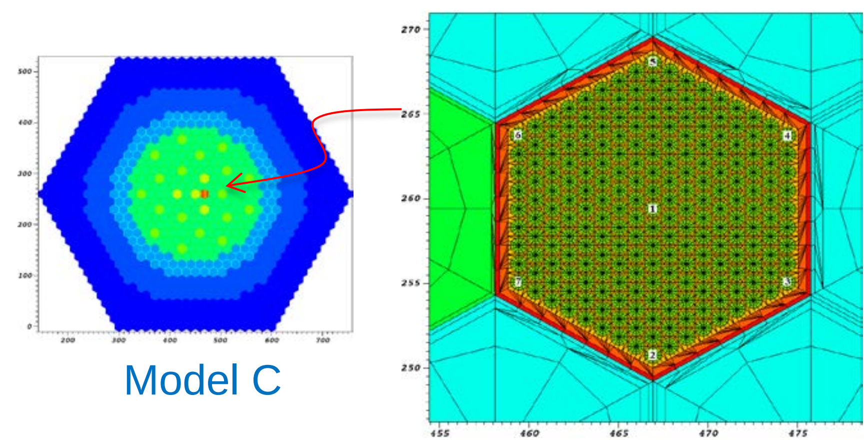


# SHARP – Multiresolution

- **Neutronics with mixed local resolutions**
  - Model A - Homogenized assembly model (as generally considered in applications of current deterministic codes, notably DIF3D-VARIANT)
  - Model B - Explicit representation of wrapper tube and inter-assembly sodium gap for all fuel regions
  - Model C - Explicit pin by pin representation of a single assembly in the inner core, leaving a full material homogenization in all other assemblies



Model B



Model C

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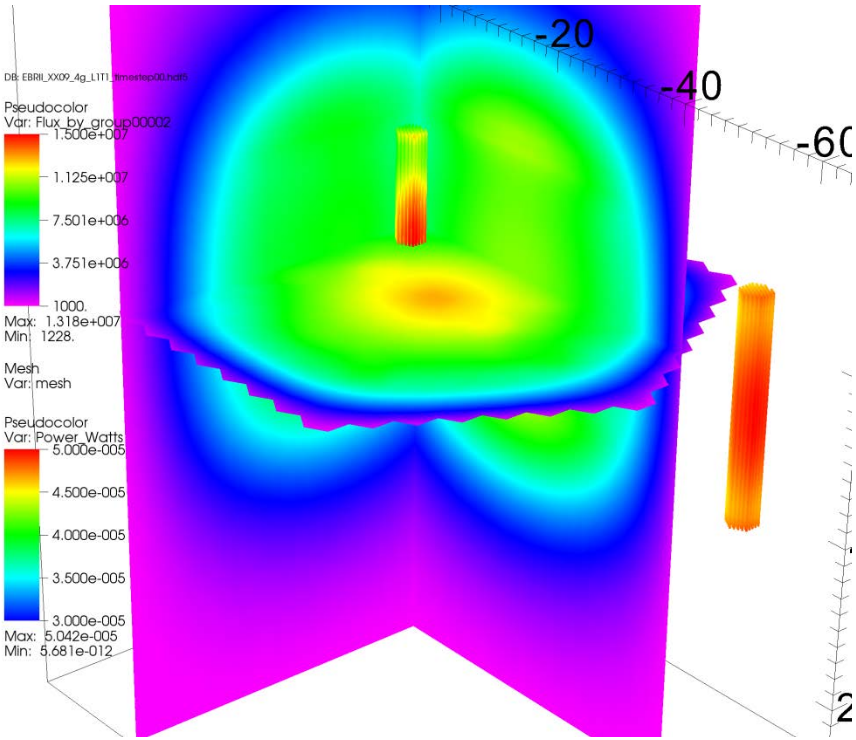
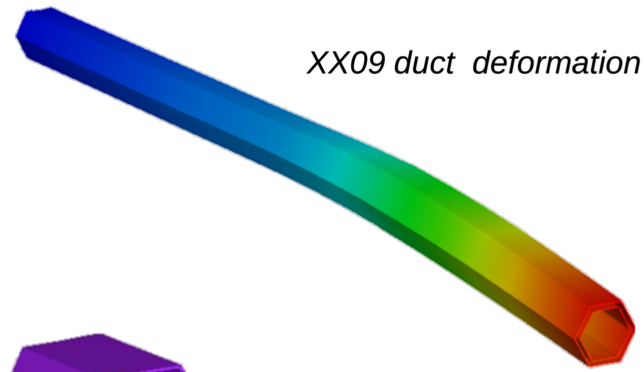
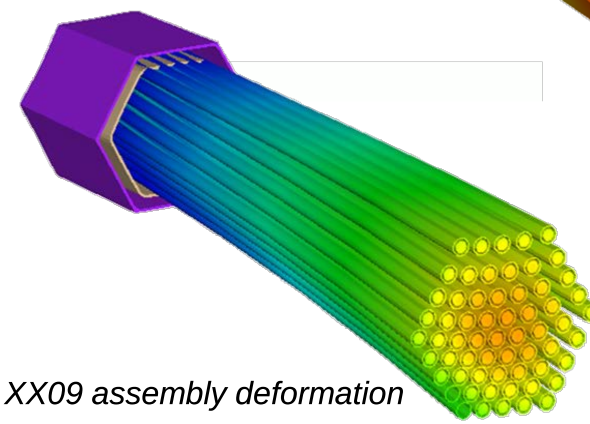
# SHARP – Multiresolution (cont.)




*EBR-II power distribution, note XX09 assembly in the middle*



*XX09 duct deformation*



*XX09 assembly deformation*

**EBR-II simulations have demonstrated capability to mix fully heterogeneous regions ("pin-by-pin") with homogenized assemblies.**

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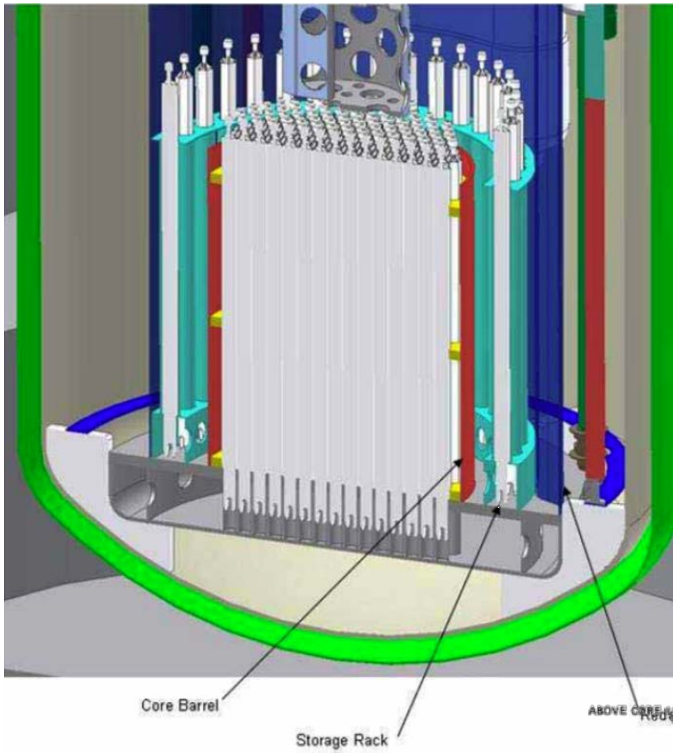
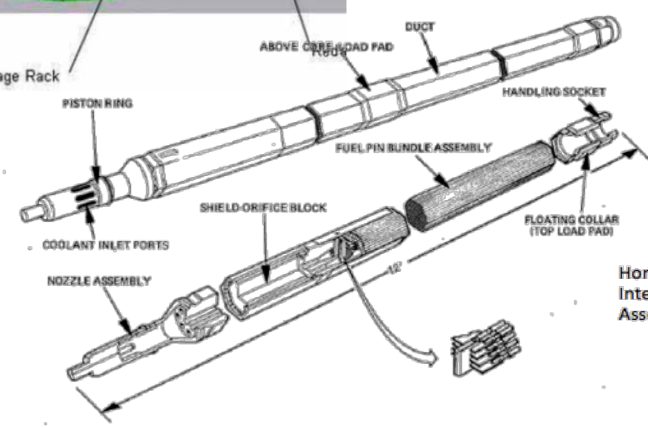
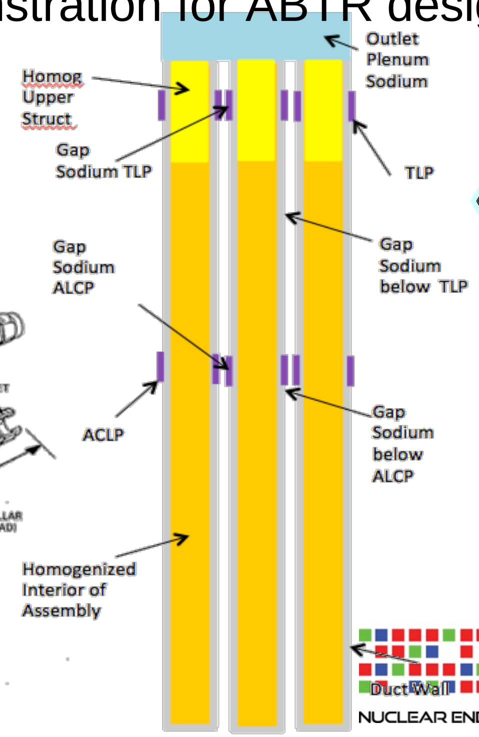
# SHARP – Multiphysics SFR Core Deformation

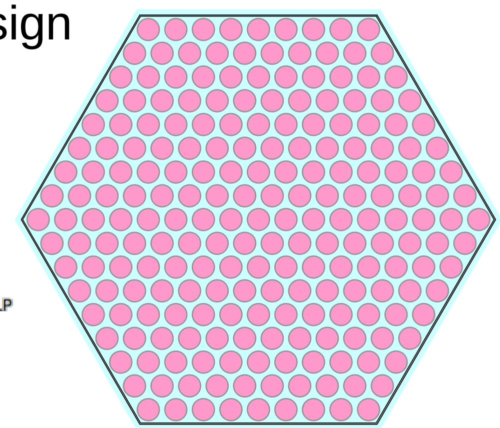
- Core thermal expansion is one of the primary reactivity feedback mechanisms for FR safety
- Geometry deforming due to temperature gradients in the presence of restraining contacts
- By appropriate design of the core restraint system, neutron leakage is enhanced
- Demonstration for ABTR design




*CAD model and drawing of the Advanced Burner Test Reactor (ABTR) core*



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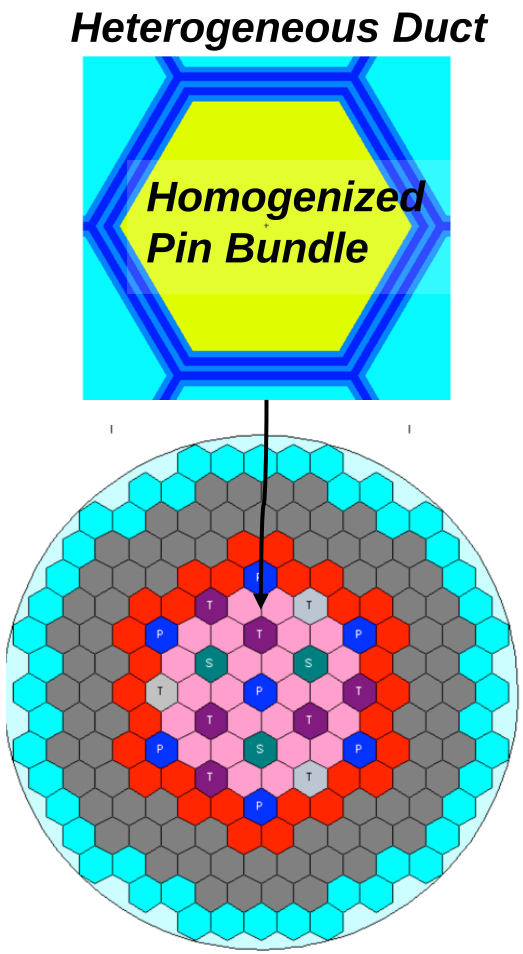
# SFR Core Deformation: Neutronics Homogenization

- **For the SHARP simulations of core structural deformations, want to:**
  - Explicitly model the duct walls
  - Homogenize the interior pin bundle to reduce computational cost
  - Not possible with conventional nodal transport tools (e.g. DIF3D)
- **Approach cross-verified by comparing to MCNP for various homogenization approaches**

| | Sum of All Control Rod Worths ($\Delta k$) |
|---|---|
| MCNP (1σ) | 0.12061±0.00015 |
| PROTEUS (33 groups) | 0.12042 |
| PROTEUS (70 groups) | 0.12036 |
| PROTEUS (116 groups) | 0.12065 |

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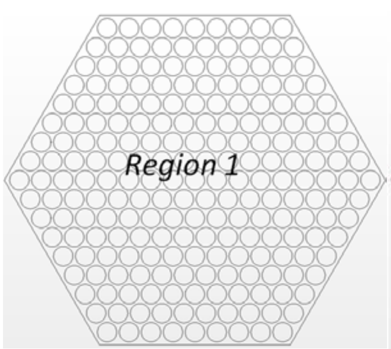
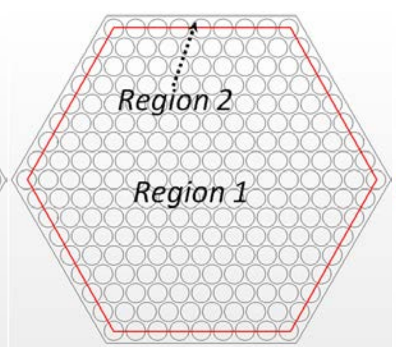
# SFR Core Deformation: T/H Homogenization

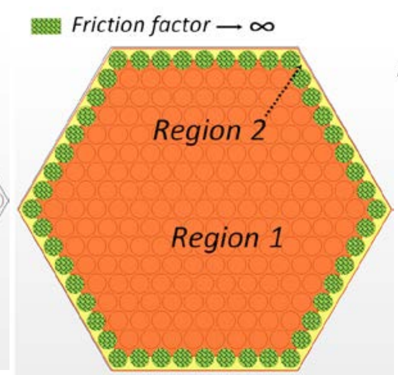
- **Deformation is driven by thermal expansion of the duct walls**
- **Explicit-geometry CFD is prohibitively expensive computationally**
- **Need to develop porous media models (~300x faster):**
  1. Single-region: Uniform q''', porosity, and inlet velocity
  2. Two regions: Different volumetric heat generation rates
  3. Two regions: Distinct q''', porosity, and inlet velocity



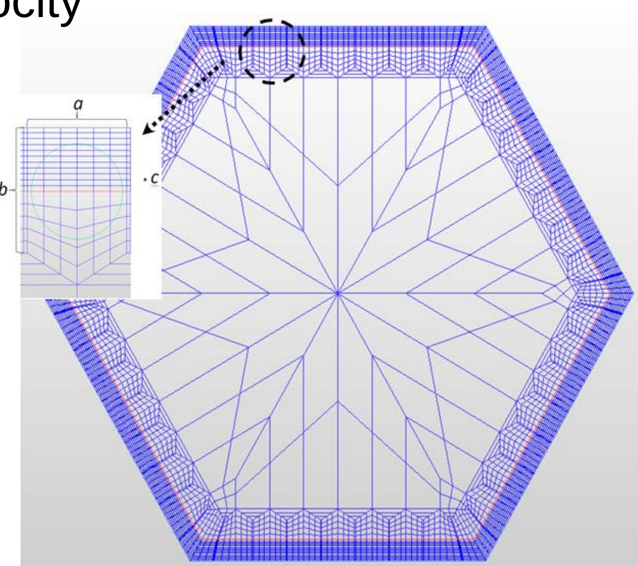

***Porous Media 1***




***Porous Media 2***




***Porous Media 3***



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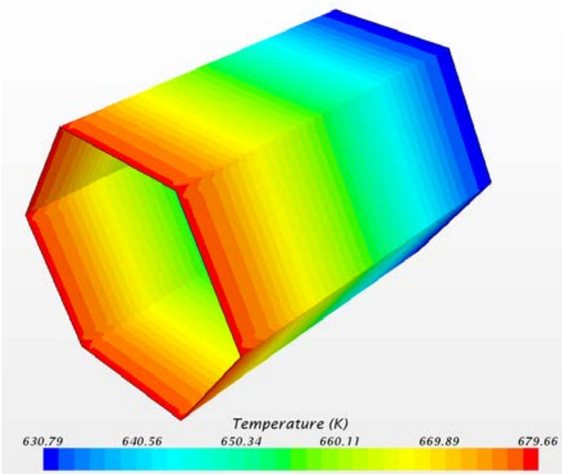
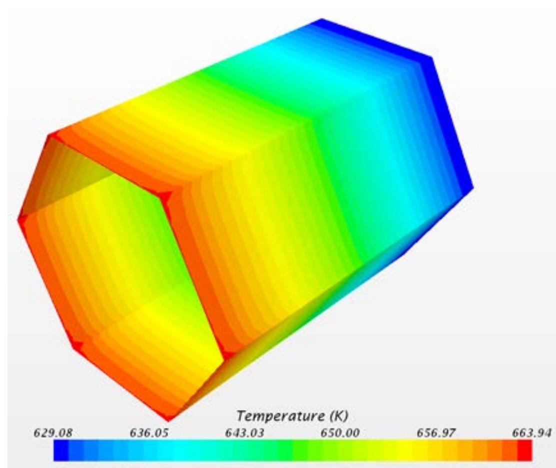
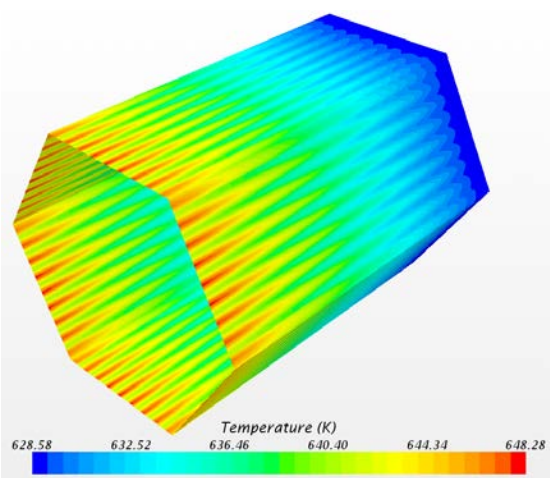
# SFR Core Deformation: Temperature Prediction



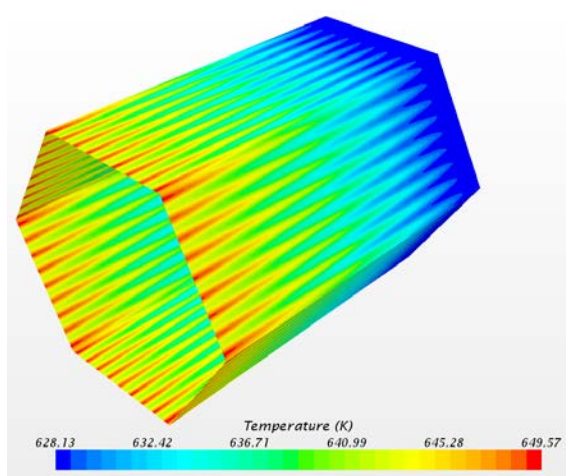

***Porous Media 1***




***Porous Media 2***




***Porous Media 3***

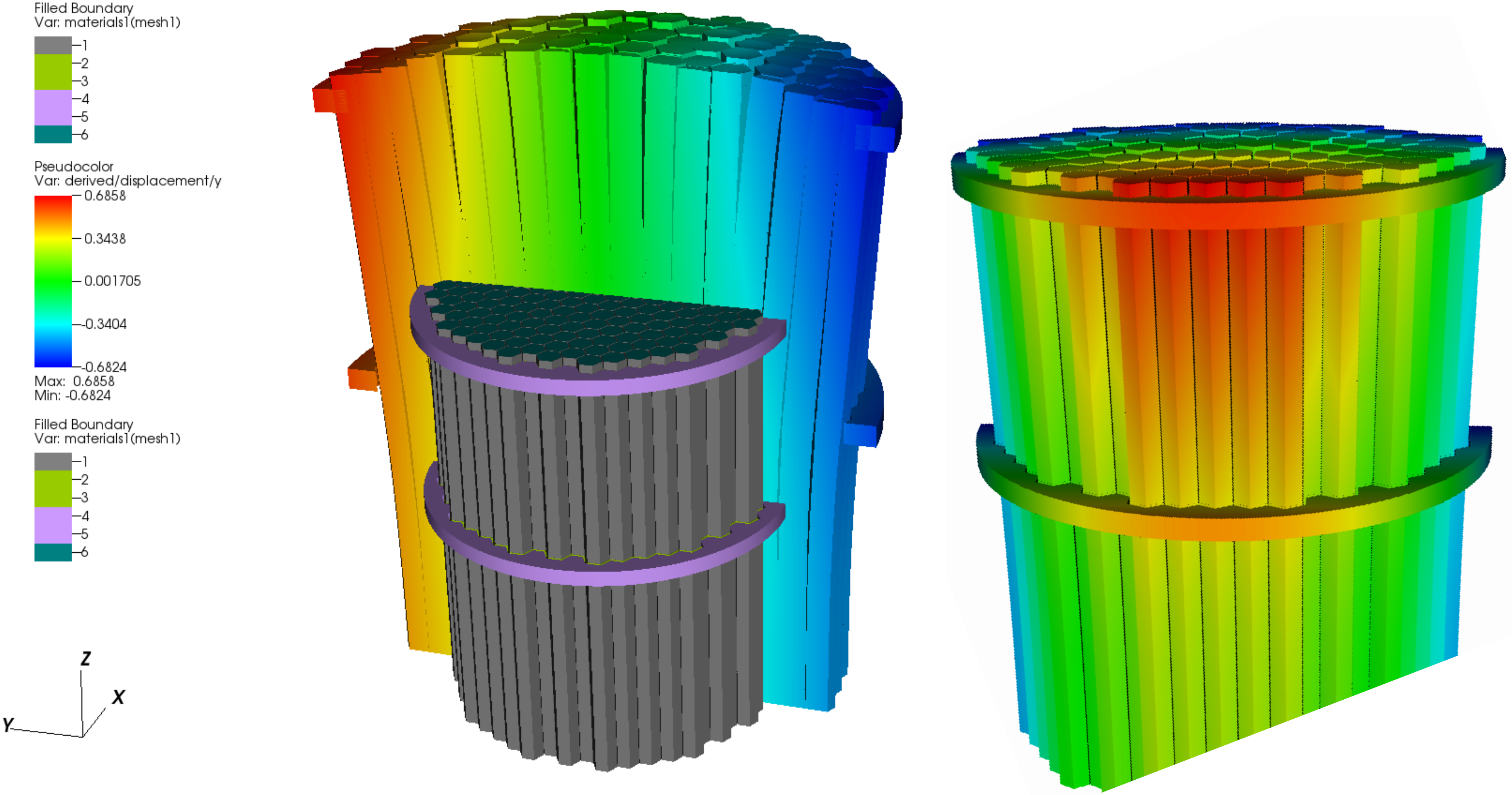



***Reference CFD (pin-by-pin)***

- Peak wall temperature rise above 630K:
  1. 50 K (off by 2.5x)
  2. 34 K
  3. 18 K

  Reference CFD: 19 K

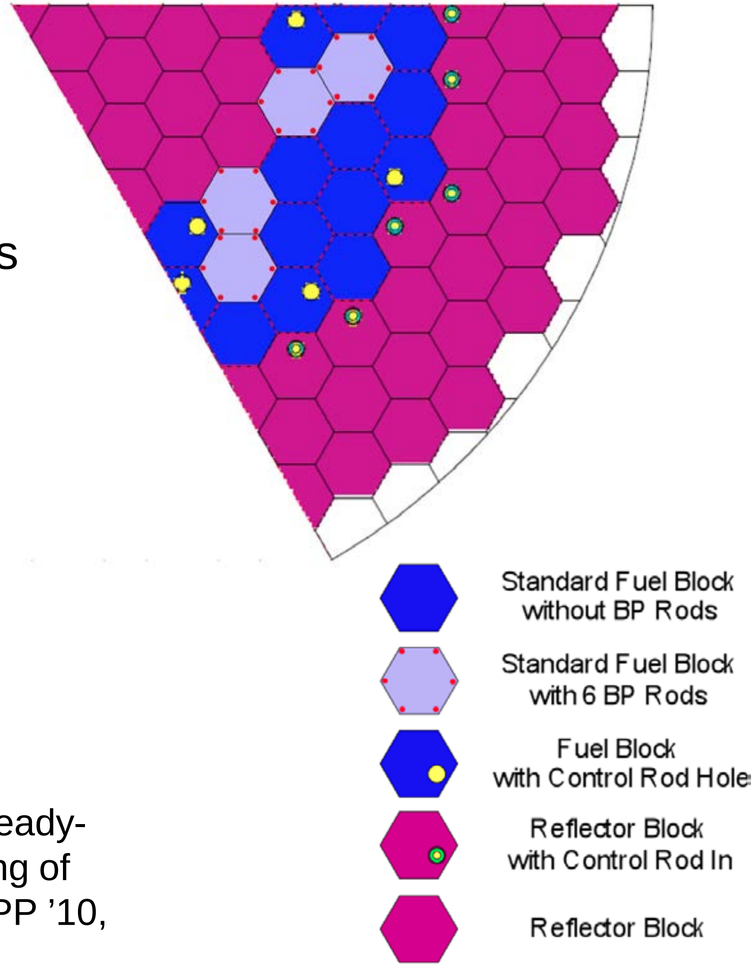
# Full ABTR coupled calculations




*ABTR full core displacement in the y direction magnified by 100 x*

# VHTR Model

- **Benchmark model based on GT-MHR**
  - 60° periodic boundaries
  - 3 rings of fuel columns
  - Control rod channels open in fuel columns
  - Control rods fully inserted into reflector columns (“operating rods in”)
  - Burnable poisons biased towards inner ring to flatten power shape




J. W. Thomas, C. H. Lee, W. D. Pointer, and W. S. Yang, “Steady-State, Whole-Core VHTR Simulation with Consistent Coupling of Neutronics and Thermo-Fluid Analysis”, Proceedings of ICAPP ’10, San Diego, CA, USA, June 13-17, 2010

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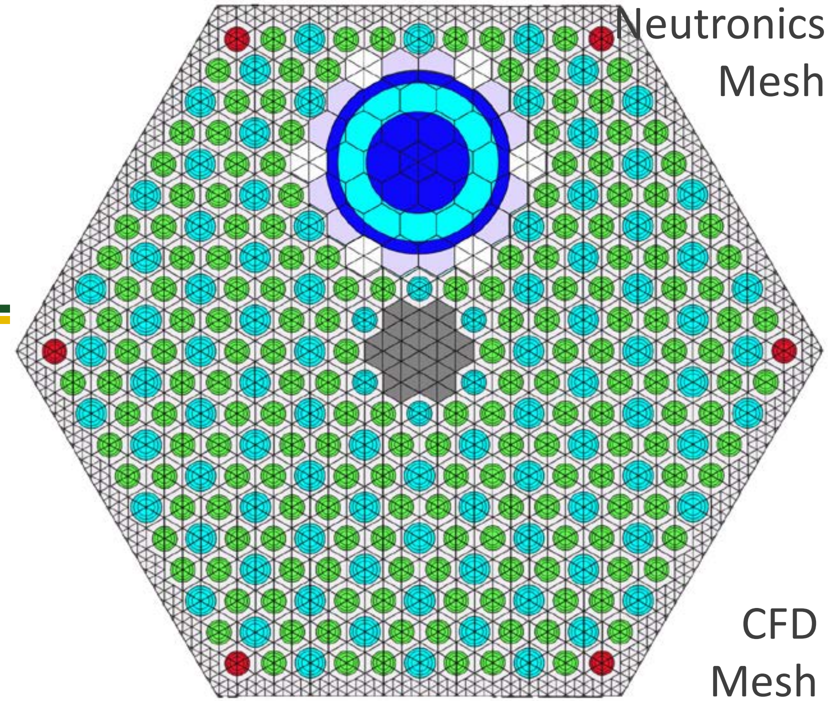
# VHTR Model (cont.)

## Neutronics model

- Global k-eff solution from multigroup CMFD problem with pin-cell mesh
- Coupled to 2-D planar MOC
  - Provides multigroup cross sections (equivalence theory)
  - Gets axial source from global CMFD
- Subgroup resonance treatment

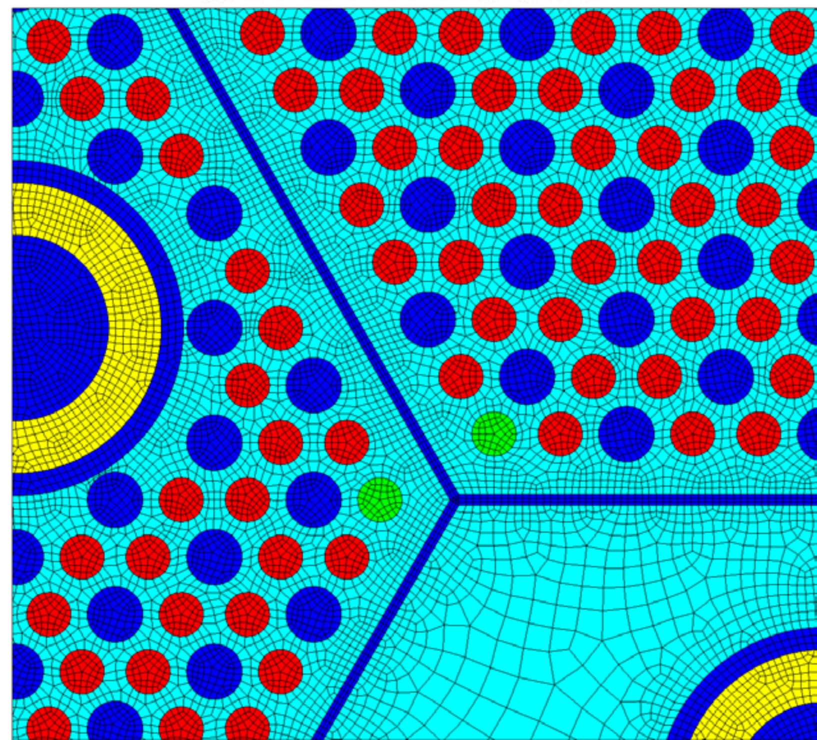
## CFD model

- Geometry includes fuel compacts, flow channels, and bypasses through gaps
- Coolant flow paths connected by common inlet and outlet plena
- 20M cells
- High-Re Realizable k-epsilon RANS

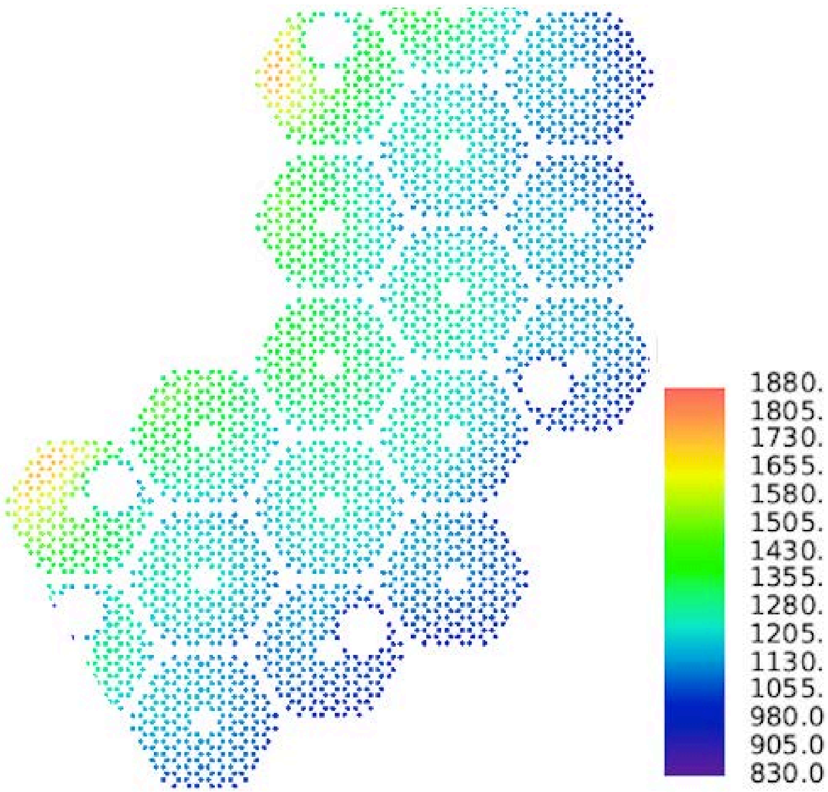


Neutronics Mesh

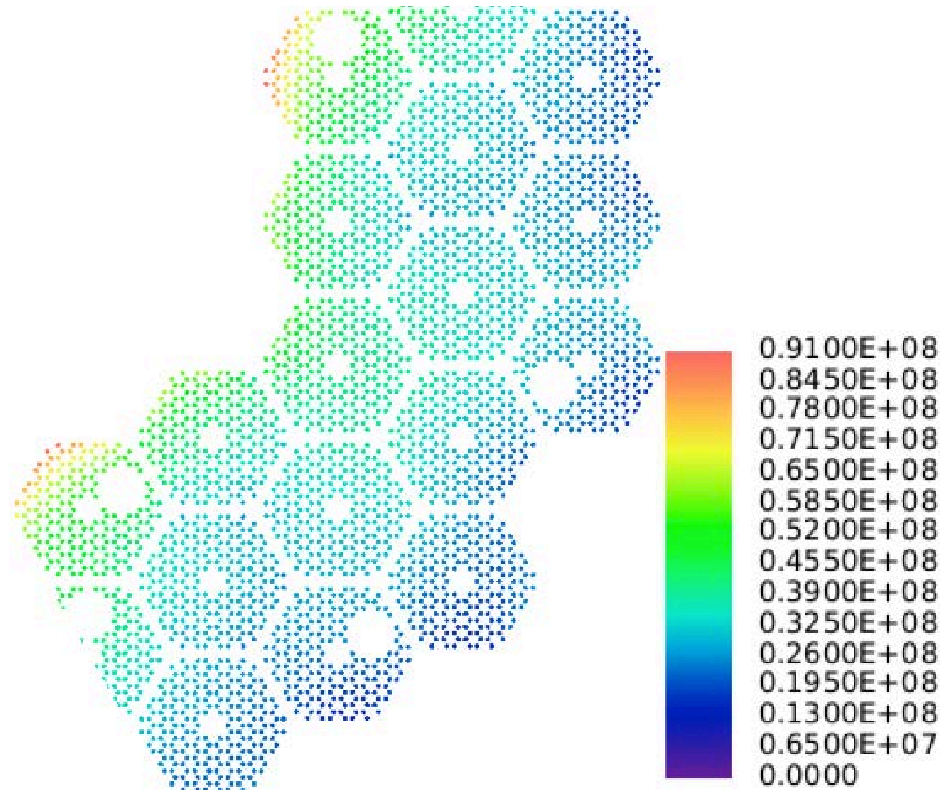
CFD Mesh



# VHTR Multi-Physics Demonstration




CFD Prediction of Temperature at Midplane




Neutronics Prediction of Heat Source at Midplane

J. W. Thomas, C. H. Lee, W. D. Pointer, and W. S. Yang, "Steady-State, Whole-Core VHTR Simulation with Consistent Coupling of Neutronics and Thermo-Fluid Analysis", Proceedings of ICAPP '10, San Diego, CA, USA, June 13-17, 2010

# Ongoing Projects

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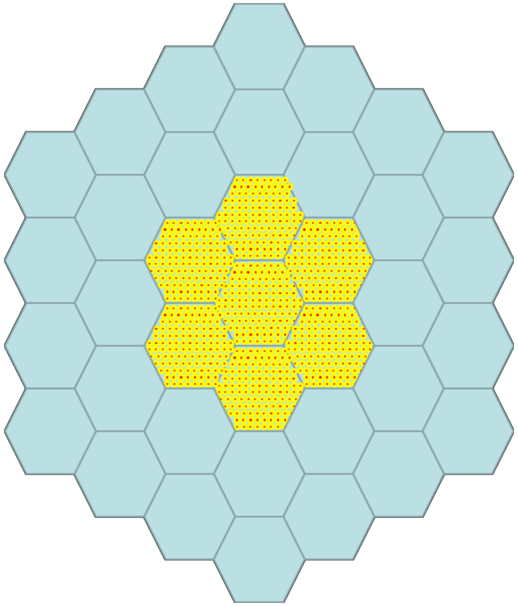
- After release of SHARP in March 2016, RPL focus shifted to assessment and V&V of its component and multi-physics analysis capabilities
  - Systematic approach for DOE-NE ART program engagement in M&S
  - Joint modeling and experiment design with ART analysts (cultivate user base)
  - Set the foundation for future work based on assessed strengths/shortcomings
- SFR challenge problems and V&V opportunities
  - Hot-channel/pin factor analysis for AFR-100
  - SHARP-zoom (analytic magnifier)
  - Coupled system-CFD analyses (to support bilaterals with Japan, France, China)
  - Wire-wrapped SFR pin bundle benchmarks (ART FOA with Areva/TerraPower, EU-Sesame, bilateral/trilateral with Japan and France)
  - Reduced-order thermal stratification modeling for SAM



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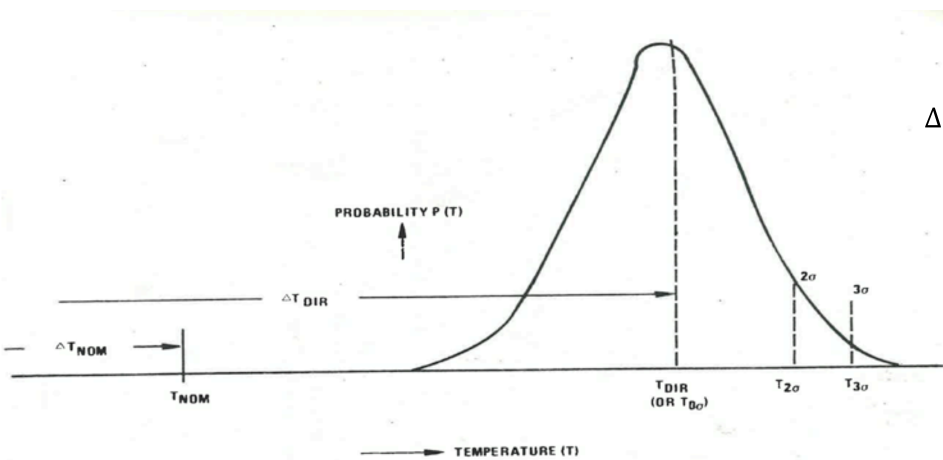
# SFR Hot Channel Factors

- Corrections of nominal values to account for uncertainties on M&S, experiments, instrumentation, manufacturing tolerance, correlations, etc.
  - J. Muraoka, et al, *Assessment of FFTF Hot Channel Factors*, HEDL-TI-75226 (**1976**)
  - F. Bard, et al, *FFTF Hot Channel Factors and Other Uncertainties Used in Safety Analysis and Life-Time Prediction for Fuel Pin Performance*, WHC-SP-0608 (**1990**) – Applied Technology
  - A. Friedland, *CRBRP Core Assemblies Hot Channel Factors Preliminary Analysis, CRBRP*-ARP-0050 (**1980**)
  - M. D. Carelli, et al, *Hot Channel Factors for Rod Temperature Calculations in LMFBR Assemblies*, Nucl. Eng. Design 62 (1980)
  - L. Briggs, *Safety Analysis and Technical Basis for Establishing an Interim Burnup Limit for Mark-V & Mark-VA Fueled Subassemblies in EBR-II*, ANL (**1995**)
  - R. Villim, *Reactor Hot Spot Analysis*, ANL, FRA-TM-152 (**1985**)
  - W. Yang, et al, *Potential Gains through Reduced Hot Spot Factors*, ANL Intra-laboratory memo (**2005**)
- Semi-statistical horizontal methods: Direct and statistical HCFs




$$\Delta T_{cool} = (\Delta T_{cool}^{nom}) \prod_{i=HCFs} DH_{cool}^{i} + \sqrt{\sum_{i=HCFs} \left(\Delta T_{cool}^{non} \times SH_{cool}^{i}\right)^2}$$

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# SFR Hot Channel Factors: Direct HCFs

| Factor | Description |
|---|---|
| Power level measurement uncertainty | • Defined as system design requirement |
| Inlet Flow Maldistribution | • Uncertainties in assembly flow distribution due to flow maldistribution in lower plenum, manufacturing tolerances in internal structures and orifice, etc. |
| Intra-assembly Flow Maldistribution | • Uncertainties of flow distribution within assembly, which are due to the simplified model and applied empirical factors of sub-channel codes. |
| Cladding Circumferential Temperature | • Due to wire-wrap, the axial velocity and temperature around a fuel pin have strongly azimuthal dependence.<br>• HCF was measured at ORNL 7 and -19 pins tests and firstly evaluated by FATH0M-360 code (NSE. 64, 1977). |
| Physics Modeling | • There are many sub-factors under this category such as flux solver approximation, 2D synthesis method), etc.<br>• In CRBR, the lumped uncertainty of the power distribution was estimated using the ZPPR mockup of CRBRP (the C/E error is about +-2% except for specific locations) |
| Control Rod Banking | • Control rods are grouped and there is manufacturing tolerance (i.e., insertion depth is not identical), which introduces asymmetric power. |

- Highlighted in yellow are targeted HCFs that will be reevaluated via high-fidelity multi-physics methods

# SFR Hot Channel Factors: Stochastic HCFs

| Factors | Description |
|---|---|
| Reactor ΔT and Inlet Temp. Variation | • Uncertainties of inlet, outlet and ΔT due to deterioration of primary components |
| Inlet Flow Maldistribution | • Uncertainties of pressure measurement, manufacturing tolerance, orifice flow rate, assembly flow rate, etc. |
| Loop Temperature Imbalance | • Loop temperature imbalance affects inlet temperature distribution.<br>• CRBR allows cold leg loop-to-loop temperature imbalance of 34 F, which results in 4.9 F (2-sigma) uncertainty in inlet temperature |
| Wire Wrap Orientation | • Analyzed by sub-channel code, COTEC, which is 1% uncertainty |
| Subchannel Flow Area | • Uncertainties of rod dimension tolerance, bow, etc. |
| Film Heat Transfer Coefficient | • Uncertainties of correlation, etc. |
| Cladding thickness and conductivity | • Uncertainties of correlation, etc. |
| Coolant Properties | • Uncertainties of correlation, etc. |
| Intra-assembly flow maldistribution | • Flow and temperature distributions were calculated using sub-channel code of COBRA, COTEC, and THI-3D. |
| Nuclear Data | • Evaluation nuclear data library uncertainties |
| Criticality | • Control rod depth error due to uncertainty in the prediction of criticality |
| Fissile Maldistribution | • Fuel manufacturing uncertainties |
| Fuel Thermal Conductivity | • Uncertainties due to pellet diameter, fresh and irradiated fuel conductivity, porosity of swollen fuel, redistribution, etc. |
| Power level measurement | • Instrument uncertainties (flow rate, temperature, etc.) and control systems. |

# SFR Hot Channel Factors: Impact on MW Temperature

- **Potential impact of improved HCFs on peak mid-wall temperature estimation using CRBR HCFs, assuming:**
  - No uncertainties on direct HCFs when they are evaluated via SHARP simulations
  - 50% reduction of statistic HCFs when they are evaluated via SHARP simulations

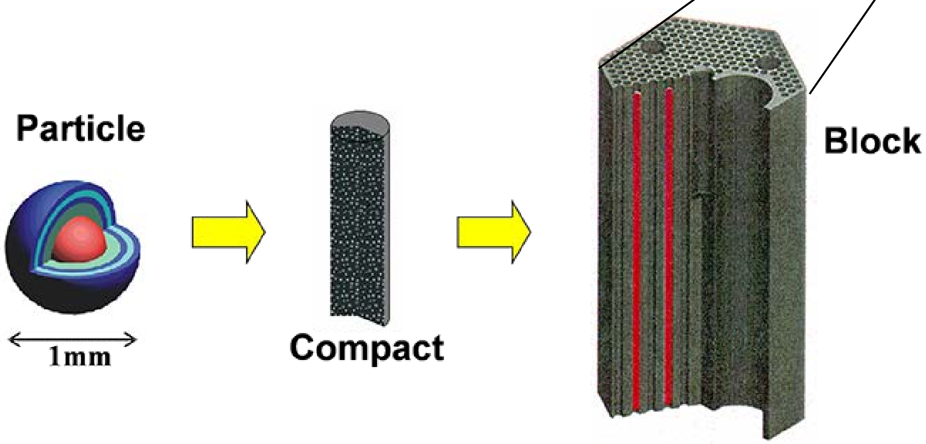
**For AFR-100, 17°C MW temperature drop (5-7% power increase)**

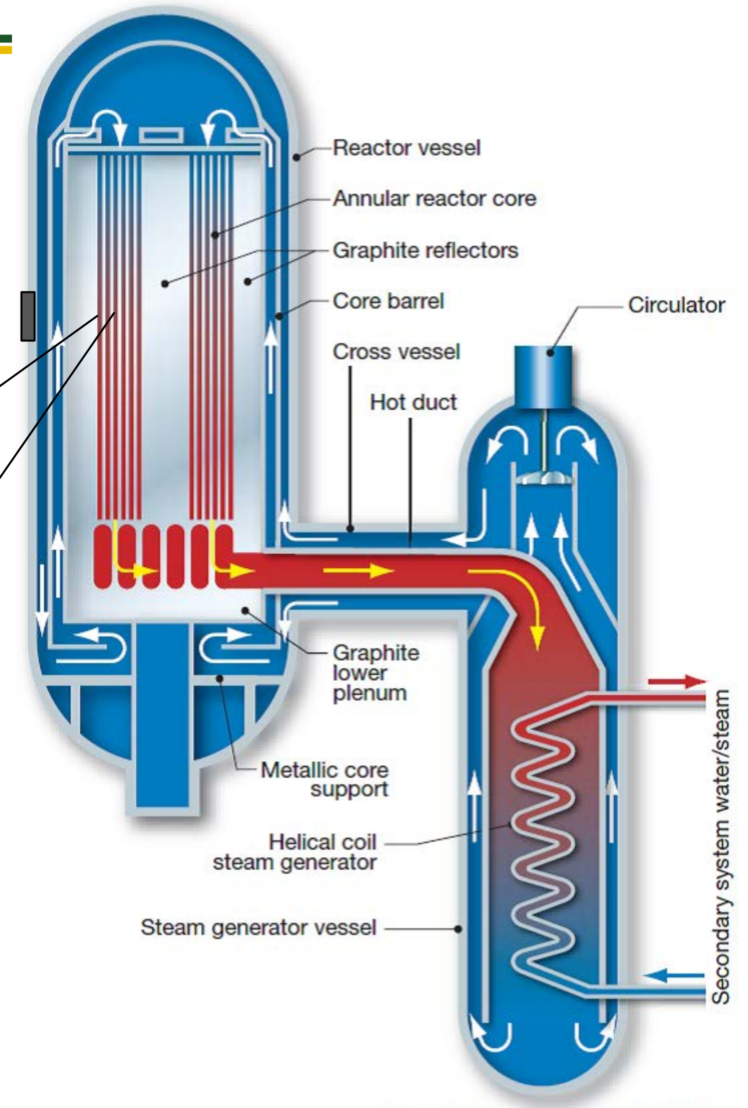
| Factors | | Coolant | Film | Clad | Peak MW Temperature |
|---|---|---|---|---|---|
| Inlet coolant temp. °C | | 395.0 | | | |
| Nominal temperatures at peak MW temperature, °C | | 566.1 | 570.0 | 581.1 | 581.1 |
| CRBR HCFs | Direct, °C | +198.3 | +10.9 | +11.7 | 632.4 |
| | Statistical (2σ) | | 21.6 | | |
| With improved CRBR HCFs (tentative) | Direct, °C | +188.7 | +4.7 | +13.3 | 615.1 |
| | Statistical (2σ) | | 18.4 | | |

# Planned activities: HTGR Challenge Problems

**Steam Cycle HTR Primary Circuit Layout**

- Core Power (200-600 MWt)
- Coated particle (TRISO) fuel embedded in graphite blocks (or pebbles)
- Helium coolant at ~4-7MPa –forced convection under normal ops




*(1 of 2 steam generators shown)*

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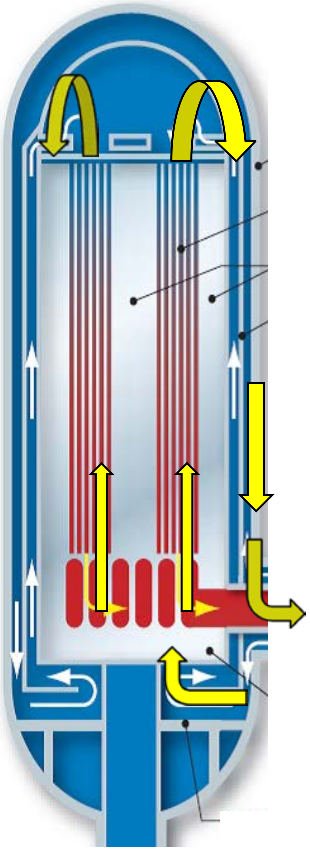
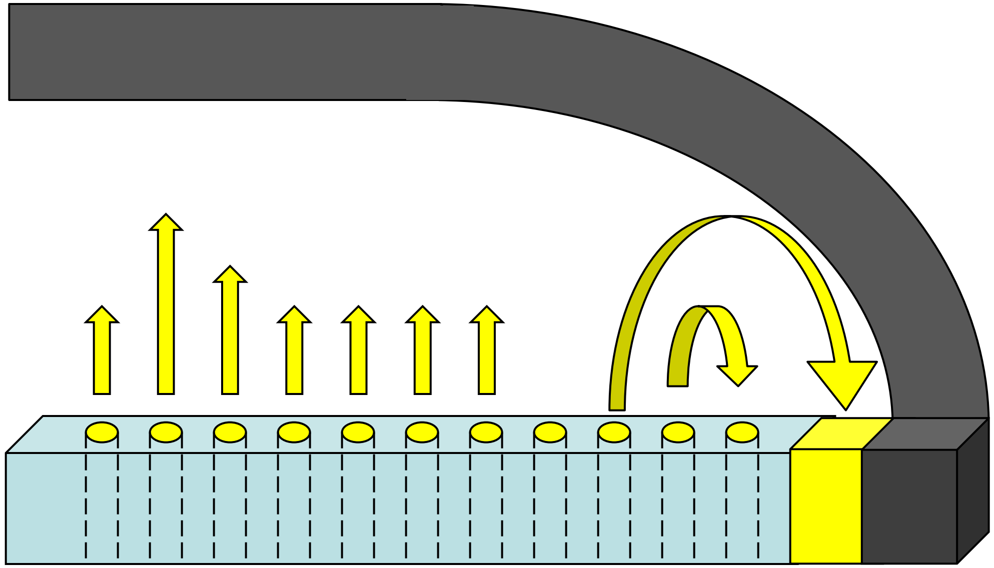
# HTGR Challenge Problems (cont.)

## Buoyancy-driven Core Channel-to-Plenum Flow Mixing

- Blower trip leads to loss of forced flow through core
- Buoyancy drives natural circulation through channels and riser
- Flow can be complex, unstable, and may, if unmitigated, lead to hot plumes impinging on upper plenum structures (fuel integrity is not threatened)
- Objective: Investigate the sensitivity of the plenum flows to channel geometry, number of channels, heating profiles, etc.





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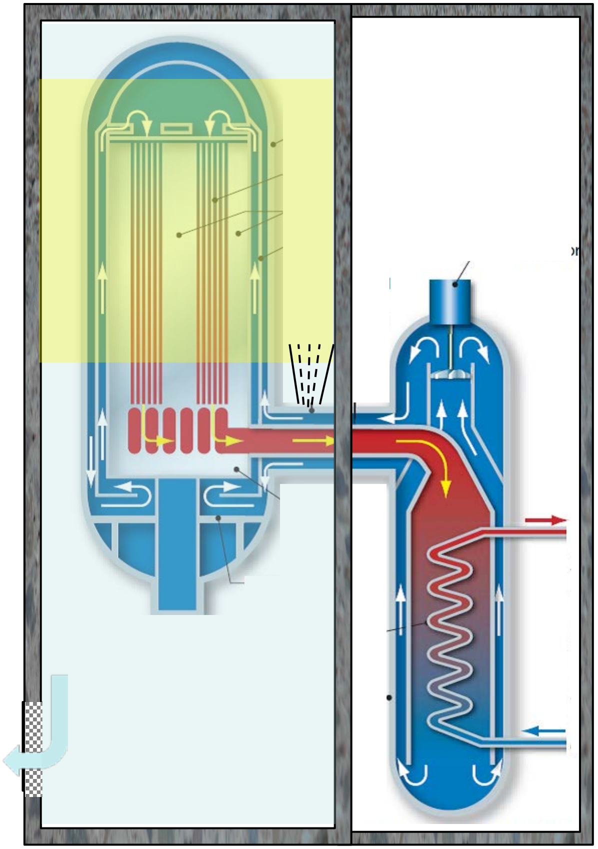
# HTGR Challenge Problems (cont.)

## Break in primary boundary

- Leak or break leads to depressurization
- Helium displaces air; air may leak into the RPV, causing erosion of graphite (oxidation)
- Objective:  Investigate mixing of helium and air in the cavity and the extent to which air can enter the RPV



## Performance of Reactor Cavity Cooling System

- RCCS rejects parasitic heat losses and decay heat to the atmosphere
- Water-based systems exhibit complex flow behavior including boiling
- Objective: Investigate fluid-structure interactions and the sensitivity of fluid behavior to the number of riser channels per chimney



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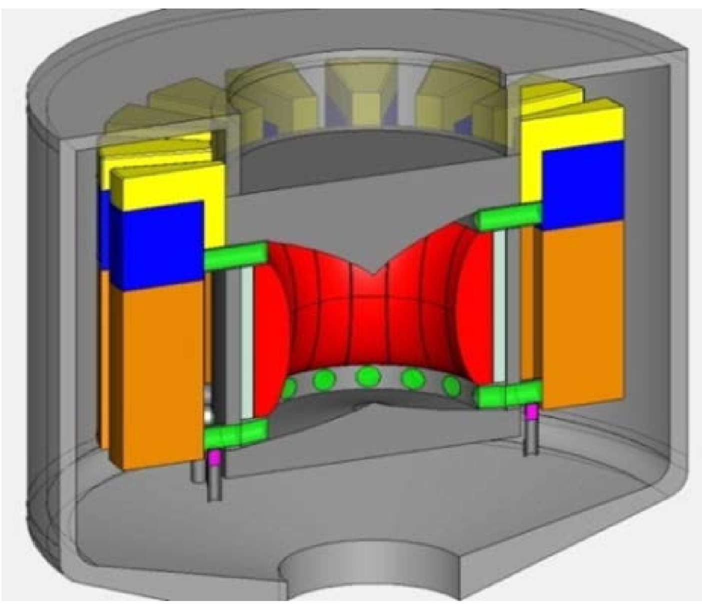
# Planned activities: MSR Challenge Problems

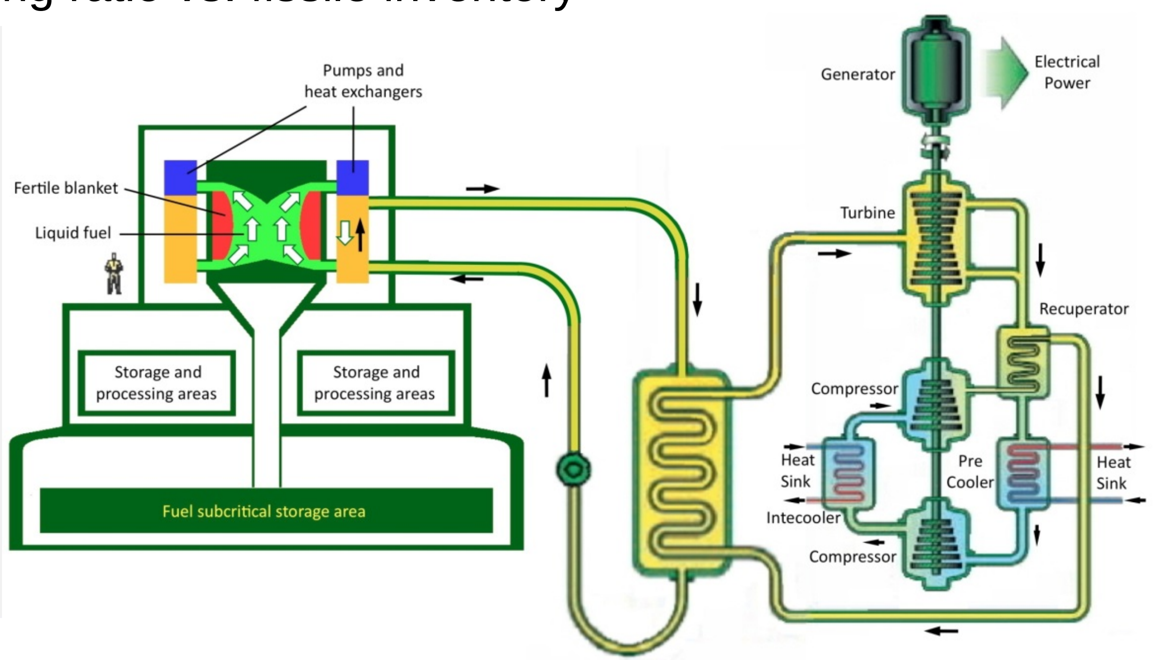
MSR designs with dissolved fuel have unique M&S needs that may not be met with systems analysis codes alone

- Heat is produced directly in the “coolant”
- Unique design with fuel circuit, an intermediate circuit, and the power conversion system
- Unique core configurations with potential recirculation and stagnation zones
- Reactivity management challenges (fissile/fertile inventory, sensitivity to local minor density variations in MSFR)
- Fission product/gas management, potential for online reprocessing
- No control rods in the core
  - Reactivity control by the IHX heat transfer rate, fuel-salt feedback coefficients, continuous fissile loading, and the core geometry
  - No requirement for controlling the flux shape
- Quick reconfiguration of the core geometry (gravitational draining) for passive safety

# MSR Challenge Problems (cont.)

- Design and fissile inventory optimization (power vs. fuel salt volume and core geometry)
- Multi-physics modeling of thermo-chemico-fluid dynamics
- Limiting factors:
  - Heat exchanger capacity
  - Irradiation damage to the structural materials
  - For fast spectrum, breeding ratio vs. fissile inventory

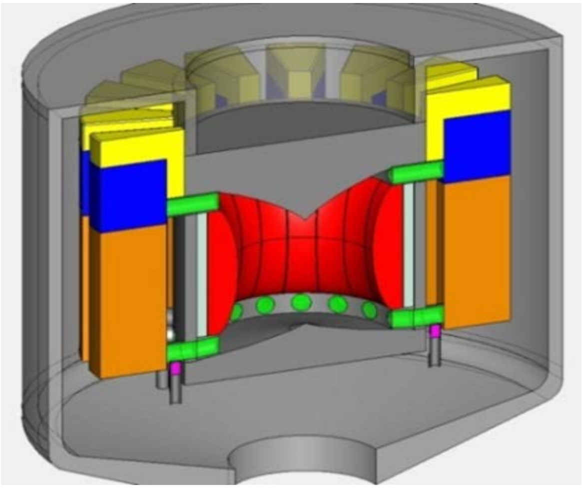


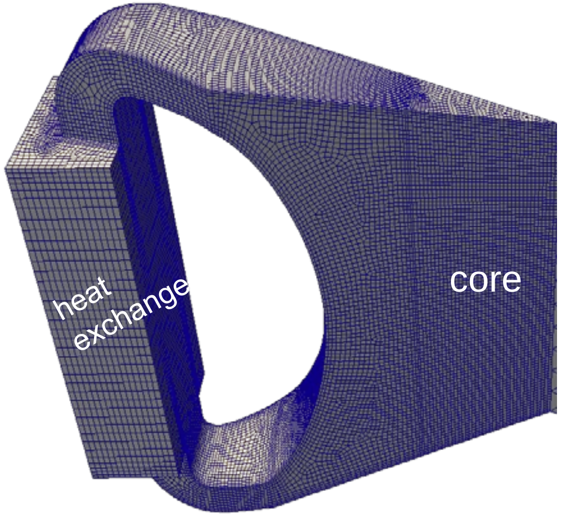


# MSR Challenge Problems (cont.)

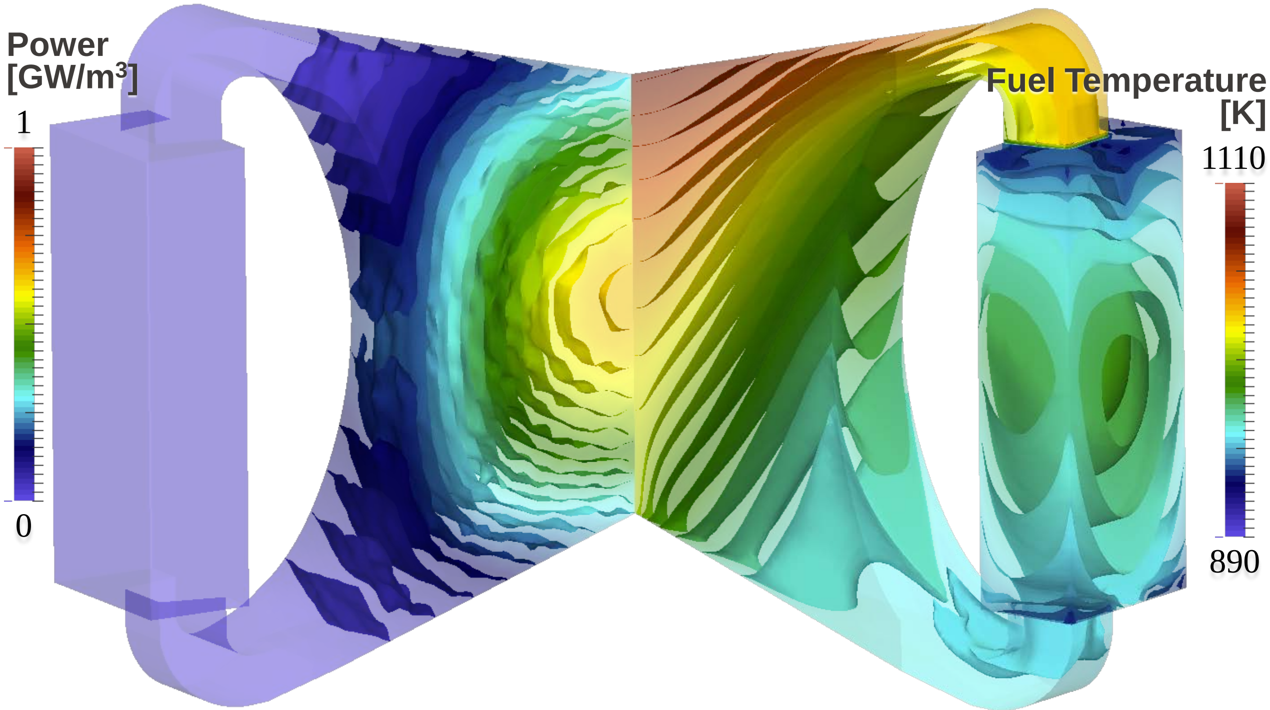
- Opportunities to leverage SHARP toolkit for MSR M&S: Coupled neutronics + thermal-hydraulics simulations
  - High-fidelity, high-resolution T&H modeling for flow and temperature distributions using CFD
  - $MC^2$-3 for thermal and fast fission cross sections
  - PROTEUS for neutronics with full-spatial resolution of potentially complex core geometry
  - REBUS or ORIGEN to support depletion analysis toward an equilibrium cycle
  - PERSENT for calculation of kinetic parameters and reactivity feedback
    - Delayed neutron source
    - Doppler feedback effect
    - Density feedback effect
  - System Analysis Module (SAM) for the intermediate circuit and power conversion system response.

# MSR Challenge Problems (cont.)






Results for CEA Samofar MSFR design using coupled Monte-Carlo and OpenFoam codes (http://samofar.eu/project)



# MSR Challenge Problems (cont.)

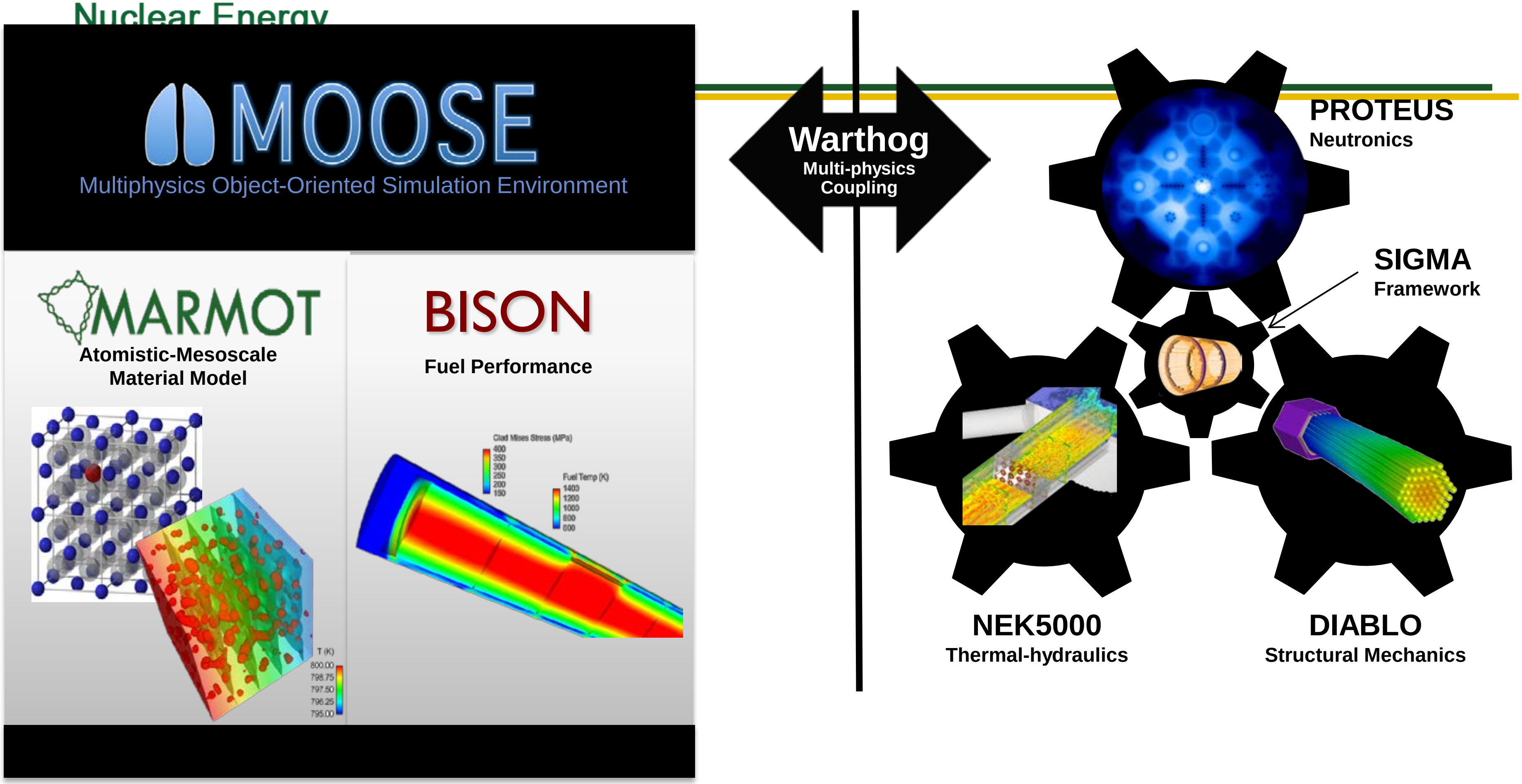
Potential support for MSR accident analysis needs:

- Fuel circuit accidents
  - Loss of Heat Sink
  - Loss of Fuel Flow
  - Station blackout
  - Overcooling
  - Reactivity anomalies
- Draining system accidents (draining blockage)
- Balance of plant upsets
  - Steam generator tube rupture

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

# Overview of Warthog

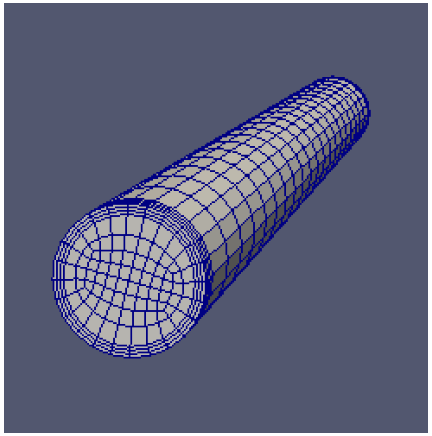



Warthog serves to couple tools in the SHARP suite with those using the MOOSE Framework

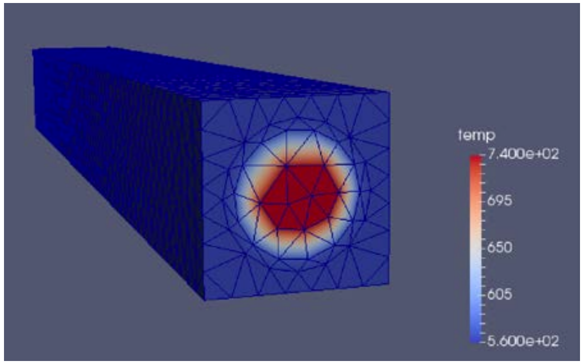
NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

# Status on Warthog

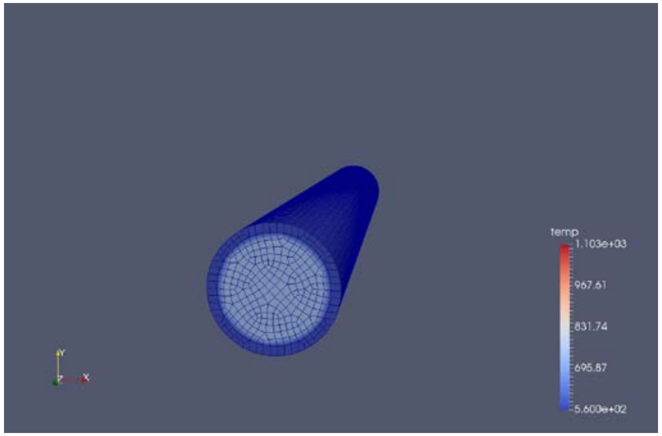
- **Currently supports PROTEUS -> BISON coupling**
  - Pin cell coupling has been demonstrated
  - Assembly model work ongoing



BISON Mesh




PROTEUS Mesh
with Initial Temp.




Temperature from BISON
over one hour

# Summary

- SHARP leverages advanced single-physics computational tools to solve multiphysics problems in a manner closer to first-principles
  - Provide insight into core/component design that can't be easily measured or accounted for with conventional tools/methods
- Aims is to capture the integral effects with multiresolution when the system codes provide information on key parameters with large uncertainty
  - Thermal-stratification in upper plena
  - Thermal-striping leading to thermal fatigue induced failures
  - Thermo-structural analysis of primary coolant boundary during accidents
  - Flow-induced vibrations
- High-fidelity multiphysics approaches are of interest for mature concepts to support commercial deployment
  - System codes coupled with appropriate sub-grid physics or higher-fidelity tools can also meet the needs of an advanced concept (next presentation)