Multiphysics Simulations for Heat Pipe Cooled Micro Reactors Using PRAGMA – OpenFOAM – ANLHTP

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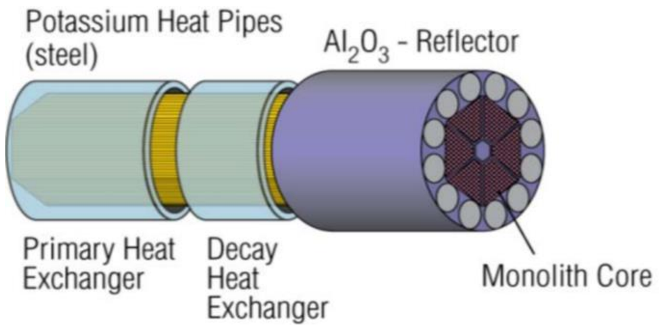
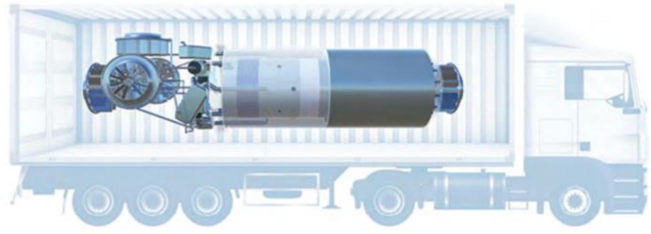
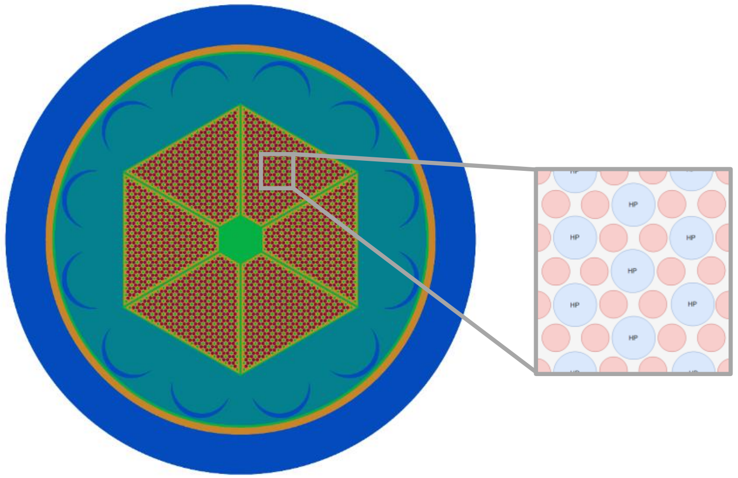
Contents

- **Heat Pipe Cooled Micro Reactor**
  - **Advantages**
    - Compact design and mobility with easy installation
    - Enhanced system reliability and safety
    - Passive decay heat removal system using heat pipe without power
  - **Geometrical specifications**
    - A solid-state core structure where fuel rods and heat pipes are irregularly inserted in stainless steel monolith

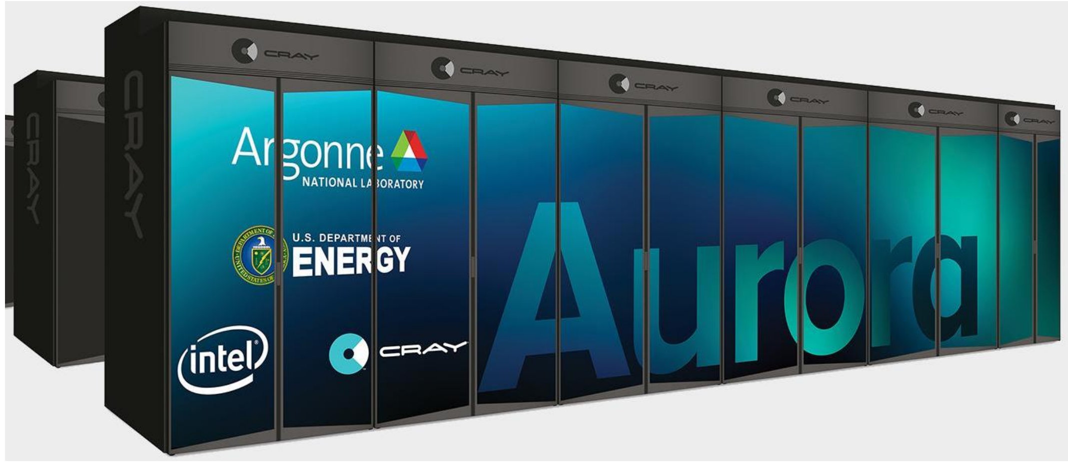




- **Key Characteristics of HPRs**
  - **Thermal stress**
    - Due to compact arrangement of fuel rods and heat pipes
  - **Passive self-regulation by reactivity feedback**
    - Due to thermal expansion of the solid-state core
  - ➢ **Need for high fidelity multiphysics simulation of heat pipe cooled reactor with thermo-mechanical solver**



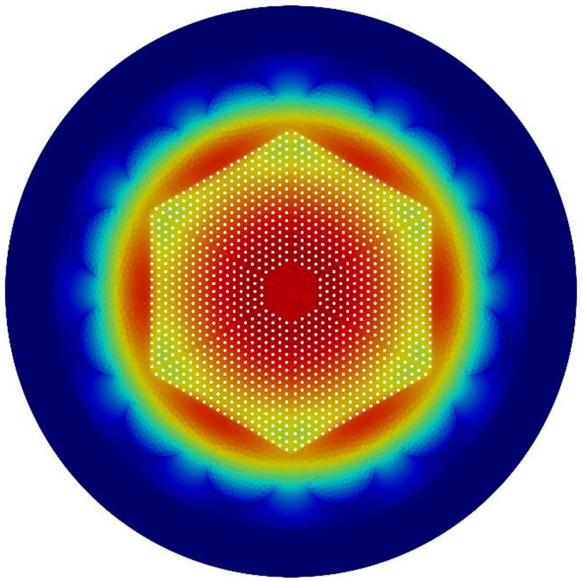
- **Previous Researches on Multiphysics Analysis for HPRs**
  - **Deterministic approach (Method of Characteristics, S_N)**
    - DireWolf in MOOSE framework[1)], PROTEUS-FLUENT-ANLHTP[2)]
  - ➢ **Necessity to employ HPC resources over tens of thousands of cores**
  - **Stochastic approach (Monte Carlo with CSG representation)**
    - RMC-ANSYS[3)] from Tsinghua University
  - ➢ **Absence of MC Solutions directly coupled with thermomechanics**

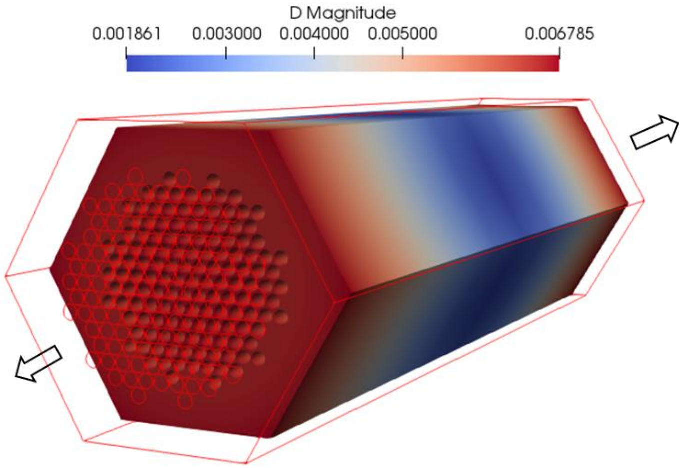


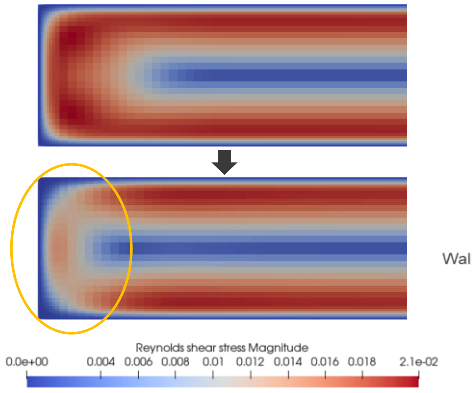
1) C. Matthews et al., “Coupled Multiphysics Simulations of Heat Pipe Microreactors Using DireWolf,” Nuclear Technology (2021).
2) C. H. Lee et al., “Micro Reactor Simulation Using the PROTEUS Suite in FY19,” ANL/NSE-19/33 (2019).
3) Y. Ma et al., “Coupled Irradiation-Thermal-Mechanical Analysis of the Solid-Sate Core in a Heat Pipe Cooled Reactor,” Nuclear Engineering and Technology (2022).

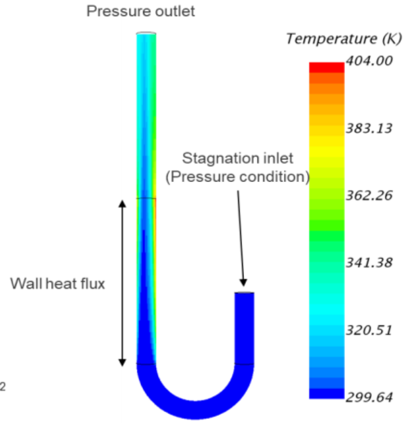
Statement of Research Purpose

- **SNURPL – NuTHEL Joint Research Project**
  - **Title : Development and Validation of Thermal Analysis Methodology for Heat Pipe Cooled Micro Reactor**
  - **Period : 2020.04 – 2024.12 (57 Months)**
  - **Main Objectives :**
    - ➢ Establishment of neutronics – thermo-mechanical – heat-pipe coupled multiphysics analysis system
    - – Development of heat pipe cooled micro reactor core thermal analysis code
    - – Validation of developed code through heat pipe – monolith heat transfer experiment









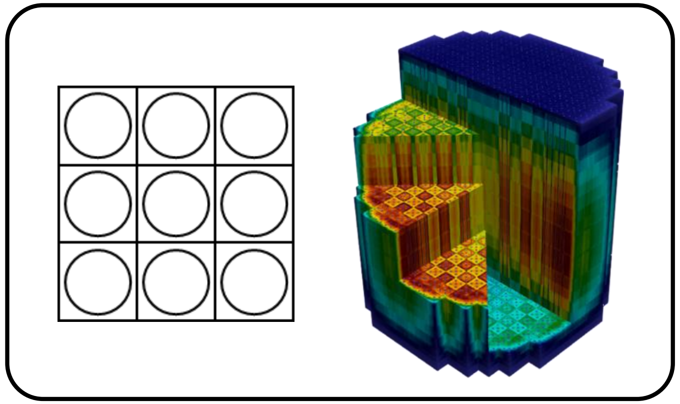
PRAGMA for Advanced Reactors

- PRAGMA: GPU-Based Continuous Energy MC Code
- Unstructured Mesh Representation
- Graphics Ray Tracing for Neutron Transport

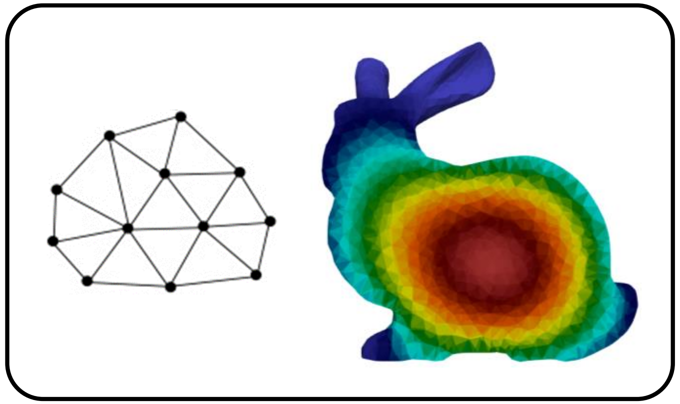
PRAGMA: GPU-Based Continuous Energy MC Code

- **PRAGMA Power Reactor Analysis using GPU-based Monte Carlo Algorithm**
  - **Development funded by the Korea Hydro & Nuclear Power company.**
  - **Written in modern CUDA C++ with the consideration of GPU acceleration from the very base of the code.**
  - **Employs specialized geometry module and schemes for commercial PWR analysis and realizes massive particle simulations with practical time and resources by exploiting the exclusive computing power of GPUs.**
    - Spent less than 10 minutes for over 10 billion particles simulation of APR1400 3D full-core analysis.
    - Completed BEAVRS two-cycle depletion calculation with half a trillion histories in total within a day.
  - **Supports general unstructured mesh geometry module powered by graphics ray tracing technology.**
    - Dedicates to advanced reactor applications including complex shapes.
    - Enables efficient neutron transport simulation on GPUs by leveraging hardware acceleration of the optimized ray tracing algorithm.
    - Attains feasibility for explicit geometry deformation coupled with finite element-based structural analysis codes.

PWR Lattice Geometry

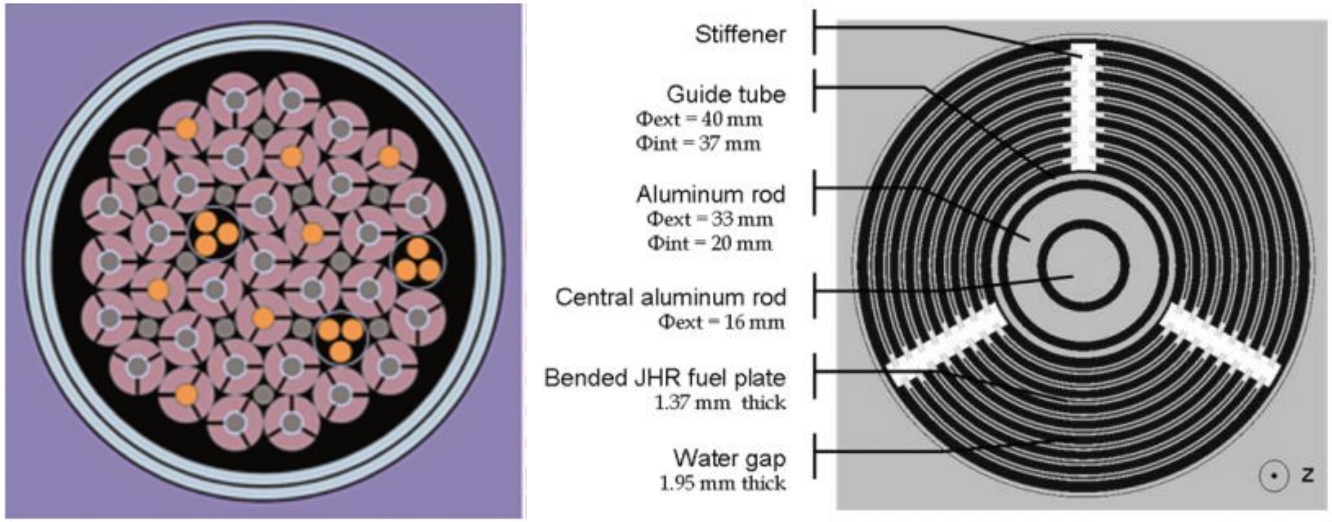


Unstructured Mesh Geometry

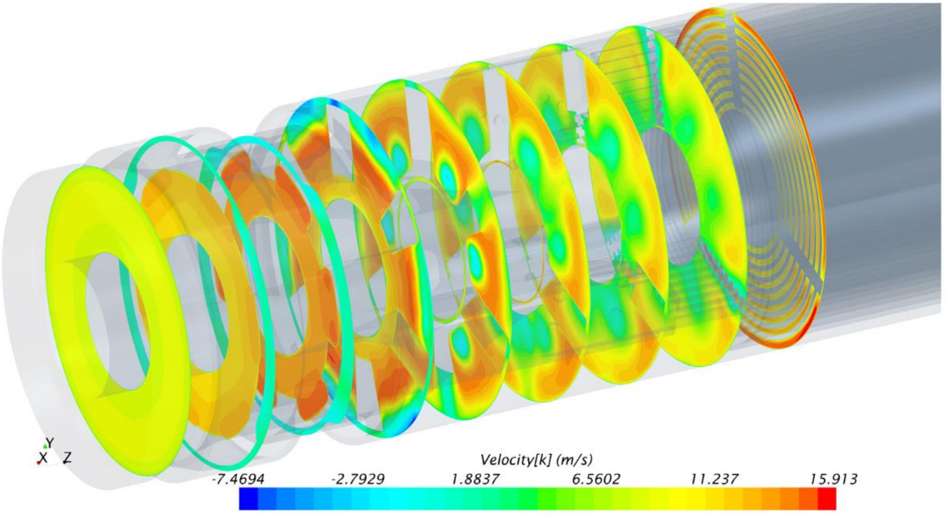


- **Need for Unstructured Mesh Treatment**
  - Future reactors are increasingly going multipurpose, and the reactor designs are becoming irregular.
  - To perform multi-physics simulations of such irregular reactors, coupling with CFD and structural analysis codes are inevitable.
  - CFD and structural analysis codes typically employ finite element methods embedded in unstructured meshes.

Jules Horowitz Reactor (JHR)

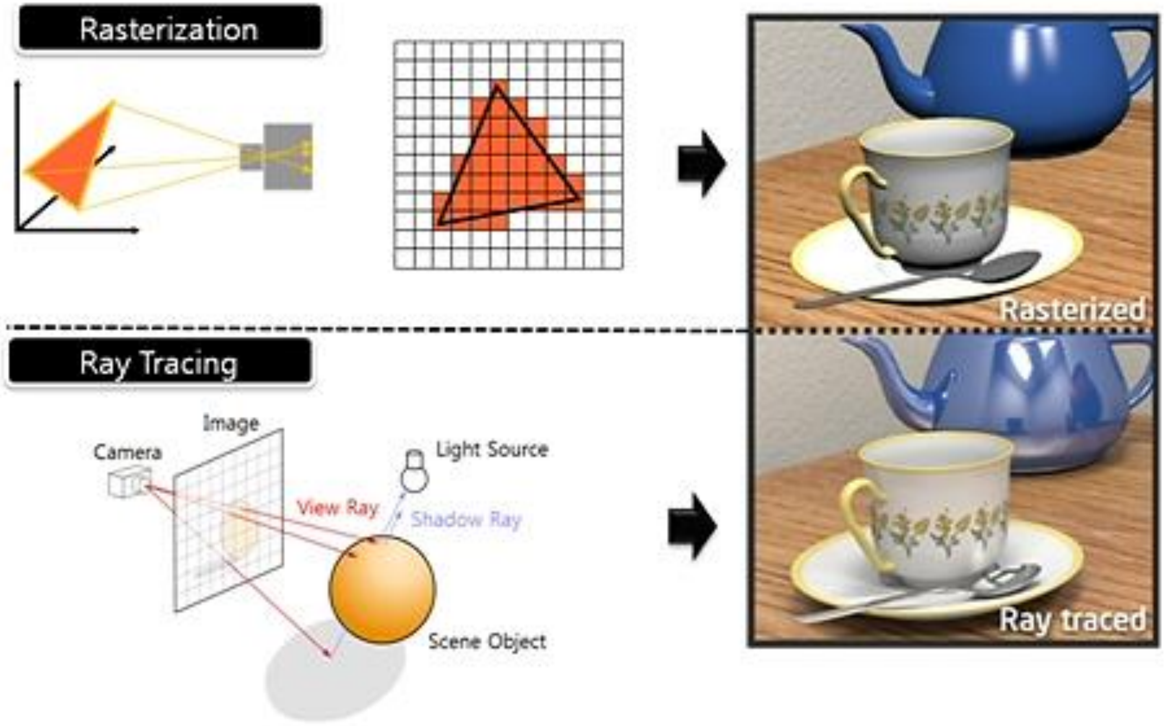


CFD Analysis of JHR Fuel Element



R. Pegonen et al., "Hot Fuel Element Thermal-Hydraulics in the Jules Horowitz Reactor," Nuclear Engineering and Design 300 (2016).

- **Graphics Rendering Techniques: Rasterization vs Ray Tracing**
  - **Rasterization : takes a vector graphics image and projects it into a pixel image.**
  - **Ray tracing : simulates actual light rays using an algorithm to trace the path that a beam of light would take in the physical world.**
  - **Rasterization is fast but does not prescribe a particular way to compute the color of pixels, so it cannot take physical light into account.**
    - Additional illumination techniques are used, which are only approximate.
  - **Ray tracing is computationally intensive but is capable of simulating a variety of optical effects, so it is being increasingly utilized with the advances of hardware.**

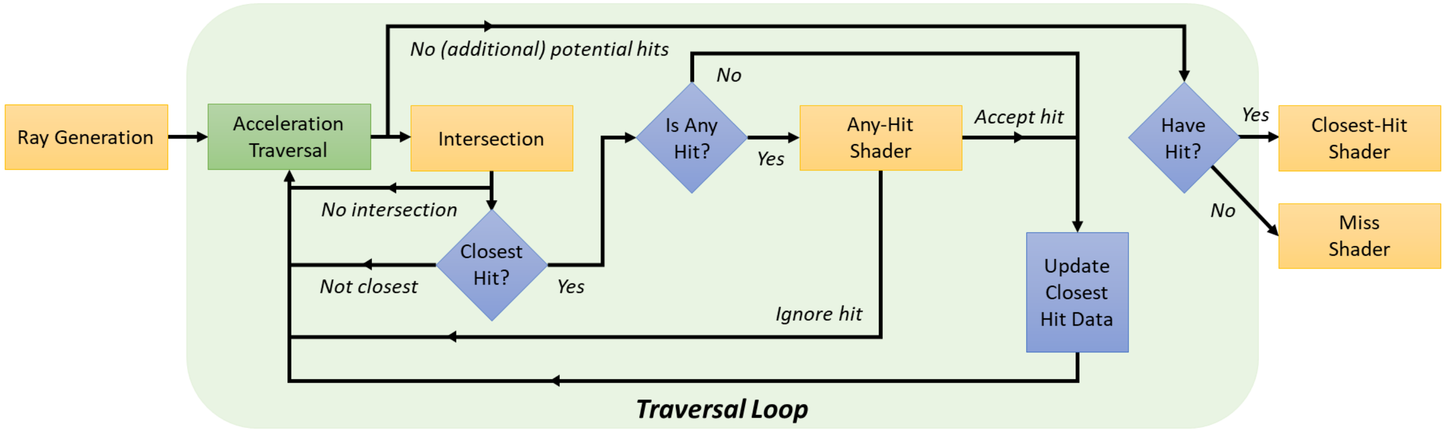


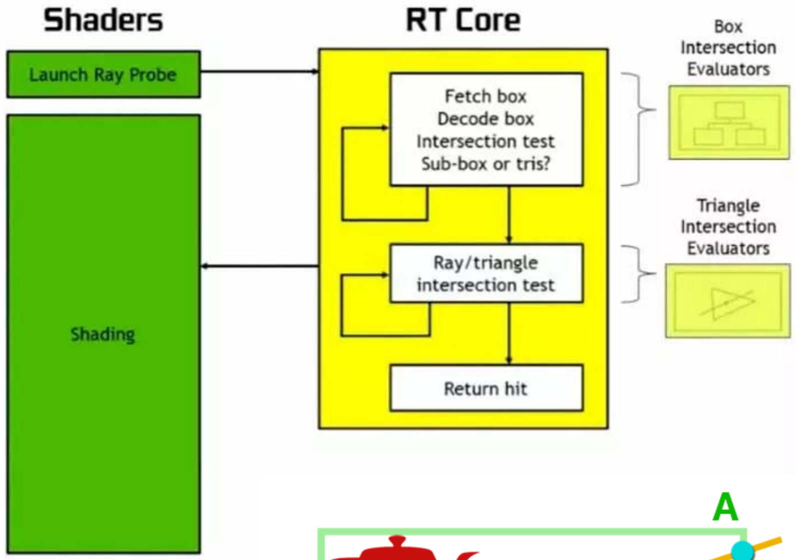
- **Ray Tracing for Neutron Transport**
  - **Any physical wave or particle phenomenon with linear motion can be simulated with ray tracing.**
  - **Ray tracing can be utilized in DTS calculation and cell search in the MC neutron transport.**

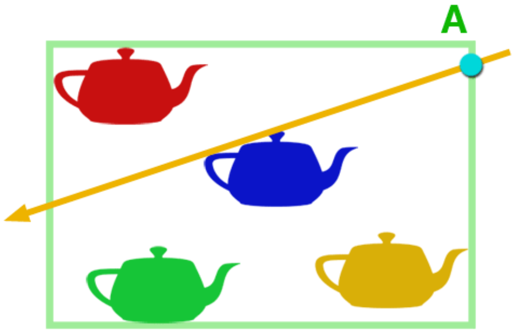
- **NVIDIA OptiX Ray Tracing Engine**
  - **A CUDA-centric ray tracing API optimized for NVIDIA GPUs.**
  - **Provides a programmable ray tracing pipeline allowing a user to create a custom ray tracing kernel.**
    - Bounding Volume Hierarchy (BVH) traversal is automated by the library, while other programs are user-supplied.
  - **For triangles, an optimized built-in ray tracing algorithm is provided.**
    - Leverages the hardware acceleration of NVIDIA GPUs (RT cores).

NVIDIA OPTIX™

NVIDIA GEFORCE® RTX







Heat Pipe Micro Reactor Analysis

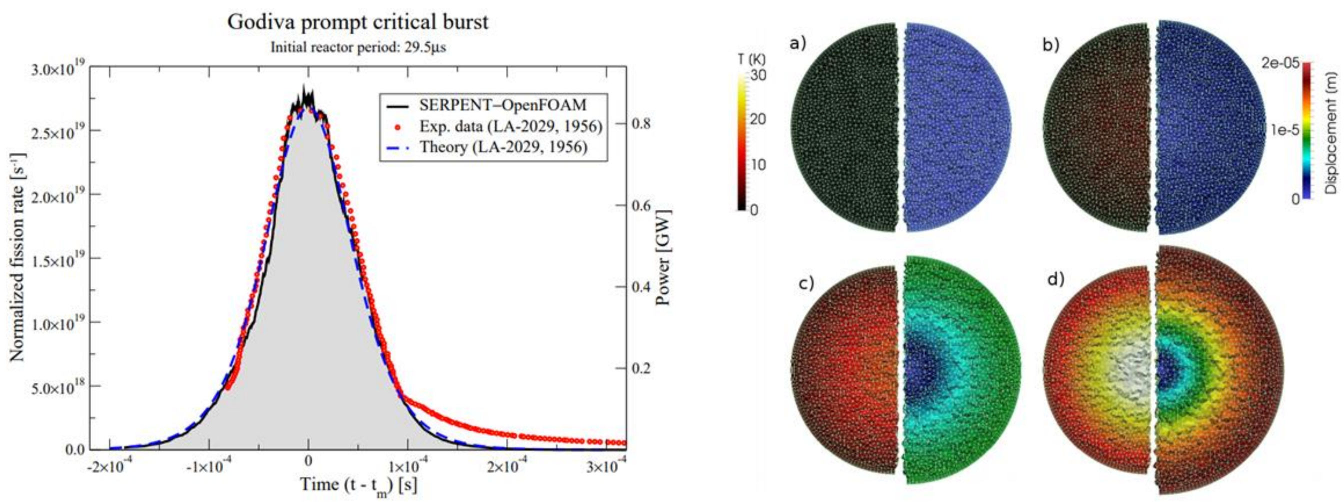
- PRAGMA – OpenFOAM – ANLHTP Coupling
- Demonstration of Multiphysics Simulation

PRAGMA – OpenFOAM – ANLHTP Coupling

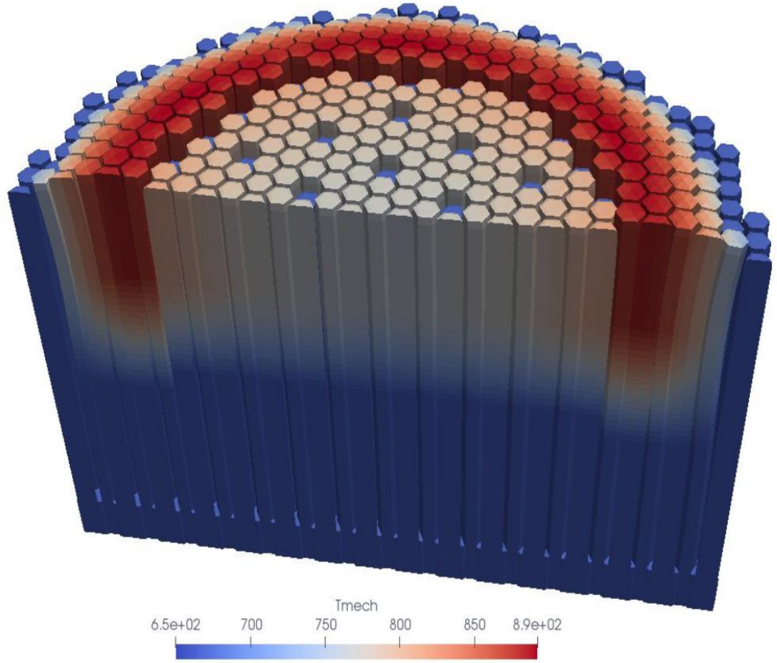
- **OpenFOAM : Thermo-Mechanical Analysis Code**
  - **Free, open-source CFD software developed by OpenCFD.**
  - **Extensive range of features to solve anything from complex fluid flows involving heat transfer to solid mechanics.**
  - **Employs a modified stress analysis solver based on solid mechanics solver of OpenFOAM official version.**

OpenFOAM®

Serpent-OpenFOAM Coupling Transient Analysis[1)]



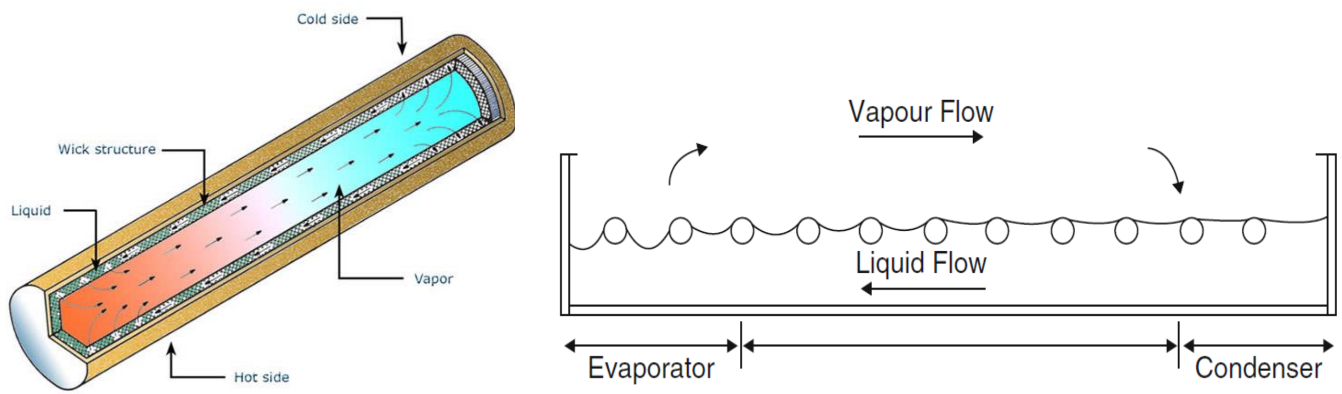
Gen-FOAM ESPR Thermal Deformation Simulation[2)]



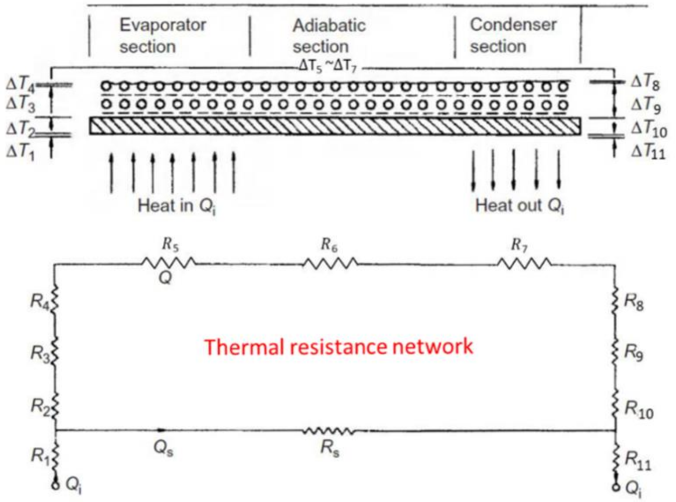
1) M. Aufiero et al., “Serpent–OpenFOAM coupling in transient mode: simulation of a Godiva prompt critical burst,” M&C (2015).
2) C. Fiorina et al., “Gen-Foam: a novel OpenFOAM® based multi-physics solver for 2D/3D transient analysis of nuclear reactors,” Nuclear Engineering and Design (2020).

- **ANLHTP : Heat Pipe Thermal Analysis Code**
  - **One-dimensional heat pipe analysis code developed by Argonne National Laboratory in the 1980s**
  - **Simulate a single sodium heat pipe employing a thermal resistance network model.**
    - Assume that the evaporator and condenser are nearly isothermal.
    - Neglect axial heat conduction along the heat pipe wall or wick.
  - **Predict heat pipe temperature distributions for steady-state and slow transient conditions.**

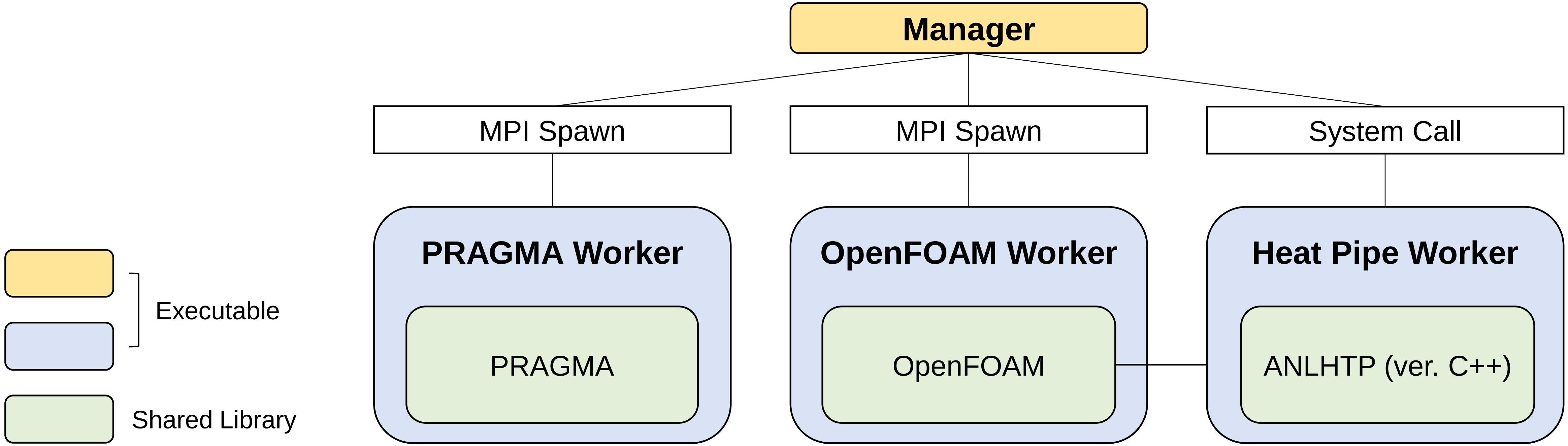
Passive Heat Transfer Mechanism of Heat Pipe



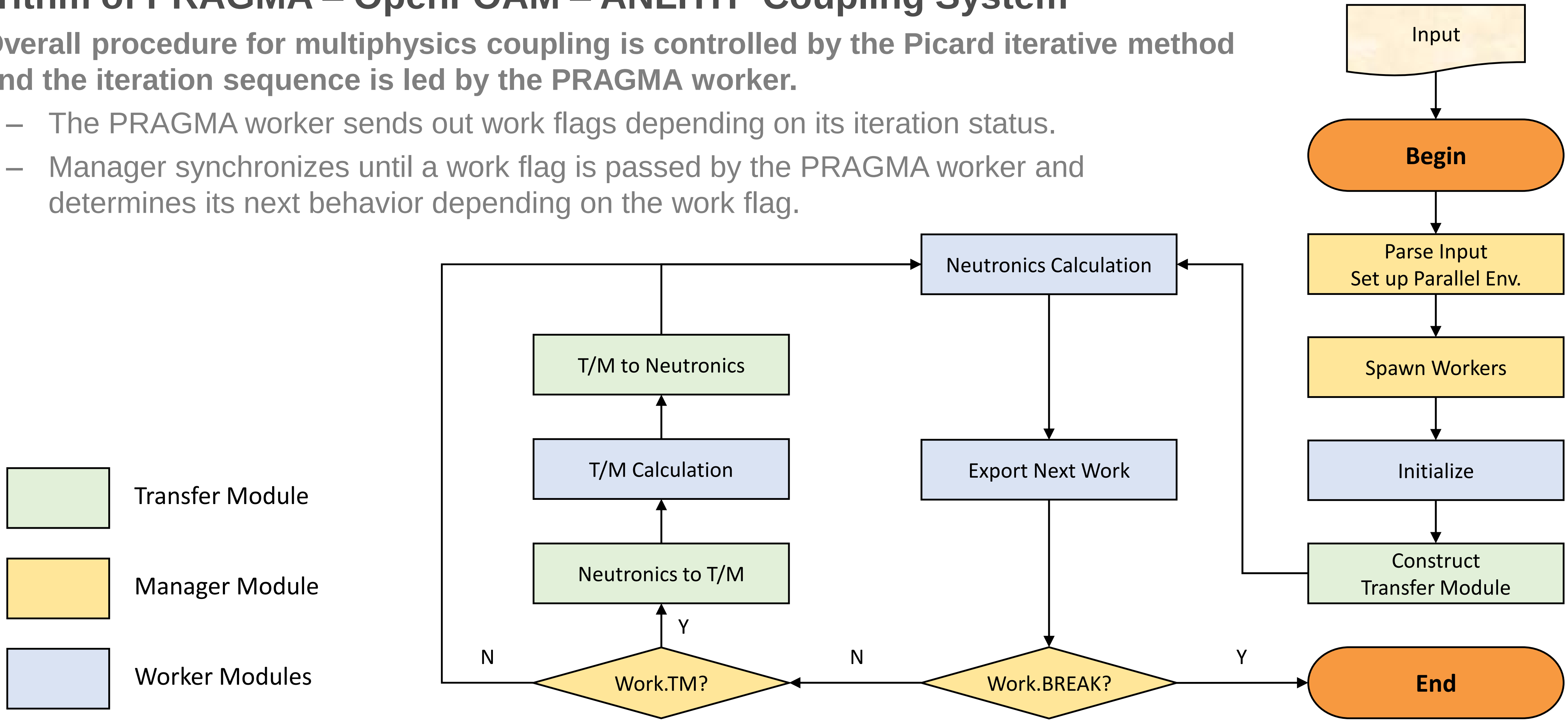
Thermal Resistance Network of ANLHTP



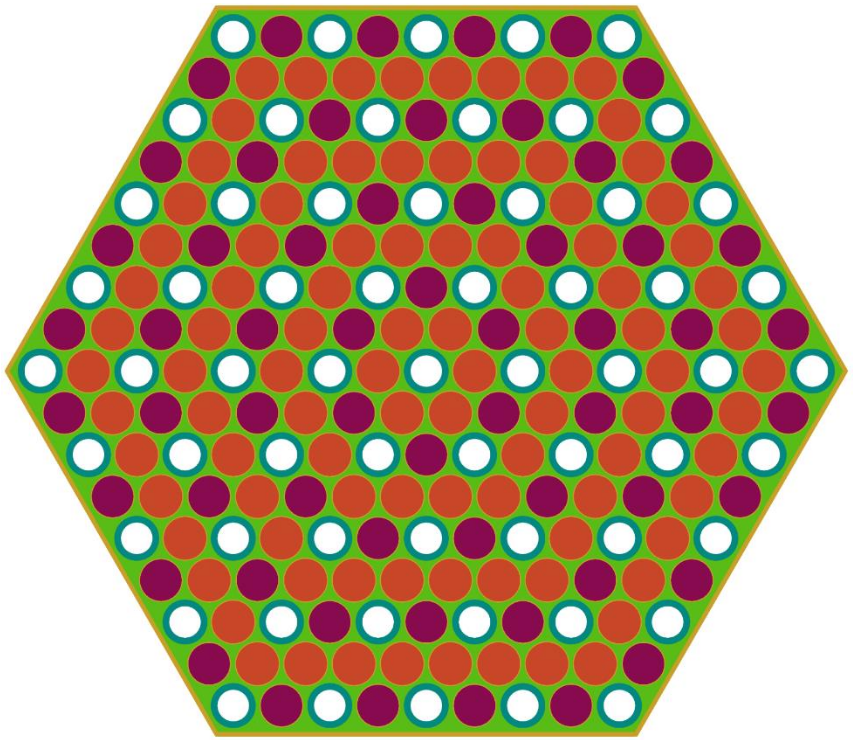
- **PRAGMA – OpenFOAM – ANLHTP Coupling**
  - **PRAGMA and OpenFOAM employ different MPI parallelization schemes, and thus the coupling is achieved using the MPI DPM model.**
    - A single manager program is executed with ordinary MPI job launch scheme, which spawns both PRAGMA and OpenFOAM with appropriate MPI launch parameters for each code.
    - Heat Pipe worker for OpenFOAM – ANLHTP coupling is run in background by a system call of the manager.

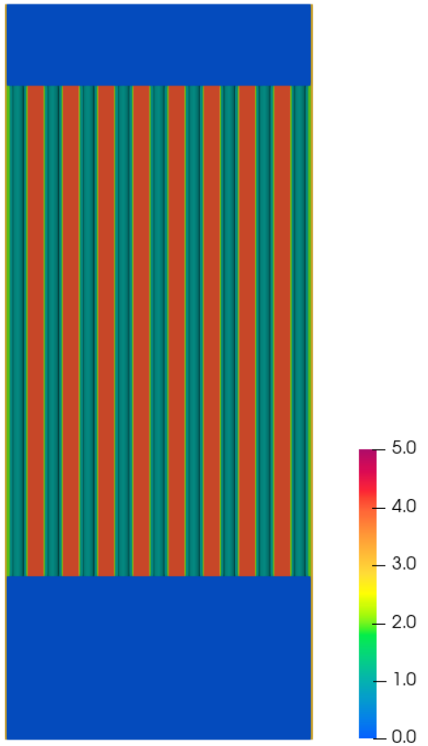


- **Algorithm of PRAGMA – OpenFOAM – ANLHTP Coupling System**
  - **Overall procedure for multiphysics coupling is controlled by the Picard iterative method and the iteration sequence is led by the PRAGMA worker.**
    - The PRAGMA worker sends out work flags depending on its iteration status.
    - Manager synchronizes until a work flag is passed by the PRAGMA worker and determines its next behavior depending on the work flag.



- **Empire 3D Assembly Benchmark**
  - Problem configuration (Material-wise)



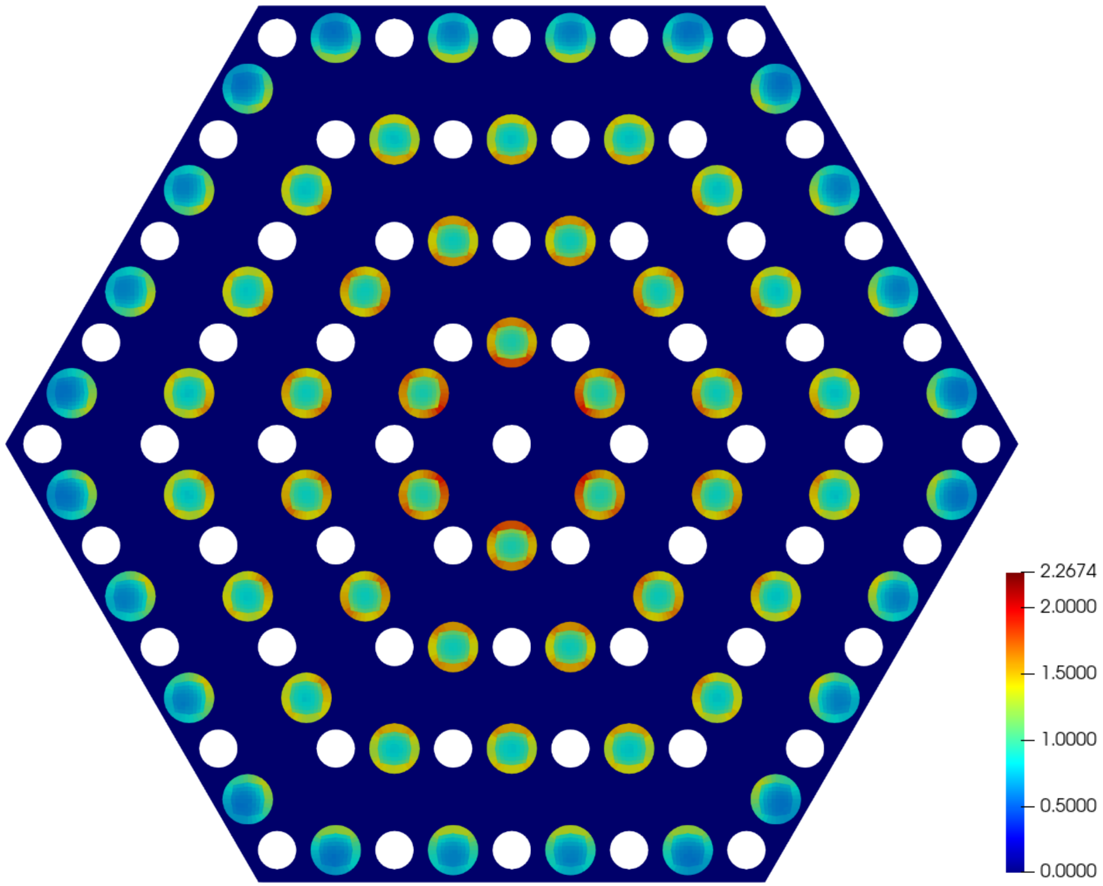


  - Calculation conditions

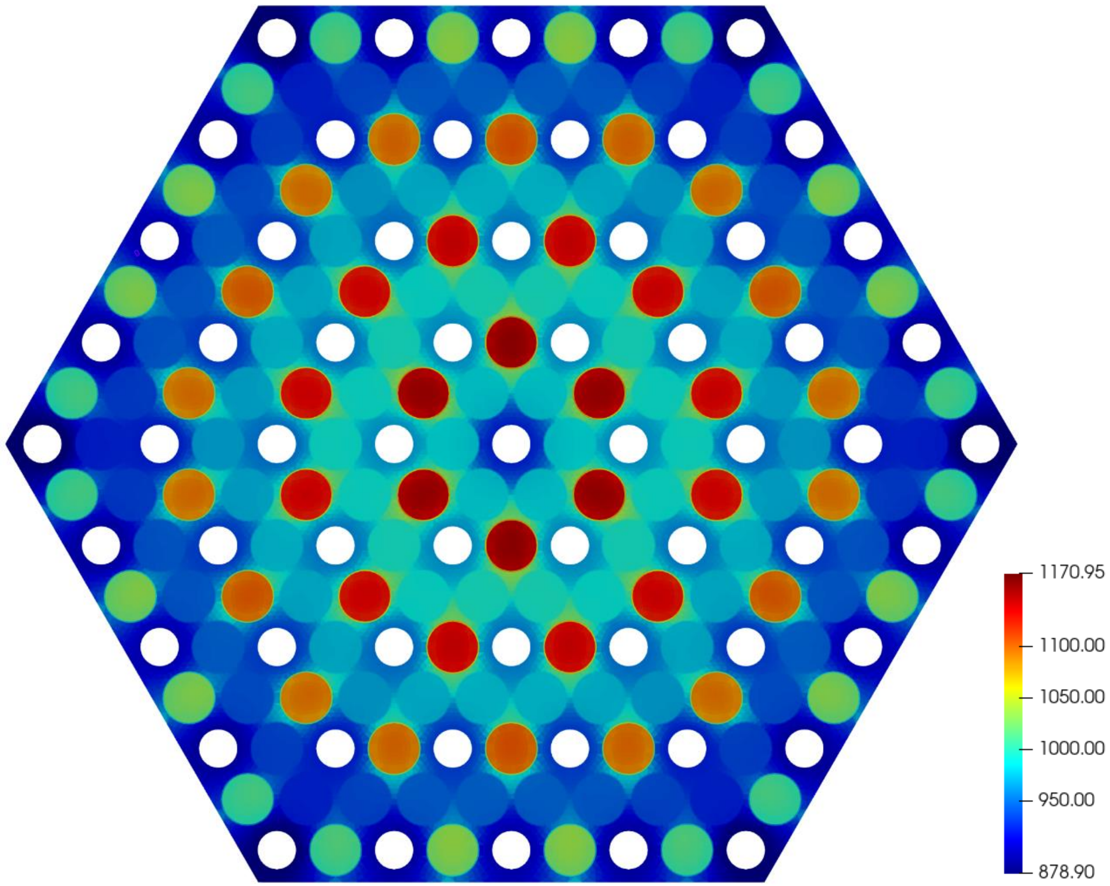
Parameter	Value
Problem	Empire 3D Assembly
# of GPUs	4 (NVIDIA RTX A5000)
# of Particles	20,000,000 (Total 1.15 Billion)
# of Cycles	25 (Inactive) / 50 (Active)
Ramp-up	On (Mode: Exponential, Factor: 20)
Core Power	0.111 MW_{th}
Feedback	On
Delta Tracking	On (zone-wise)
Grid Hashing	On (Hash size: 50)
Libraries (K)	900 / 1000 / 1100

- **Coupled Calculation Results**

Normalized Power

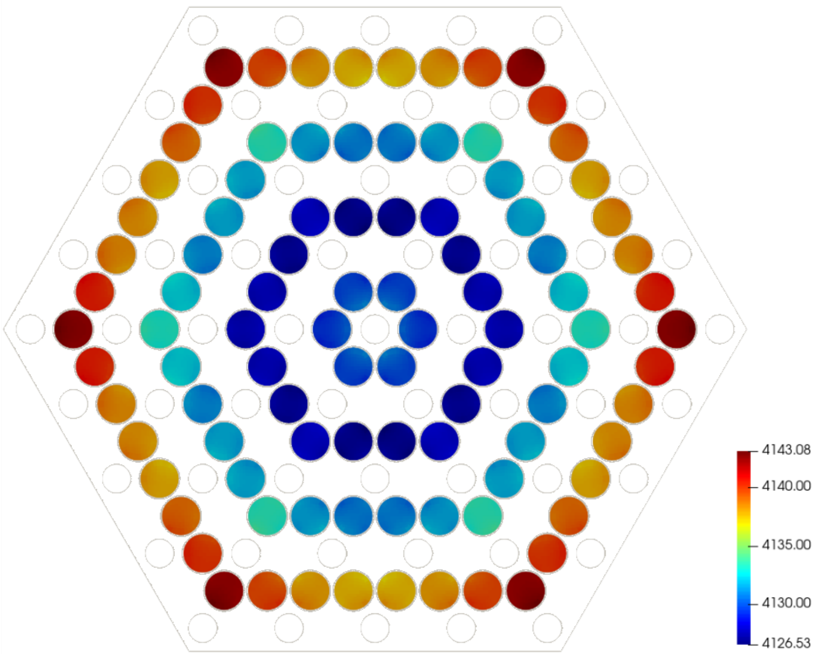


Temperature [K]

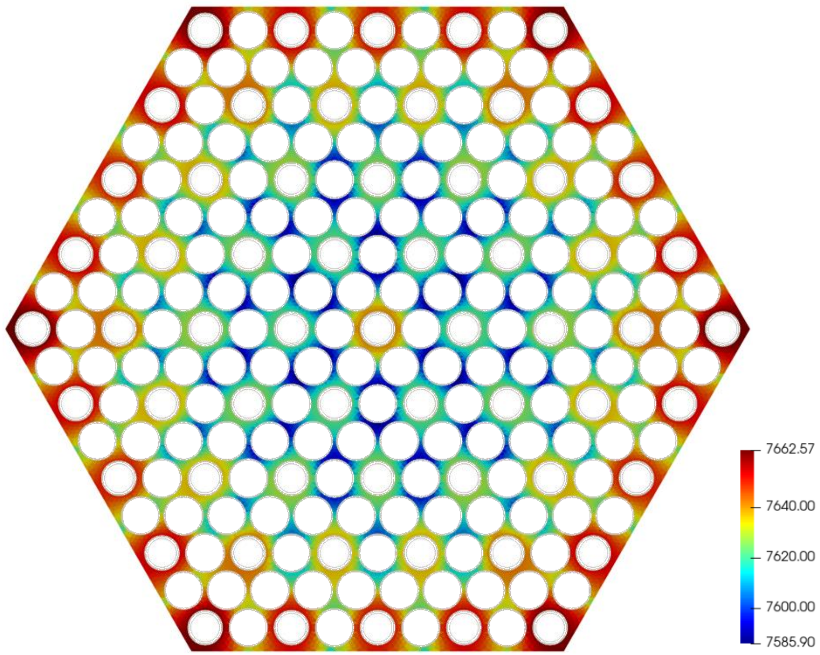


- **Coupled Calculation Results**

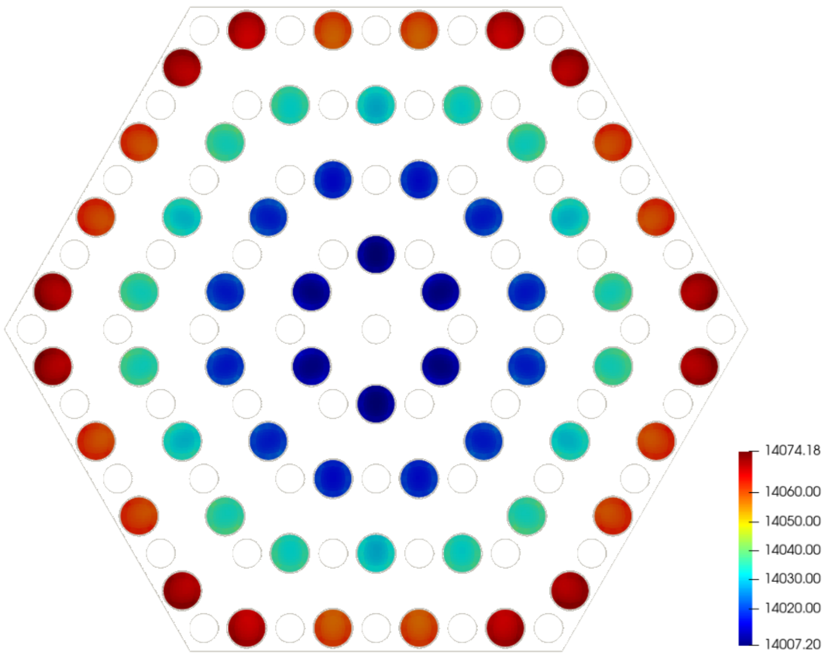
Moderator Density [kg/m³]



Monolith Density [kg/m³]

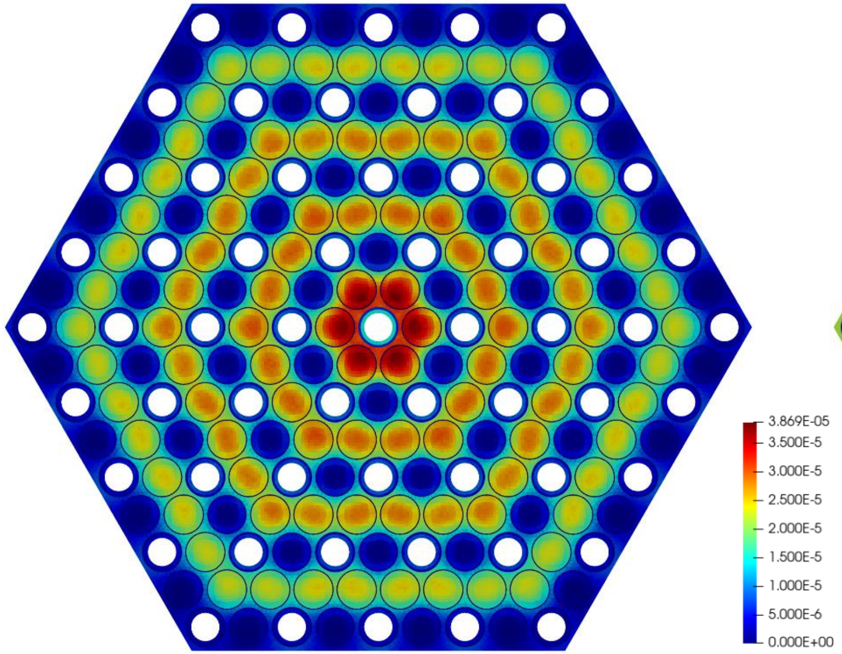


Fuel Density [kg/m³]

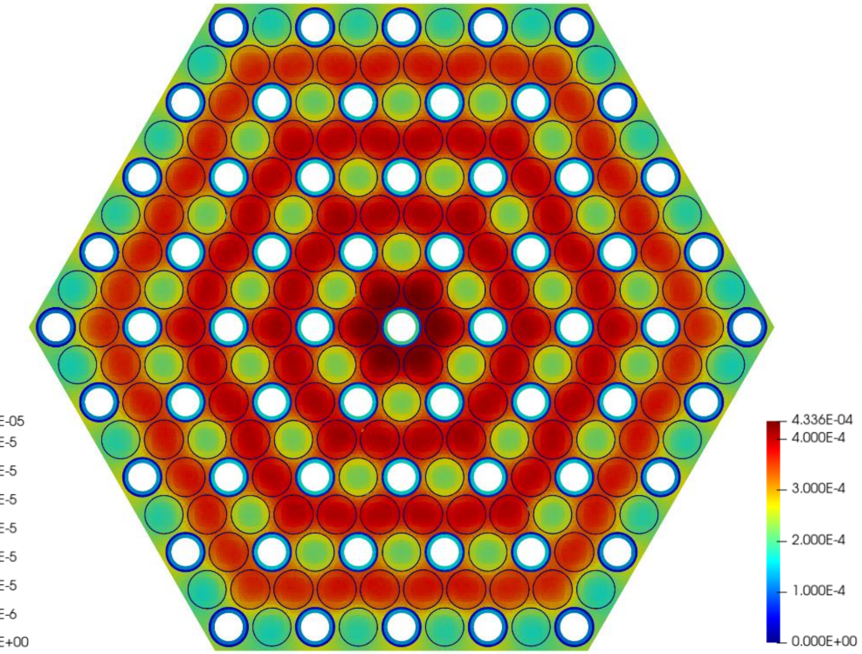


- **Calculation Results**

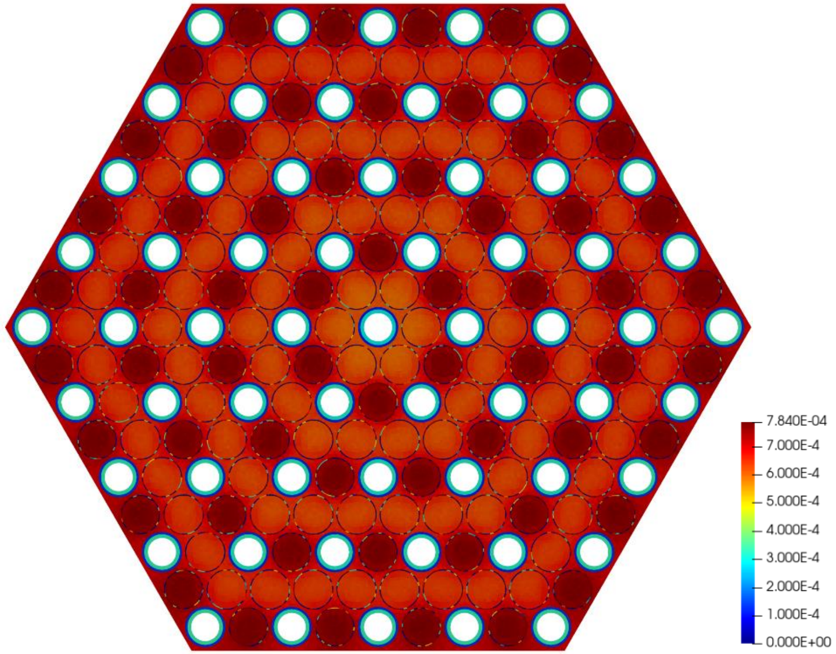
Thermal Flux (< 0.1 eV)



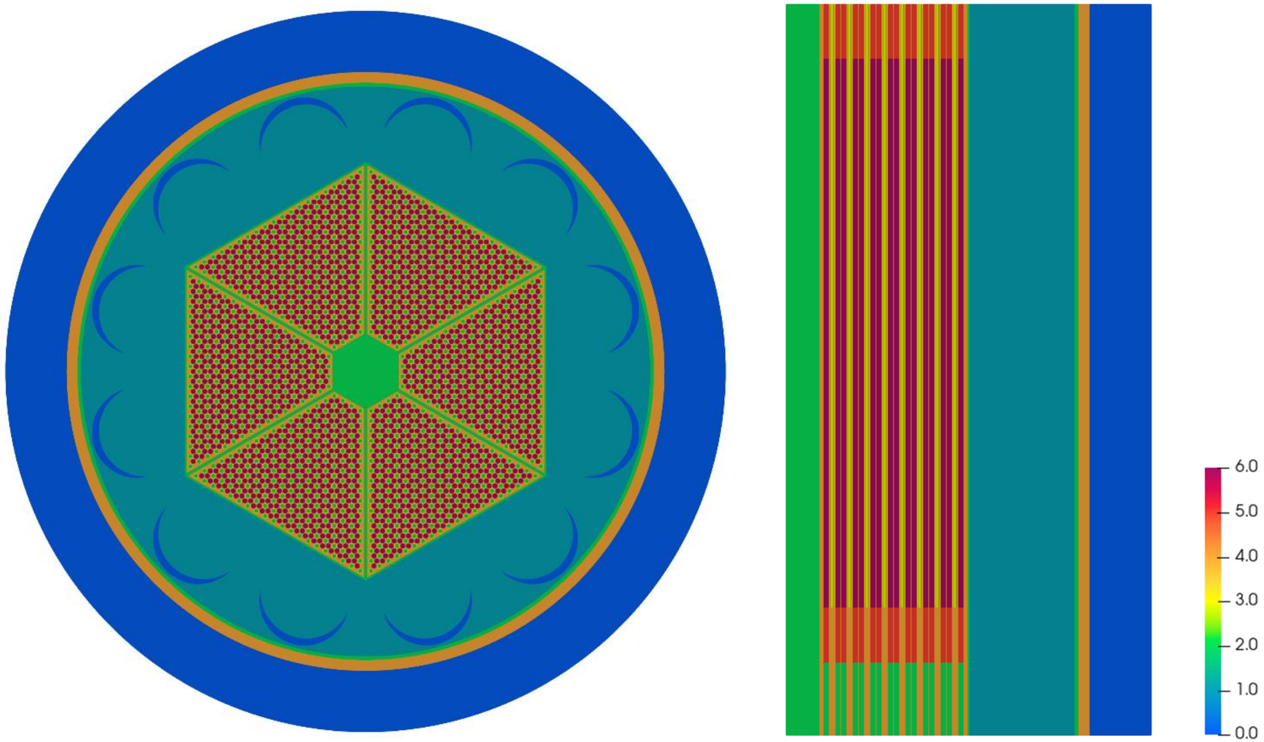
Intermediate Flux (0.1 eV ~ 9.118 keV)



Fast Flux (> 9.118 keV)



- **LANL MegaPower 3D Full Core**
  - **Problem configuration (Material-wise)**

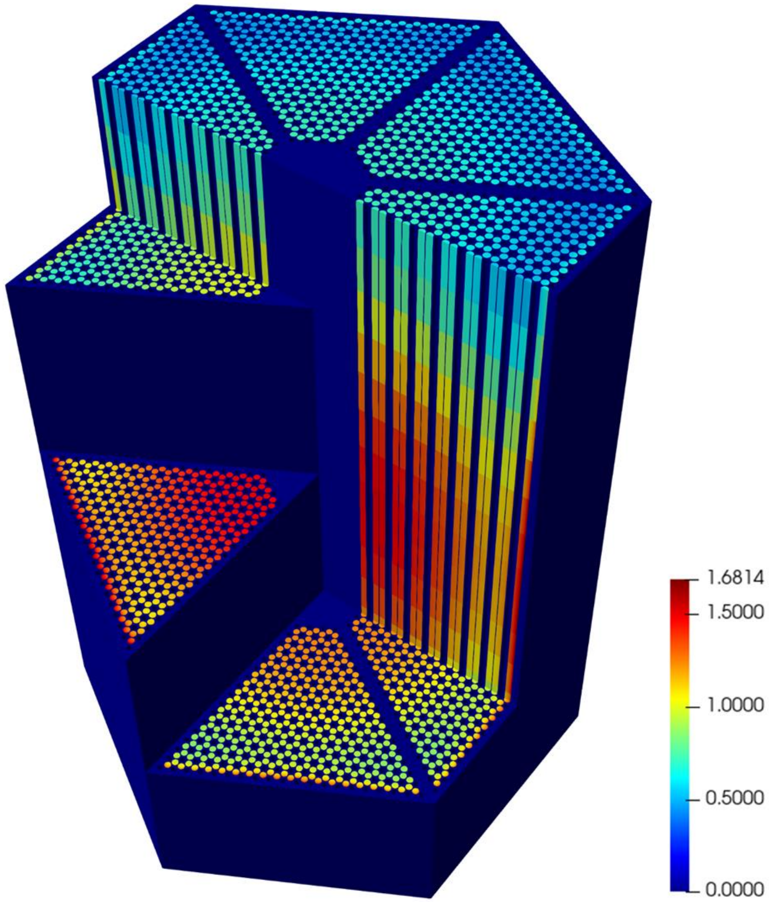


  - **Calculation conditions**

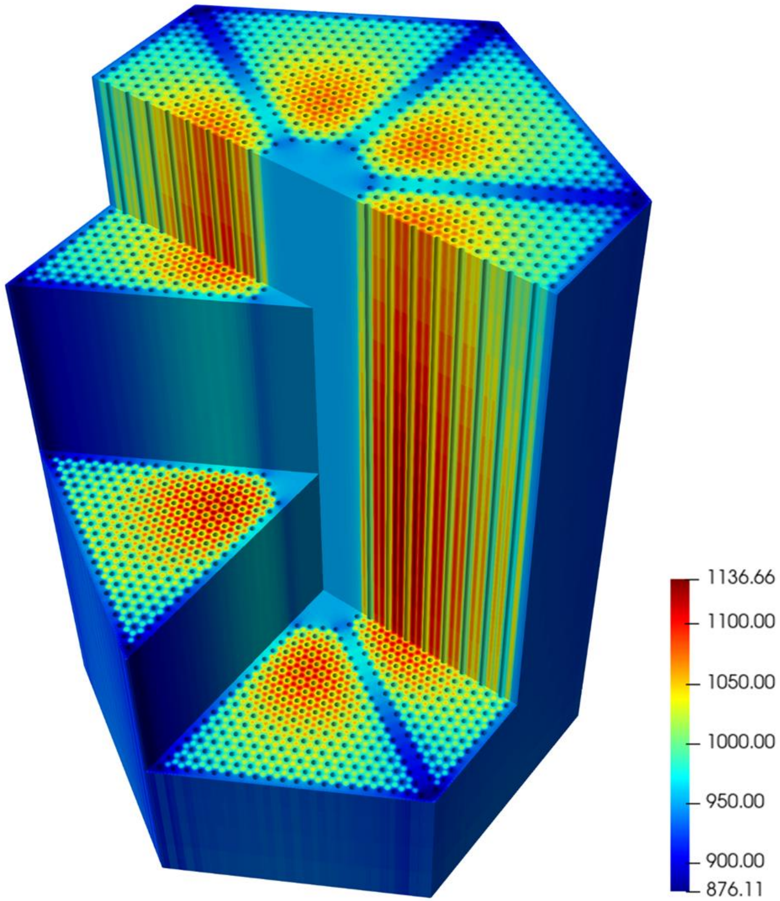
Parameter	Value
Problem	LANL MegaPower 3D Full Core
# of GPUs	24 (NVIDIA RTX A5000)
# of Particles	200,000,000 (Total 11.5 Billion)
# of Cycles	25 (Inactive) / 50 (Active)
Ramp-up	On (Mode: Exponential, Factor: 20)
Core Power	5 MW_{th}
Feedback	On
Delta Tracking	On (zone-wise)
Grid Hashing	On (Hash size: 50)
Libraries (K)	900 / 1000 / 1100

- **Coupled Calculation Results**

Normalized Power

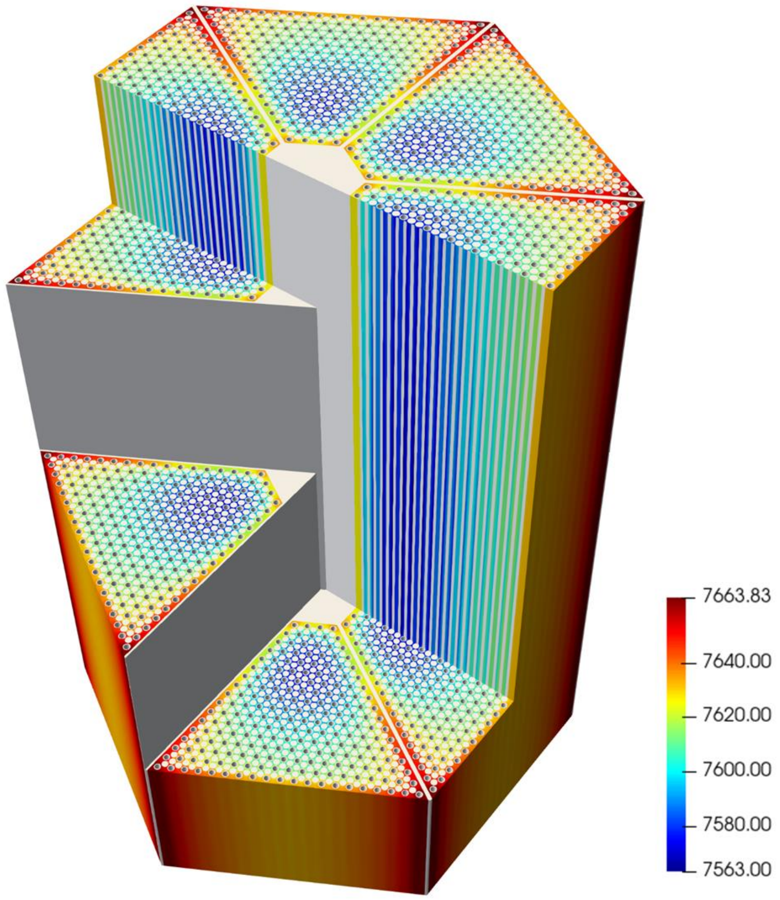


Temperature [K]

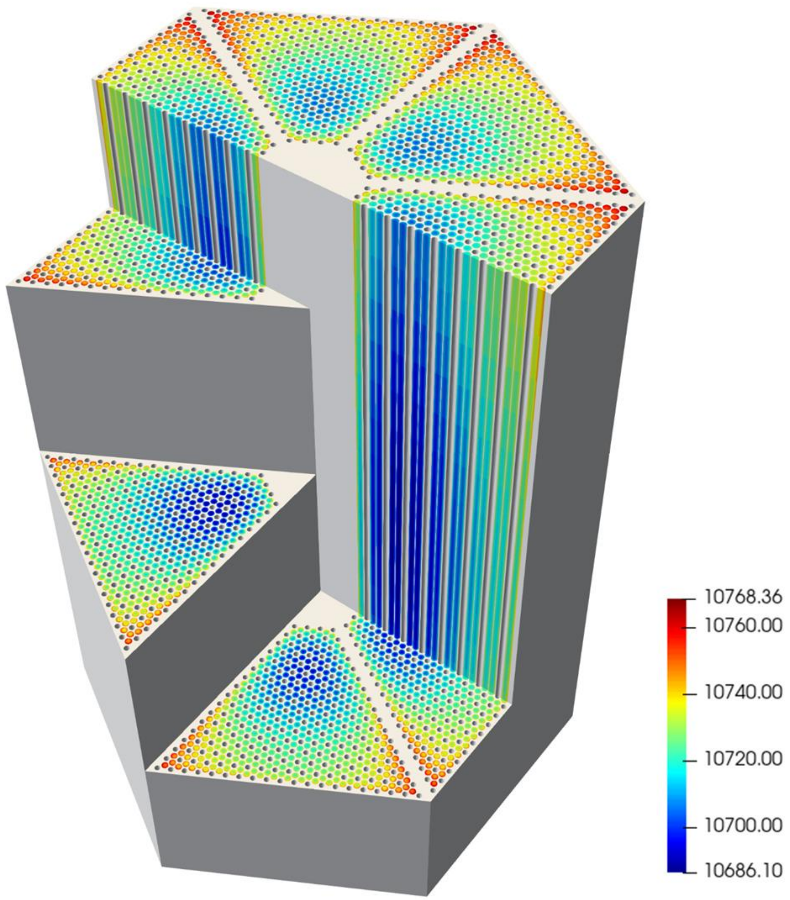


- **Coupled Calculation Results**

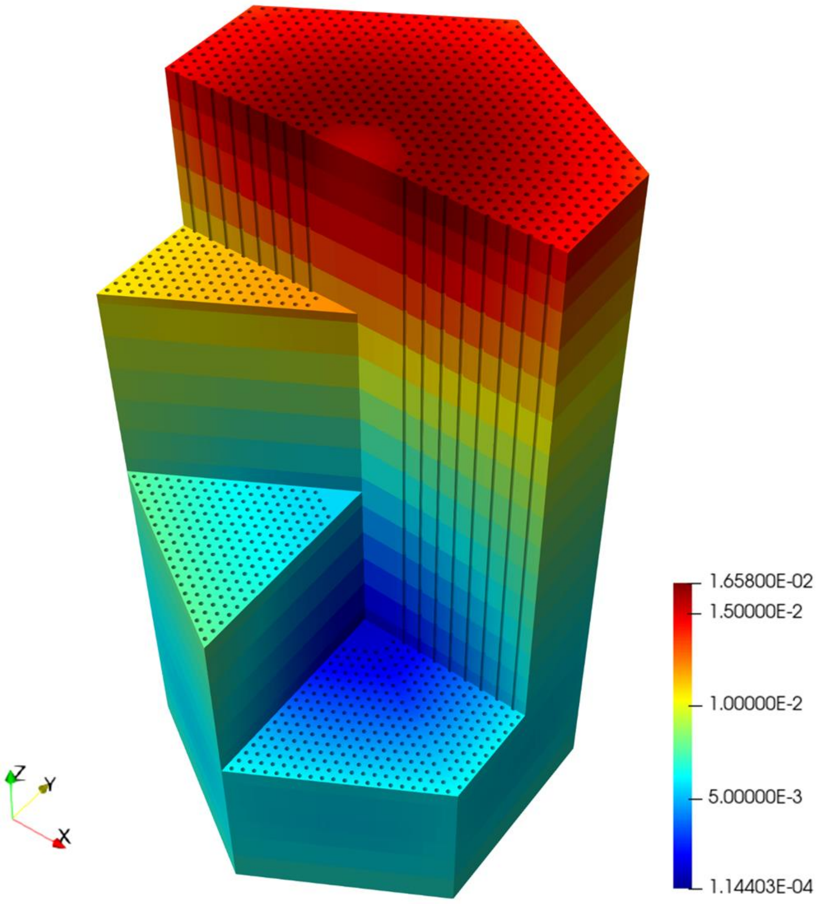
Monolith Density [kg/m³]



Fuel Density [kg/m³]

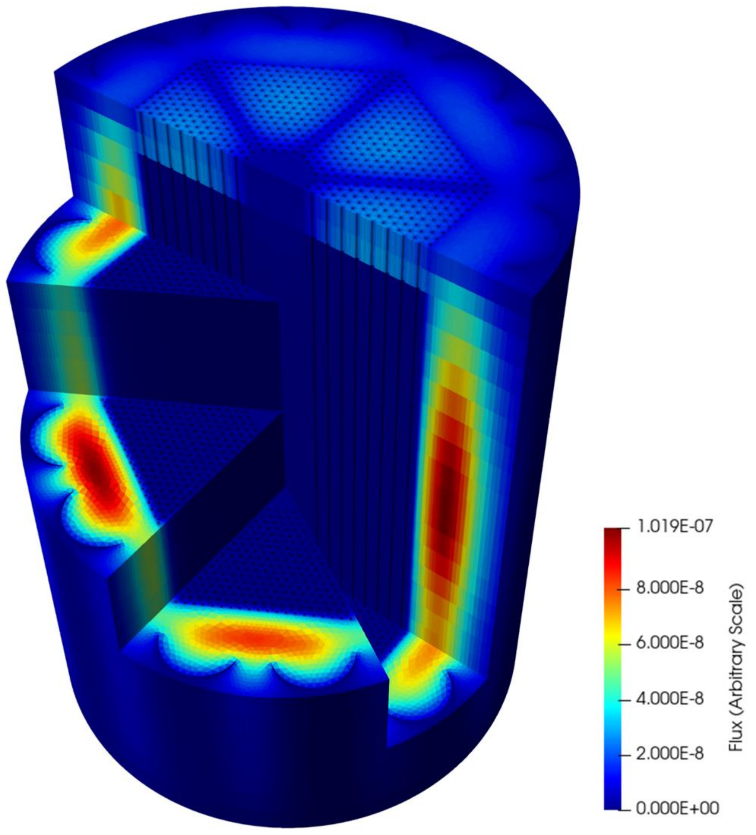


Thermal Expansion (Displacement) [m]

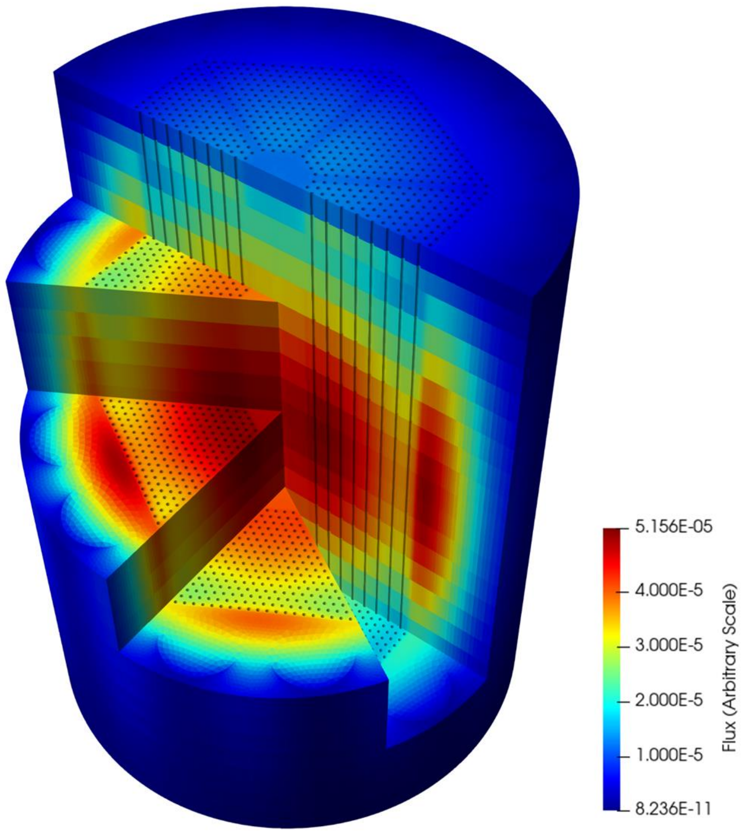


- **Calculation Results**

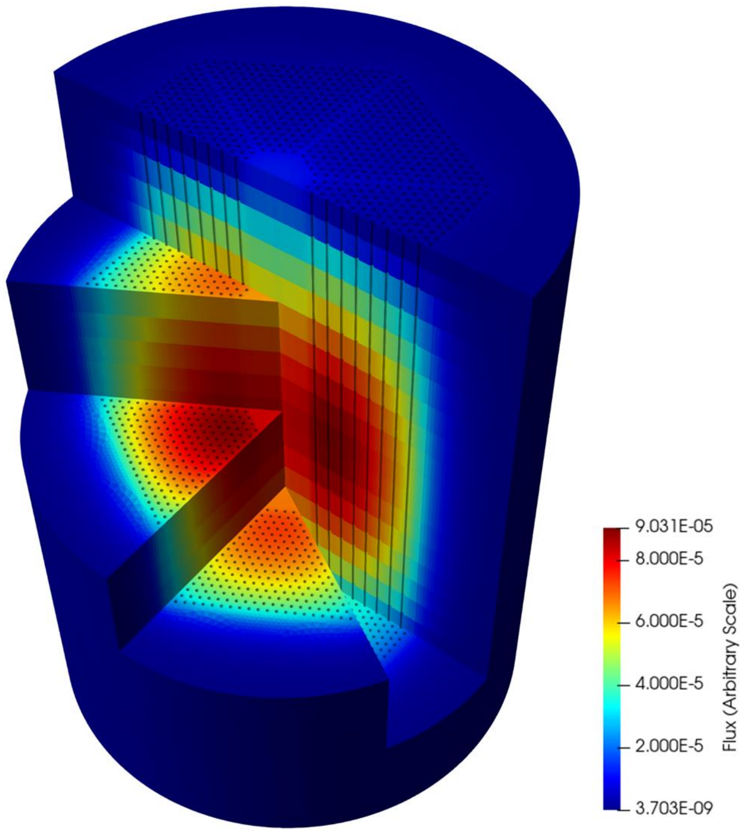
Thermal Flux (< 0.1 eV)



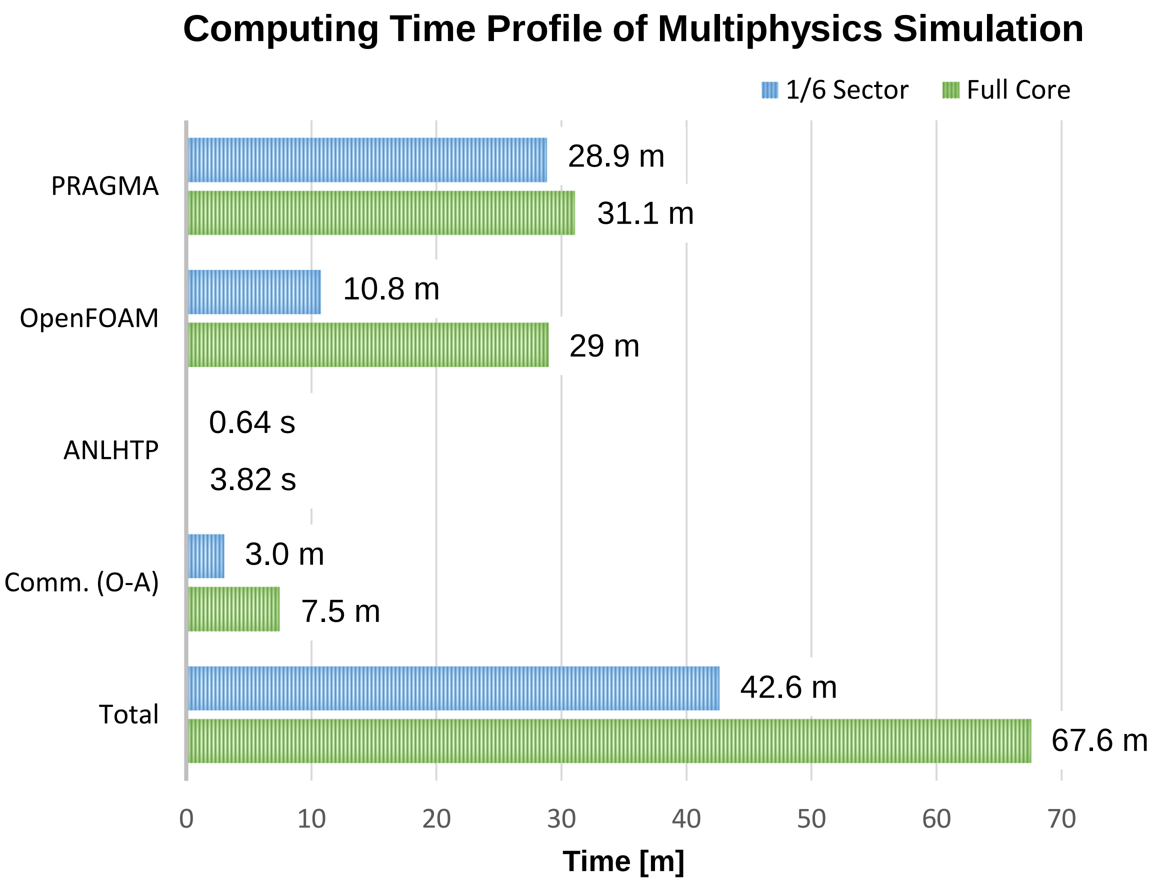
Intermediate Flux (0.1 eV ~ 0.1 MeV)

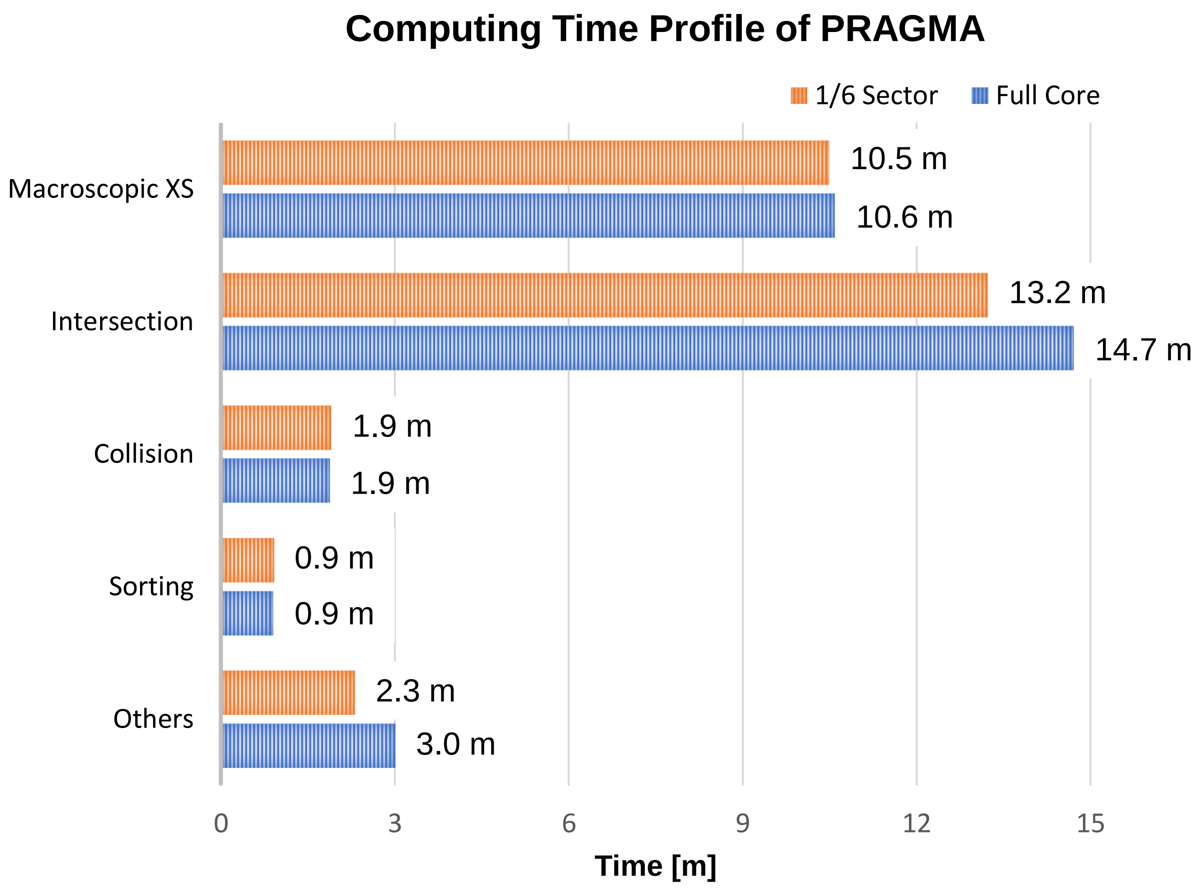


Fast Flux (> 0.1 MeV)



- **Computing Performance**
  - PRAGMA : 24 GPUs, OpenFOAM : 1 Node (52 CPU Cores), Manager & ANLHTP : 1 Node (2 CPU Cores)





- **Development of Unstructured Mesh Basis Modules in PRAGMA for Advanced Reactors**
  - **Developed a general geometry treatment module employing ray tracing technology on unstructured mesh basis.**
    - Triangulated unstructured mesh geometry to leverage the hardware-accelerated features of OptiX.
    - Resolved excessive surface detection events in the surface-tracking algorithm by employing delta-tracking algorithm.
  - **Optimized delta-tracking performance with zone-wise majorant XS.**
    - Mitigated high incidence of virtual collisions in localized heavy absorber problem.

- **Demonstration of Unique and Efficient Multiphysics Coupling System for HPRs**
  - **Established neutronics – thermo-mechanical – heat-pipe coupled multiphysics analysis system.**
    - Neutronics analysis employing GPU-based continuous-energy Monte Carlo code PRAGMA
    - Thermo-mechanical and heat pipe analysis employing OpenFOAM and ANLHTP
  - **Conducted direct coupling with OpenFOAM on the same mesh basis.**
  - **Demonstrated superior performance in completing multiphysics simulation within an hour.**

Ongoing and Future Works

- Domain Decomposition
- Multi-Mesh Approach and CMFD Acceleration
- GPU-Based Time-Dependent Monte Carlo
- PRAGMA – OpenFOAM Mesh Deformation Feedback
- Depletion in Unstructured Mesh Geometry
- Multiphysics Analysis of Molten-Salt Reactor
- …