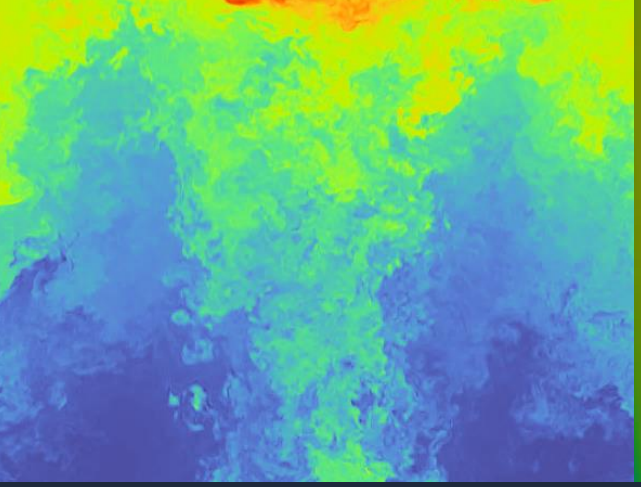
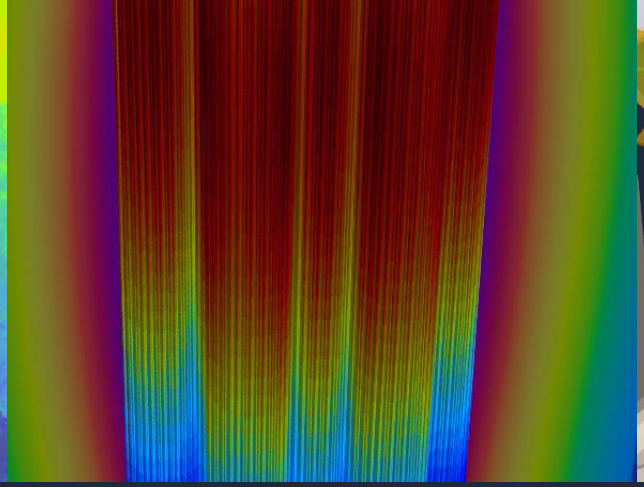



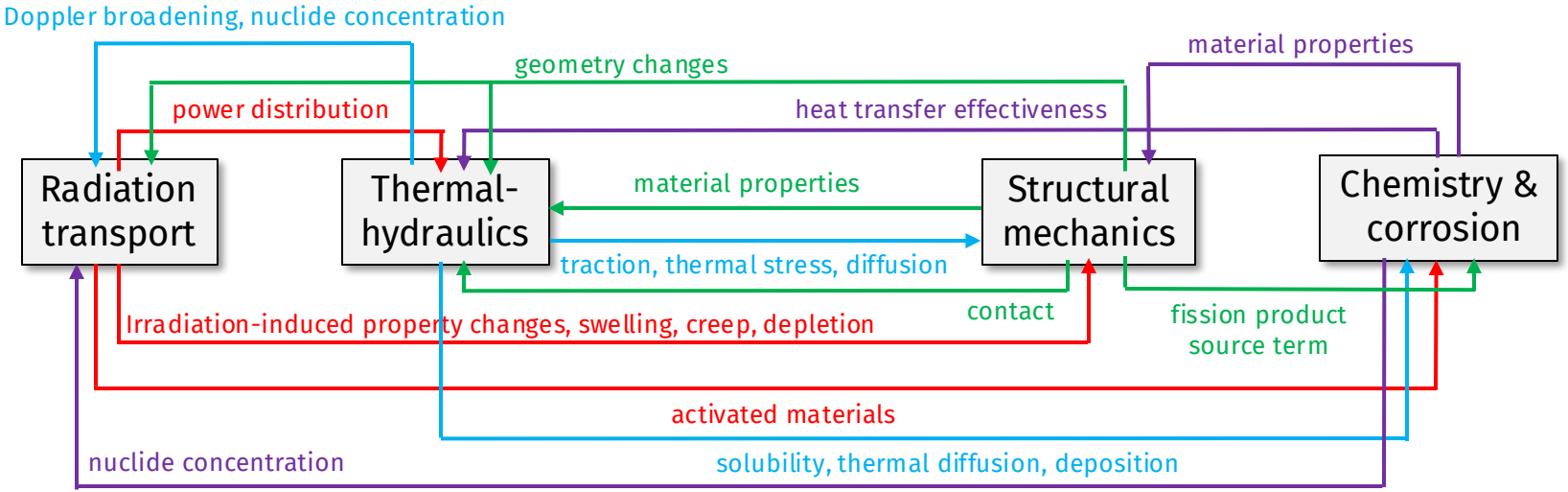

Cardinal: Integrating OpenMC and NekRS with the MOOSE Ecosystem

April Novak

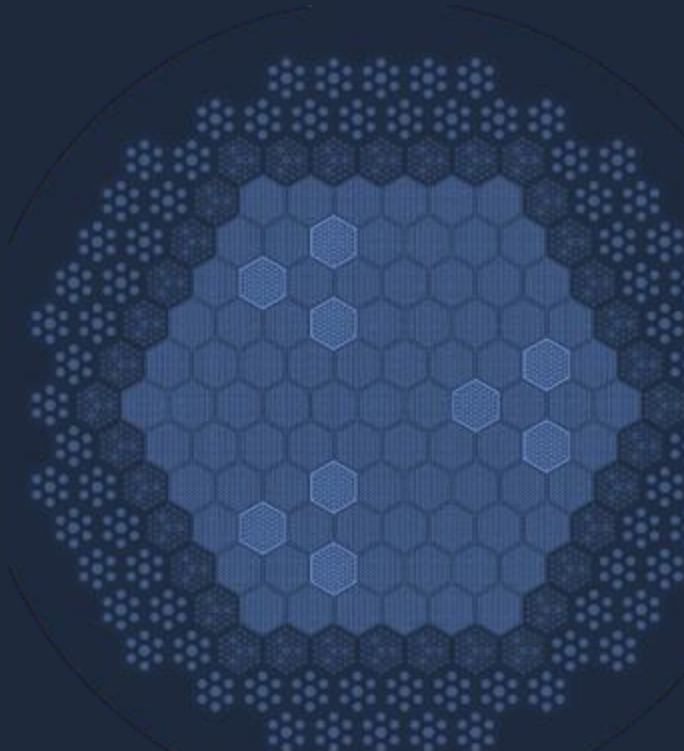
Assistant Professor
Nuclear, Plasma, and Radiological Engineering (NPRE)
University of Illinois, Urbana-Champaign

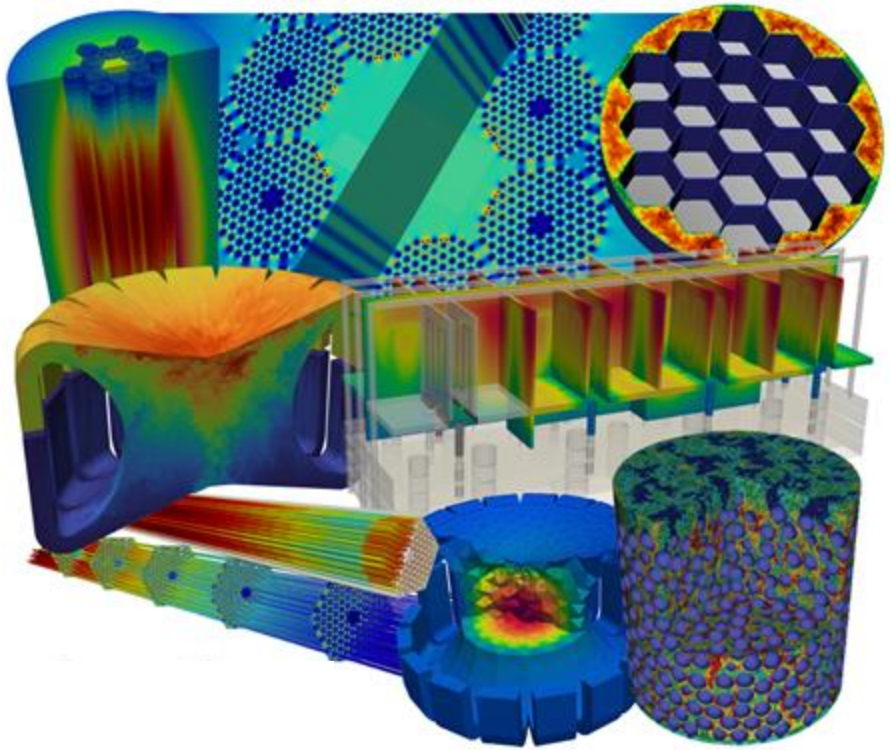
Joint Appointment, Nuclear Science and Engineering (NSE) Division
Argonne National Laboratory

Multiphysics/Multiscale Analysis



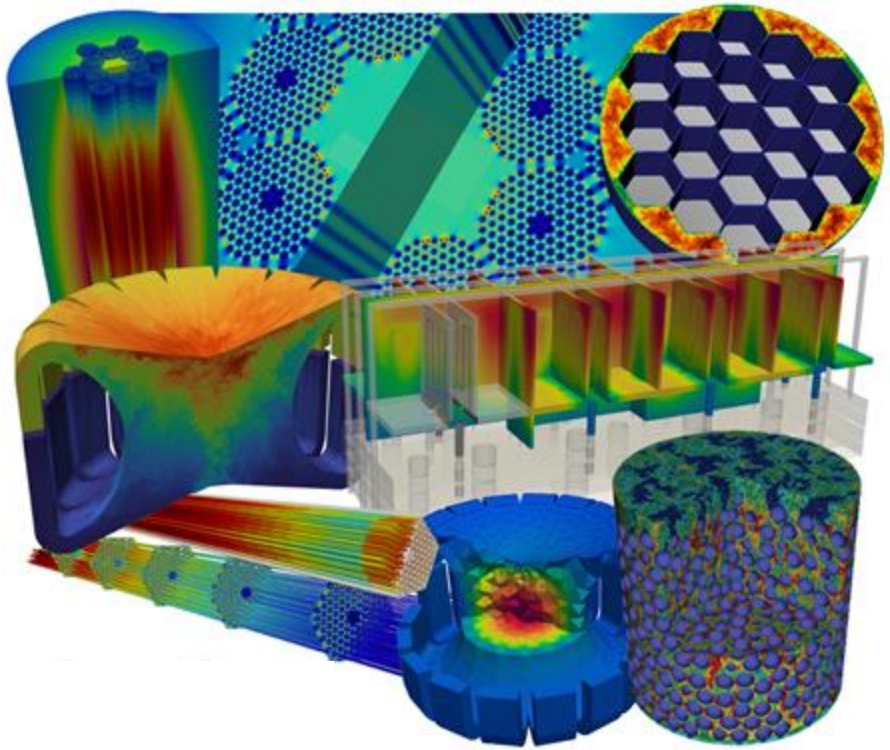
- Introducing the Cardinal software application: MOOSE, NekRS, OpenMC
- Fusion & fission application examples





Cardinal

- Open-source multiphysics coupling of **OpenMC** and **NekRS** with **MOOSE**
- Links high-fidelity radiation transport + CFD to MOOSE fusion ecosystem:
  - Plug-and-play multiphysics/scale coupling
  - Obtain reference solutions for benchmarking
  - Develop constitutive models (e.g., heat transfer coefficients, multigroup cross sections)
  - Advanced postprocessing and visualization



Cardinal

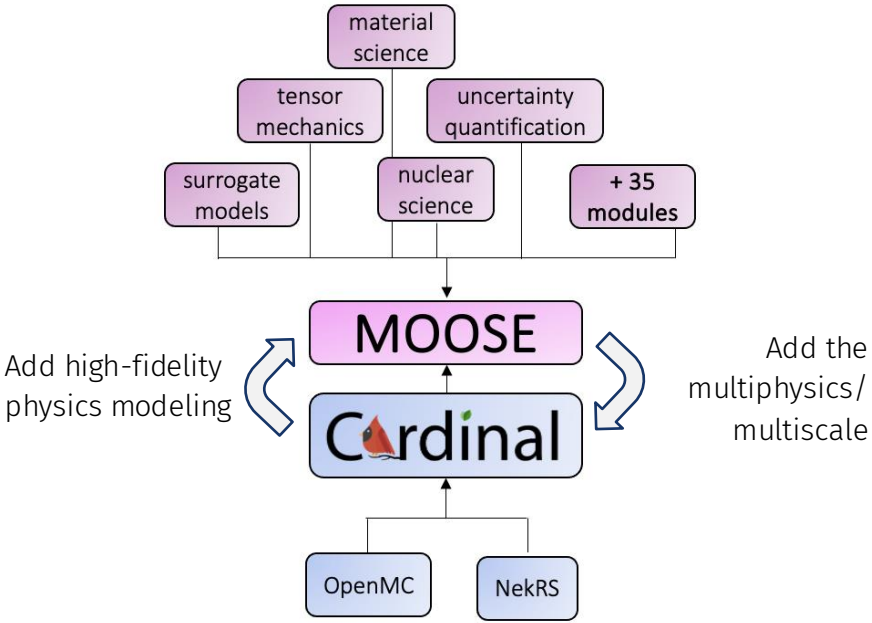
- Nuclear heating (e.g. power deposition)
- Composition changes (e.g. breeding)
- Shielding requirements
- Material activation, radioactive waste classification
- Material damage (dpa), gas production
- Non-proliferation analyses
- Diagnostics, sensor responses

OpenMC

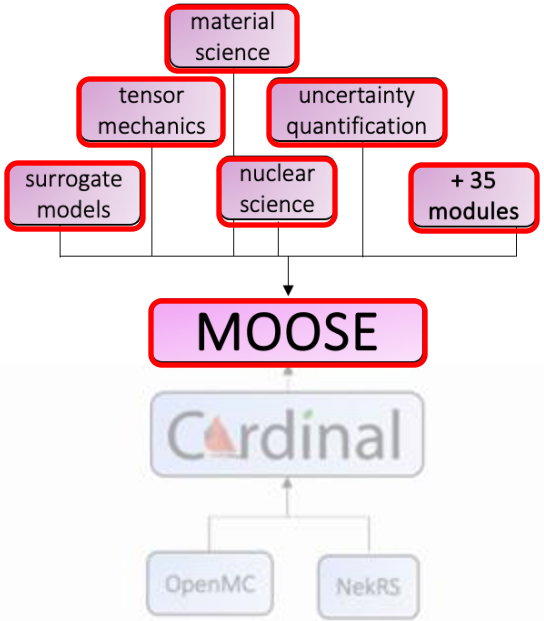
- Heat transfer and fluid flow
- Temperature and heat flux thermal limits
- Pressure losses and pumping power
- Passive scalar transport (e.g., mass transport)
- Magnetohydrodynamics
- Fluid-structure interaction

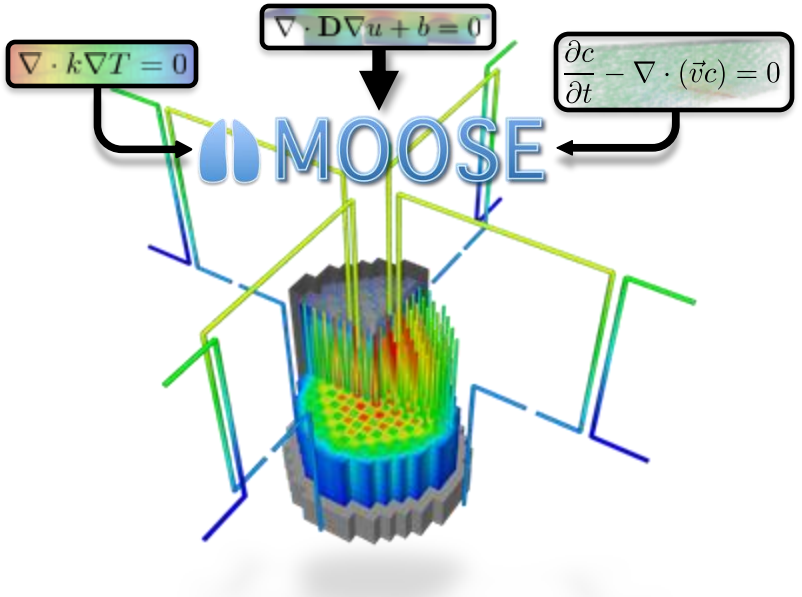
NekRS

Big-Picture: *Make OpenMC and NekRS seamlessly interoperable with MOOSE*



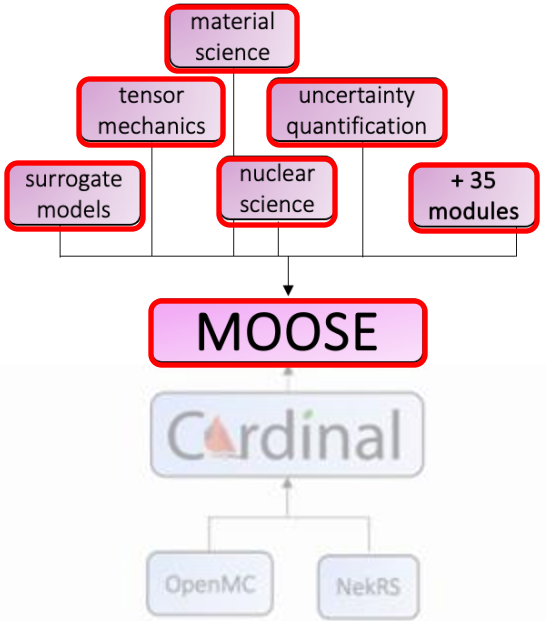
MOOSE

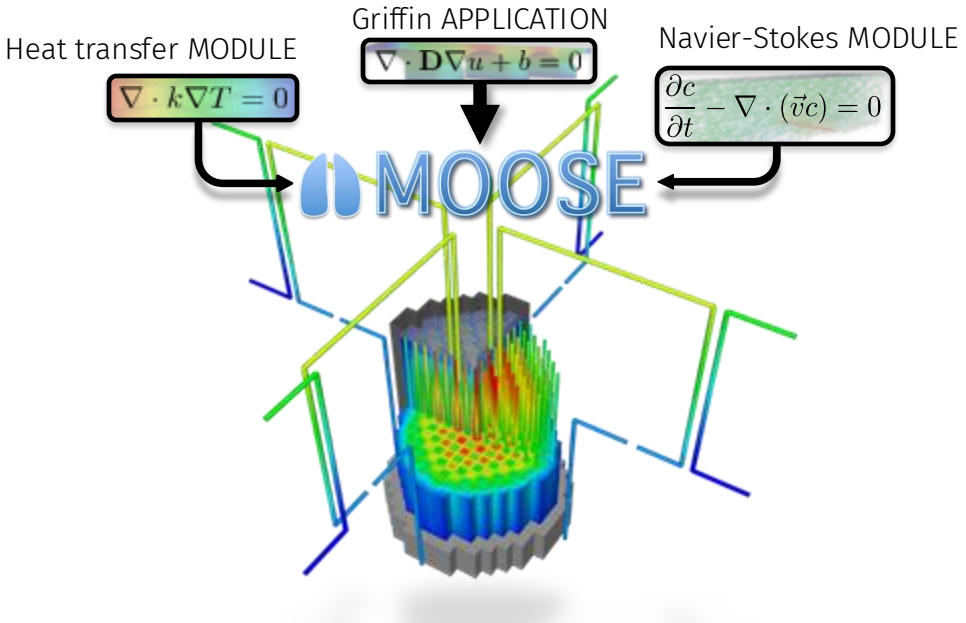




- Finite element/volume framework (Idaho National Lab)
- Plug-and-play framework for multi-scale/physics analysis
- NQA-1 (Nuclear Quality Assurance Level 1) compliant
- Used by numerous entities for nuclear analysis (private companies, R&D, U.S. Nuclear Regulatory Commission)

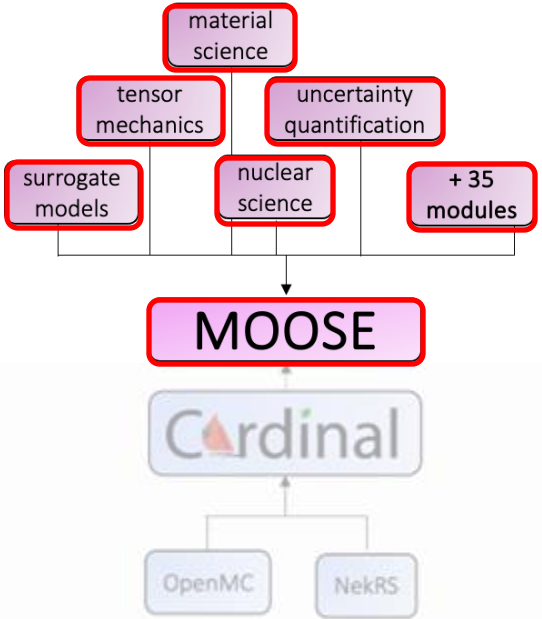
MOOSE

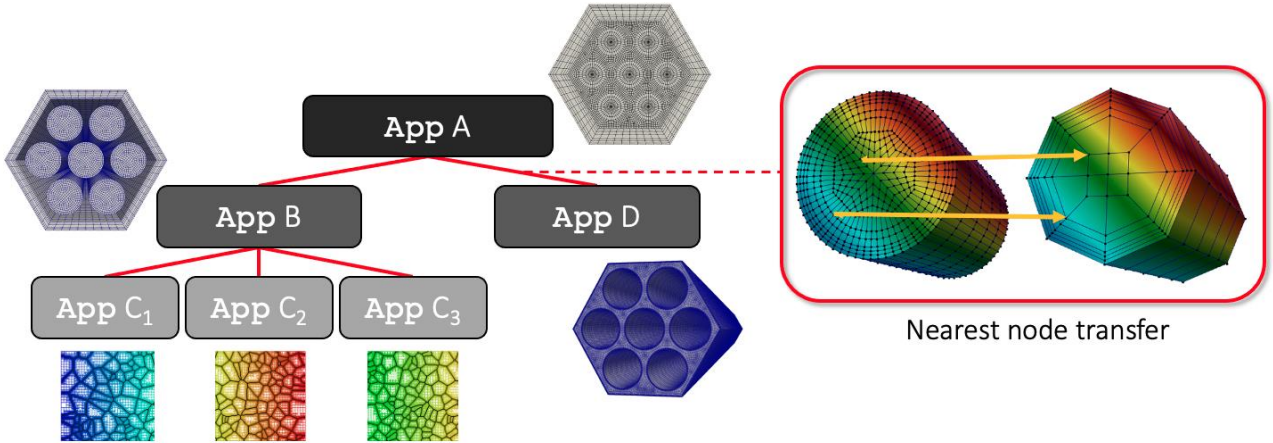




- **Framework**: complete platform of 40+ modular systems
  - Define the governing equation(s) of interest, with boundary/initial conditions
  - Specify constitutive models/closures
  - Couple equations together
  - Postprocess the solution
- **Modules**: common physics/engineering capabilities
- **Applications**: special-purpose physics capabilities

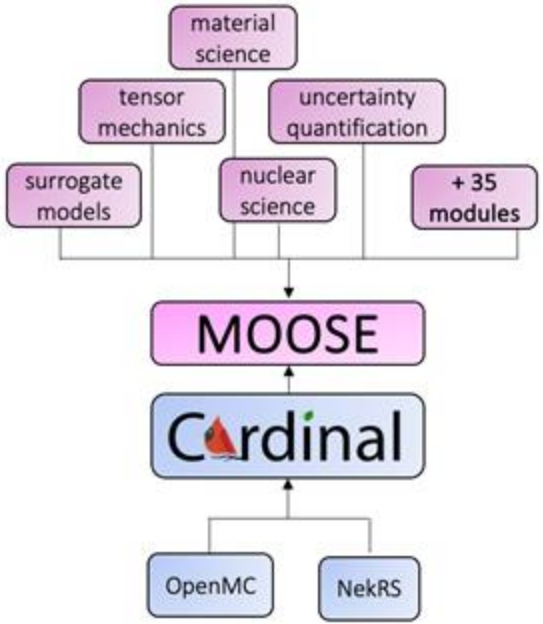
MOOSE MultiApps and Transfers

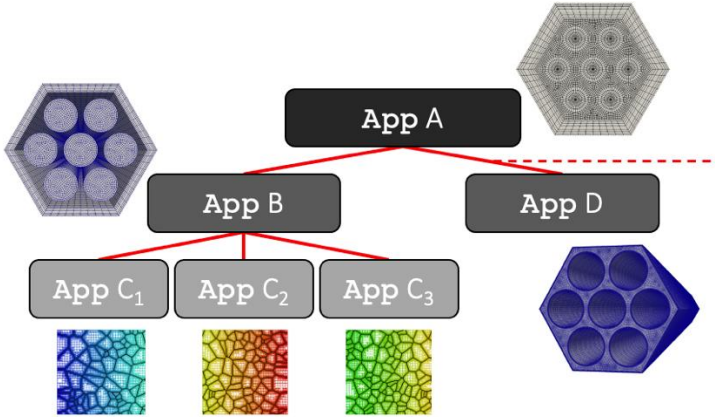


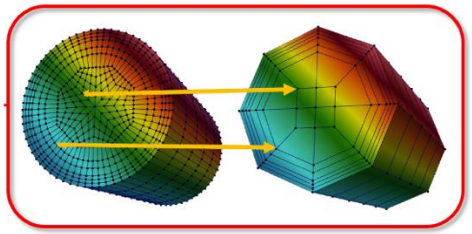


- Automatically parallel
- In-memory data transfers
- Arbitrary tree for simulations
- Flexible synchronization (unique time steps)

Big-Picture: *Add OpenMC and NekRS to the MOOSE "toolbox"*







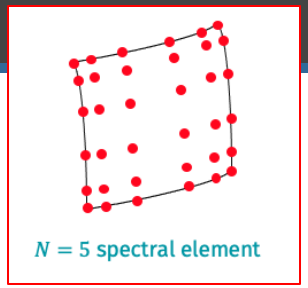
Nearest node transfer

Coupling framework

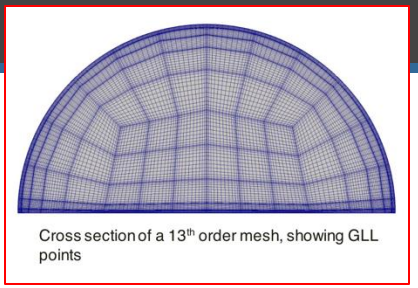
Physics applications

mesh-to-mesh data transfers		OpenMC neutron-photon transport
solution postprocessing	software QA	NekRS Navier-Stokes
mesh adaptivity	uncertainty quantification	TMAP8 tritium
checkpointing	timestep control	MOOSE thermomechanics

NekRS: *Physics and Numerical Method*



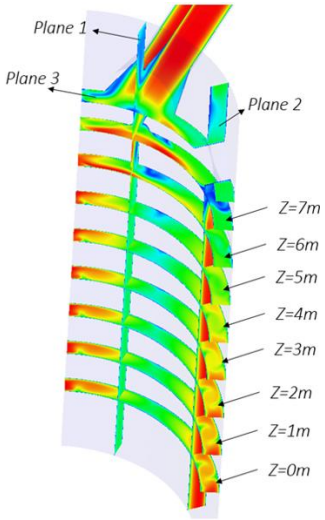
$N = 5$ spectral element



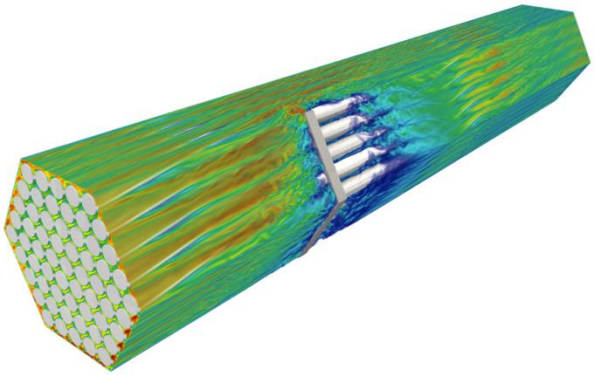
Cross section of a 13th order mesh, showing GLL points

- Navier-Stokes solver for incompressible and low-Mach flows
  - **Turbulence:** $k - \tau$ RANS, High/low-pass LES filters, and DNS
  - **Runs on both CPU and GPU** and is **massively parallel**
  - New physics and solvers are under active development

- **Spectral element method**: nodal interpolants of GLL quadrature
  - Mesh with curvilinear hexahedral elements, typically use order 5—7
  - High-order has low numerical dissipation/dispersion well-suited to long time integrations and turbulence



RANS simulation of cold water injection in a downcomer
image: Yiqi Yu



LES of a wire-wrapped pin bundle
image: Dezhi Dai

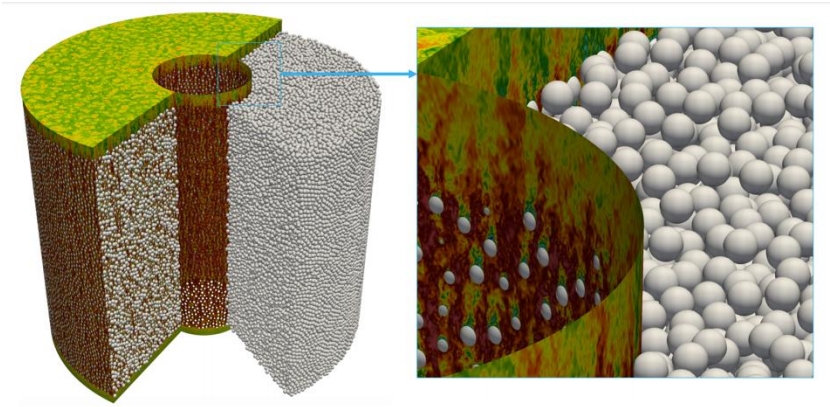
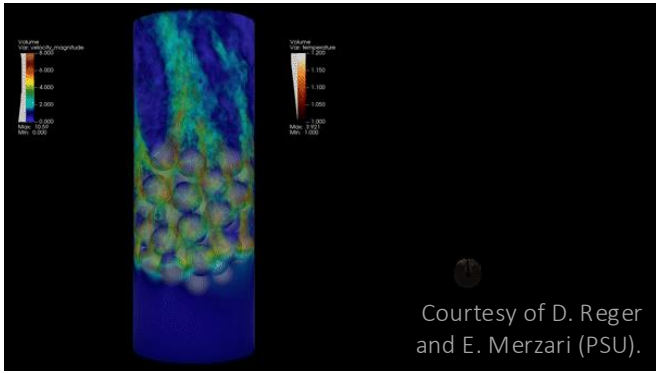
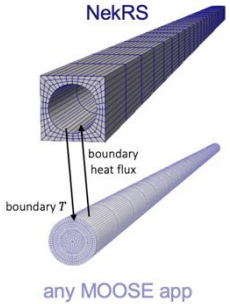


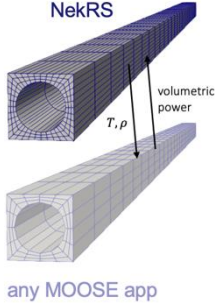
image: Misun Min (https://ieeexplore.ieee.org/document/10046048), funded through the CEED program

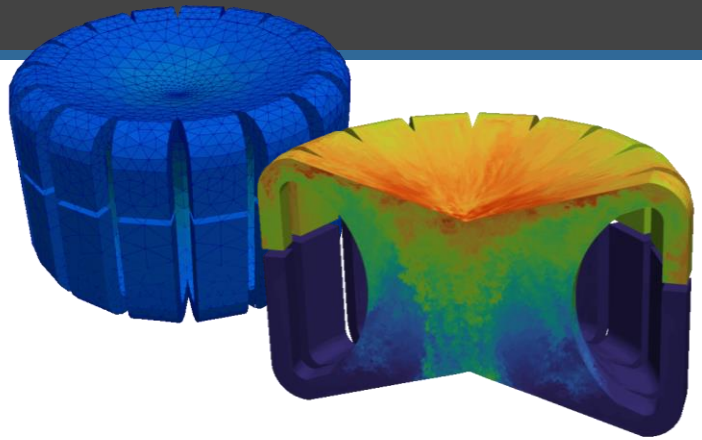
NekRS Coupling Modes



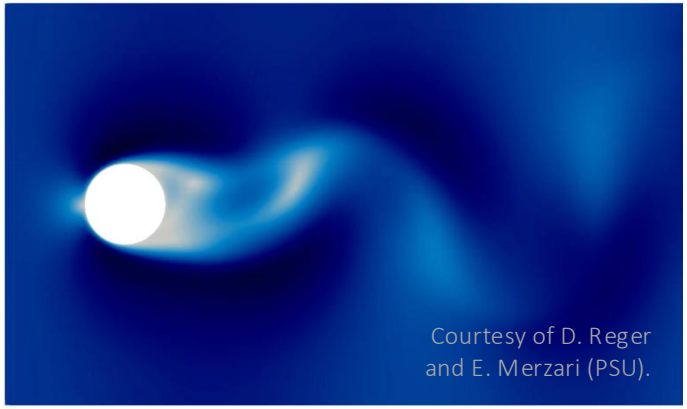


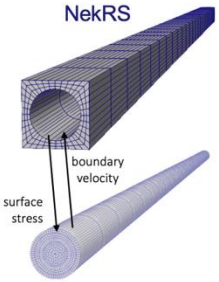
Conjugate heat transfer (NekRS + MOOSE heat transfer)



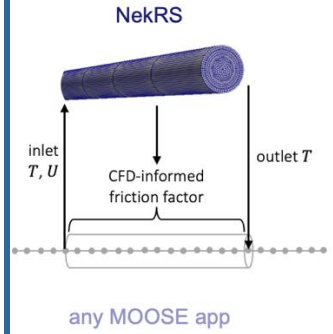


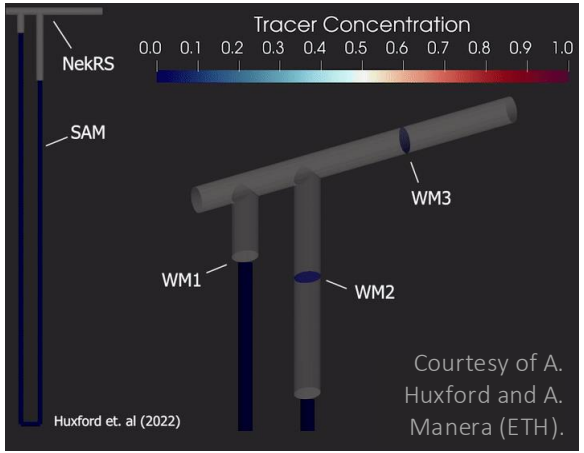
Neutronics coupling (NekRS + OpenMC)





Fluid-structure interaction (NekRS + MOOSE solid mechanics)

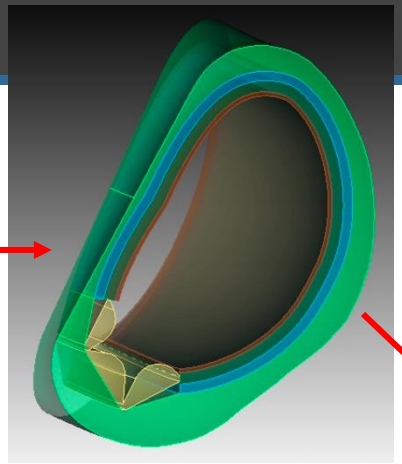




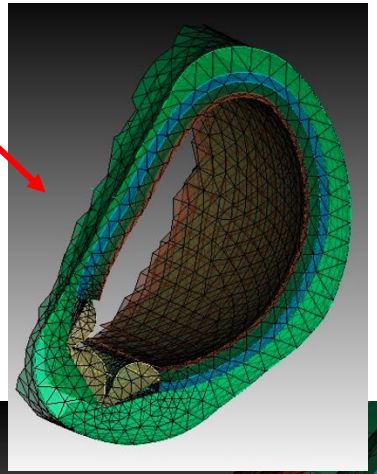
CFD-systems coupling (NekRS + SAM)

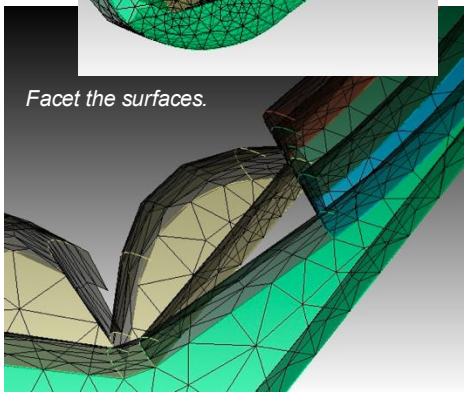
OpenMC

- **Monte Carlo neutron and photon** transport for k-eigenvalue and fixed source calculations; built-in depletion capabilities
- Geometry can be specified in either **unstructured mesh** (surface, volume) or **Constructive Solid Geometry** (CSG)
- **Runs on both CPU and GPU** and is **massively parallel**, scales from laptops to supercomputers
- First published Monte Carlo code to perform 1 million particles/s/GPU with transmuted/depleted materials



Section of a tokamak built using CAD.





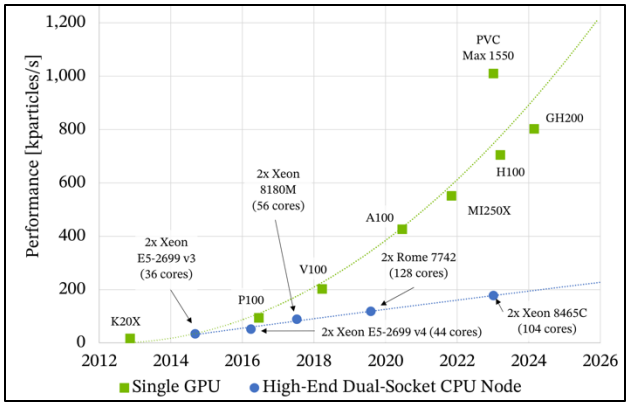
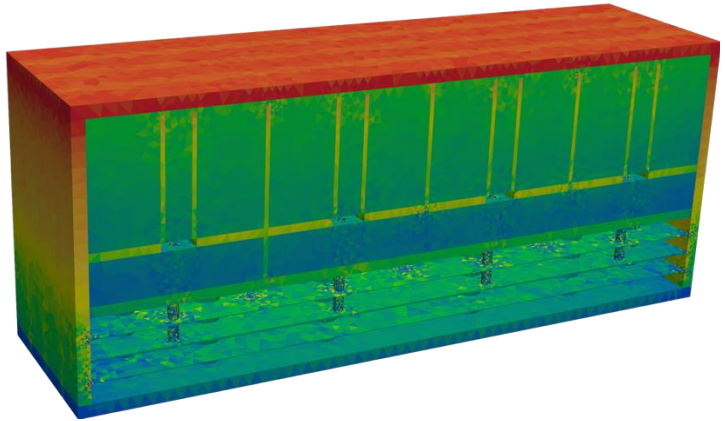


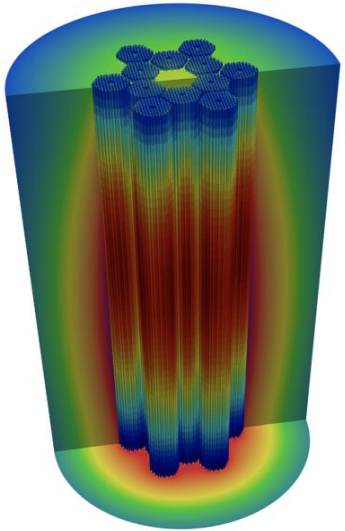
image: John Tramm (https://arxiv.org/pdf/2403.12345v1), funded by the ECP

Cardinal

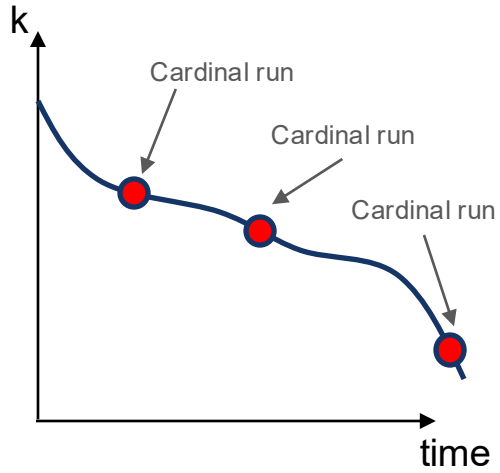
- **Modes/solvers**: Fixed-source, *k*-eigenvalue, depletion, volume calculation



Fixed source neutron-photon transport
Breeder blanket module



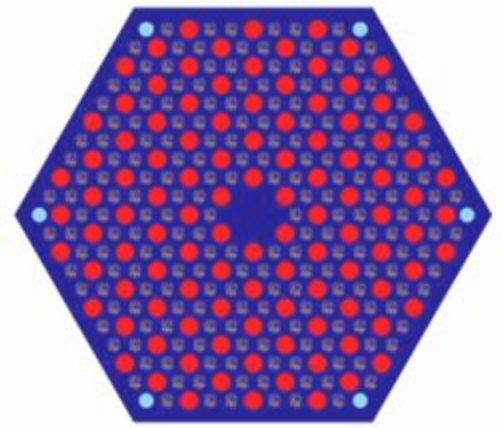
k-eigenvalue neutron transport
Fission reactor



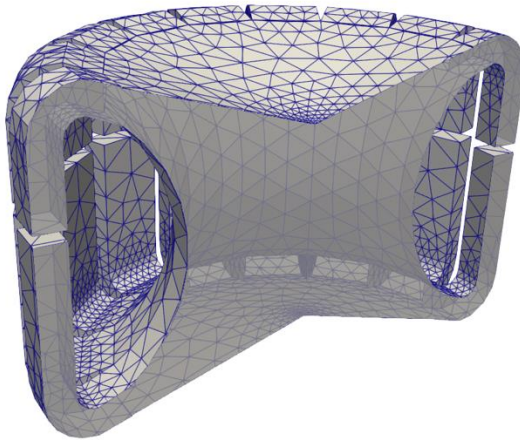
Depletion/activation

Cardinal

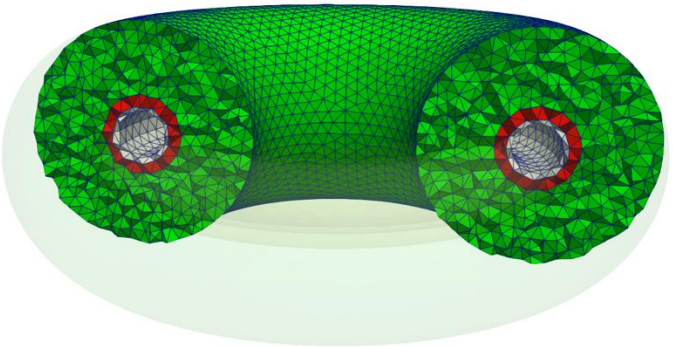
- **Modes/solvers**: Fixed-source, *k*-eigenvalue, depletion, volume calculation
- **Geometry**: Constructive solid geometry, CAD surface mesh, unstructured mesh*



Constructive Solid Geometry (CSG)



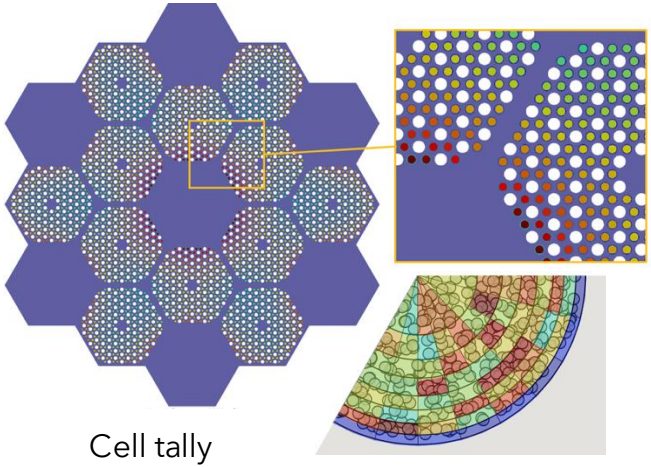
DAGMC surface meshes



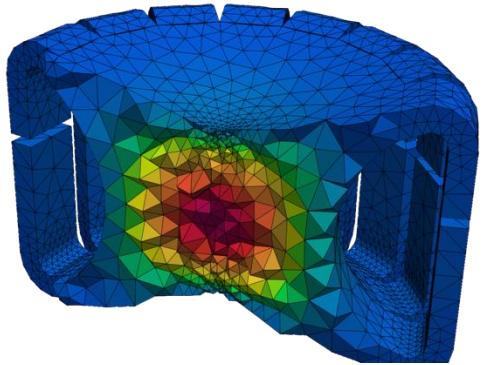
libMesh unstructured volume mesh
(*coming soon)

Cardinal

- **Modes/solvers**: Fixed-source, *k*-eigenvalue, depletion, volume calculation
- **Geometry**: Constructive solid geometry, CAD surface mesh, unstructured mesh
- **Tallies**: cell tallies, unstructured mesh tallies



Cell tally



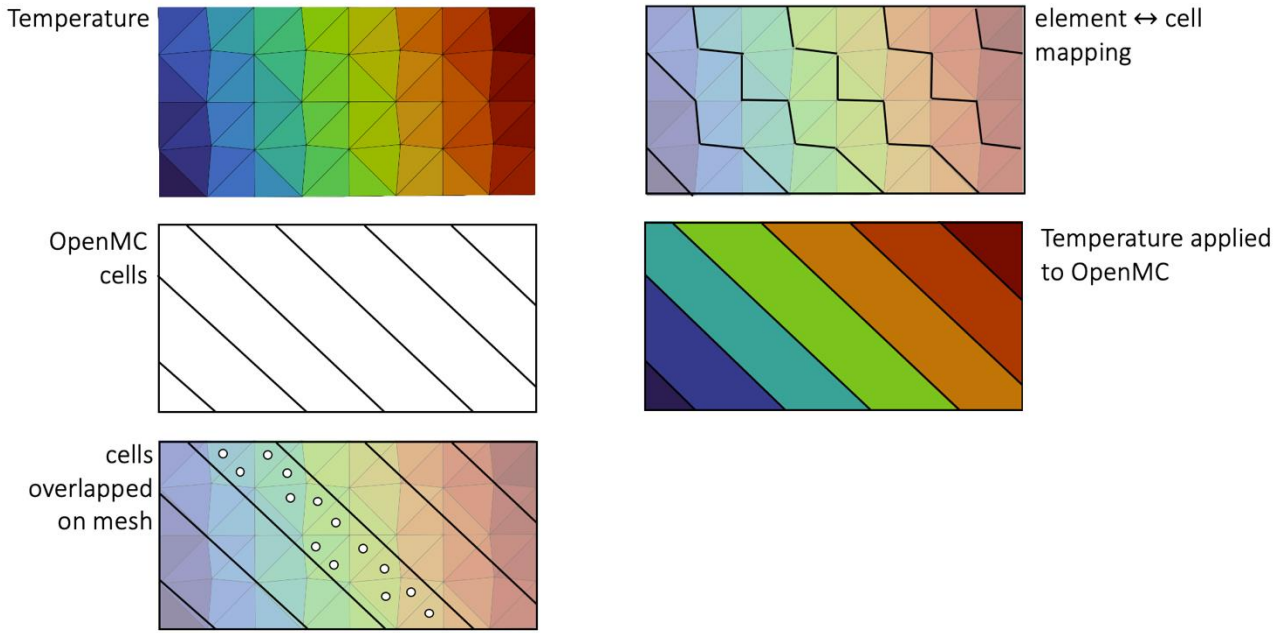
Unstructured mesh tally

Cardinal

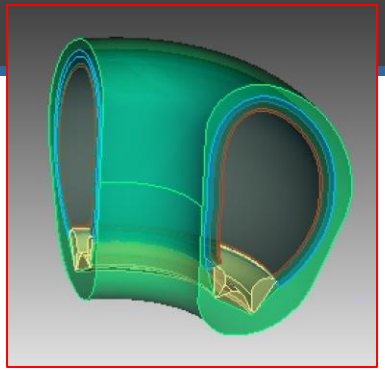
- **Modes/solvers**: Fixed-source, *k*-eigenvalue, depletion, volume calculation
- **Geometry**: Constructive solid geometry, CAD surface mesh, unstructured mesh
- **Tallies**: cell tallies, unstructured mesh tallies
- **Physics Feedback**: temperature (Doppler), density, composition, geometry, on-line multigroup cross section generation

Cardinal

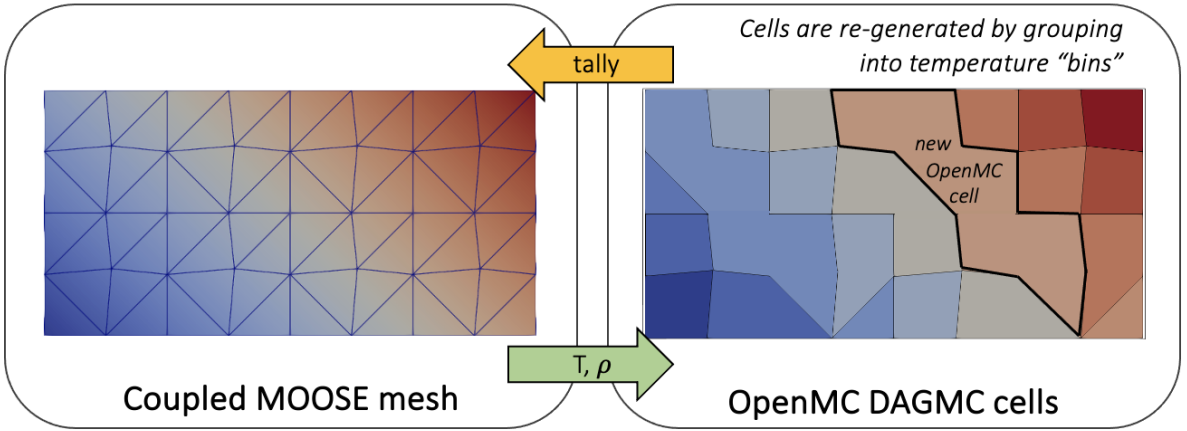
- **Data transfer:**
  - **CSG:** element-cell mapping based on element centroids
  - **CAD:** mesh-to-mesh mapping



Cardinal

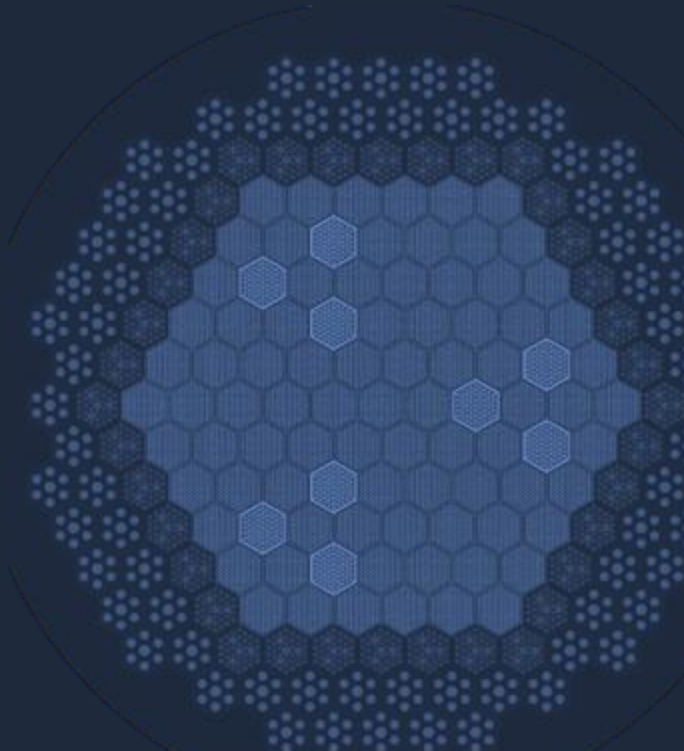


- **Data transfer:**
  - **CSG:** element-cell mapping based on element centroids
  - **CAD:** mesh-to-mesh mapping

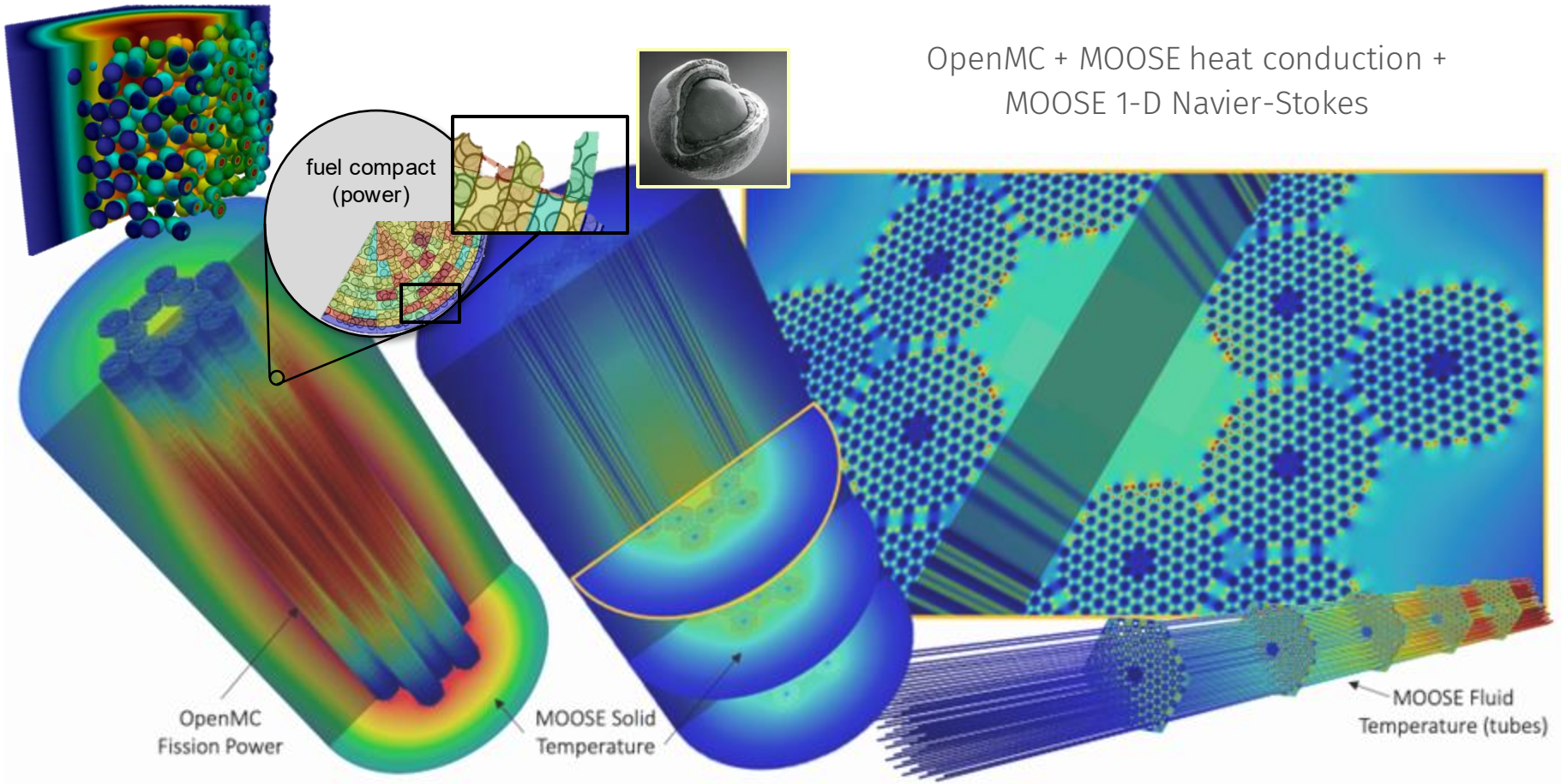


On-the-fly geometry refinement to resolve temperature, density fields (developed by Dr. Helen Brooks, UKAEA)

- Introducing the Cardinal software application: MOOSE, NekRS, OpenMC
- Fusion & fission application examples

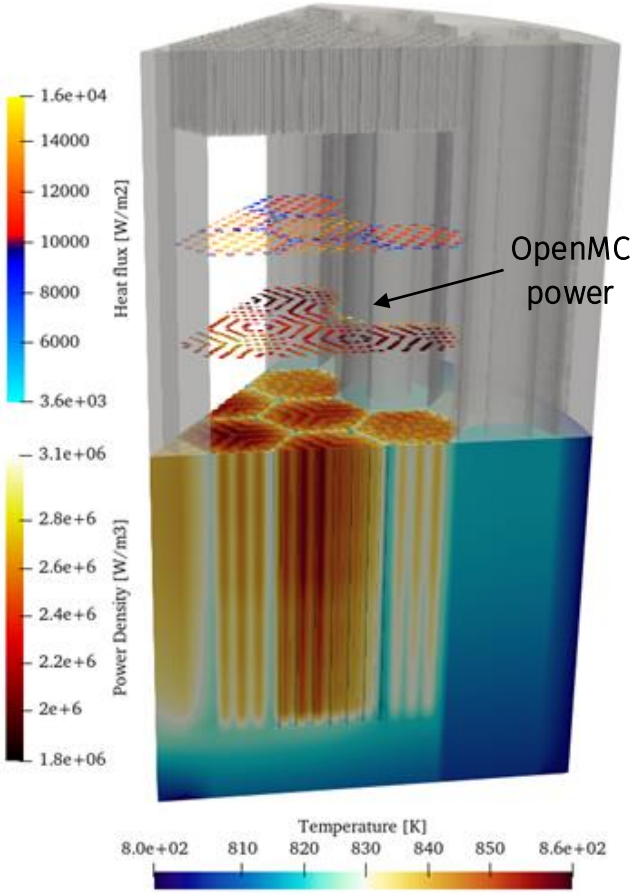


High Temperature Gas Reactors

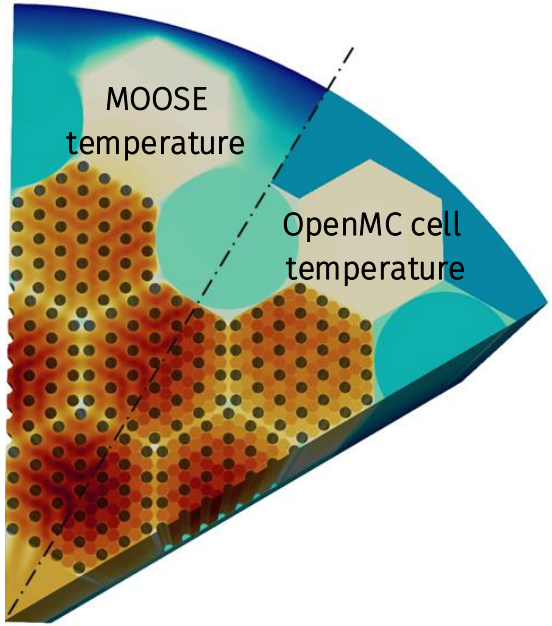


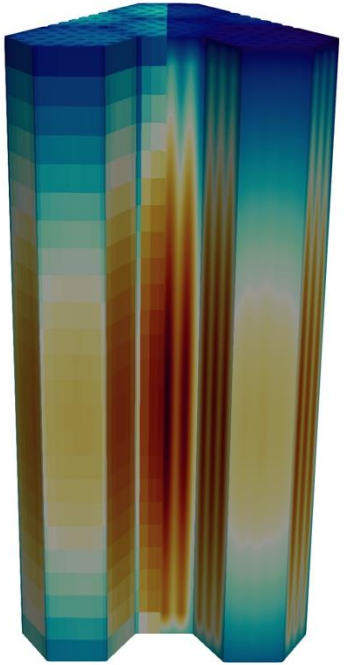
OpenMC + MOOSE heat conduction +
MOOSE 1-D Navier-Stokes

Heat Pipe Microreactors

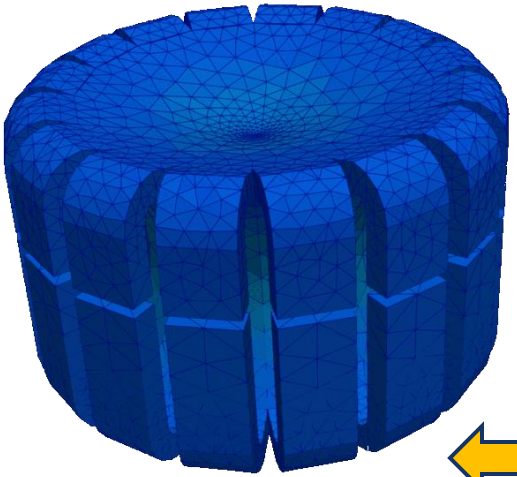


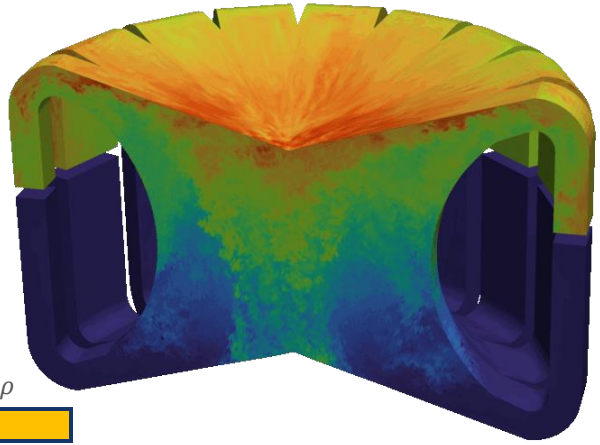
OpenMC + MOOSE heat conduction +
MOOSE 1-D heat pipes

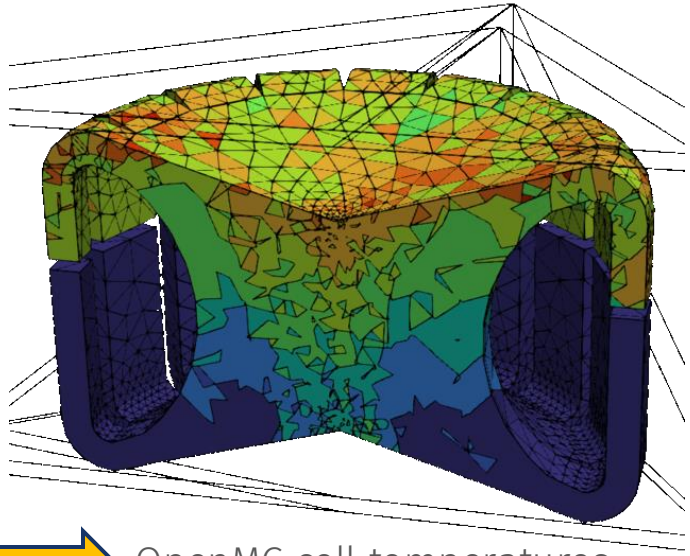




Molten Salt Reactors







T, ρ

power

NekRS temperature

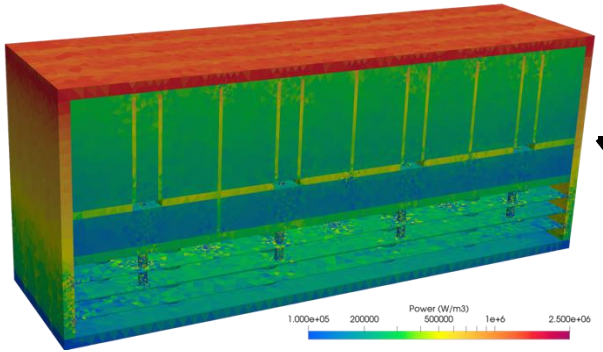
adaptive geometry

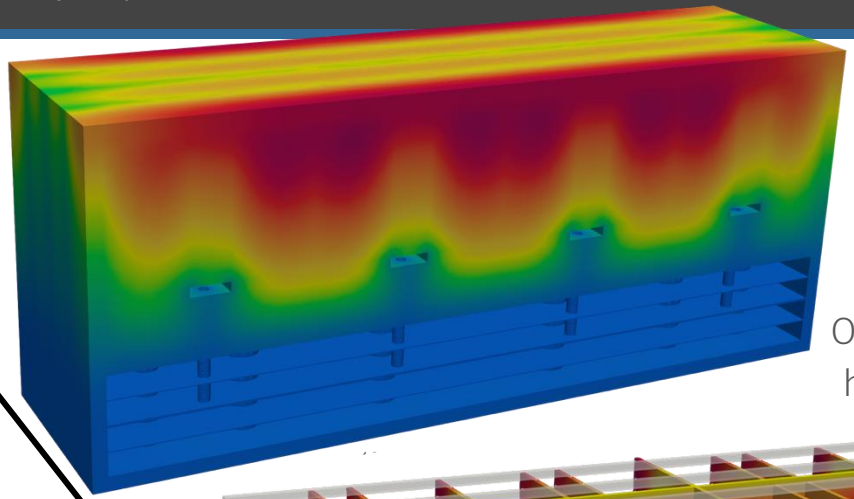
OpenMC cell temperatures

Fusion Breeder Blanket Multiphysics

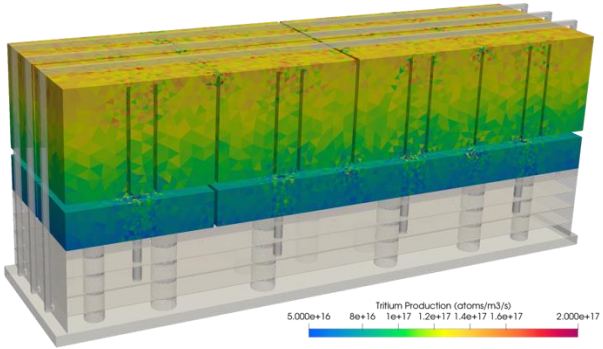
CAD geometry and mesh provided by UKAEA
(Helen Brooks, Andrew Davis)

OpenMC nuclear heating distribution

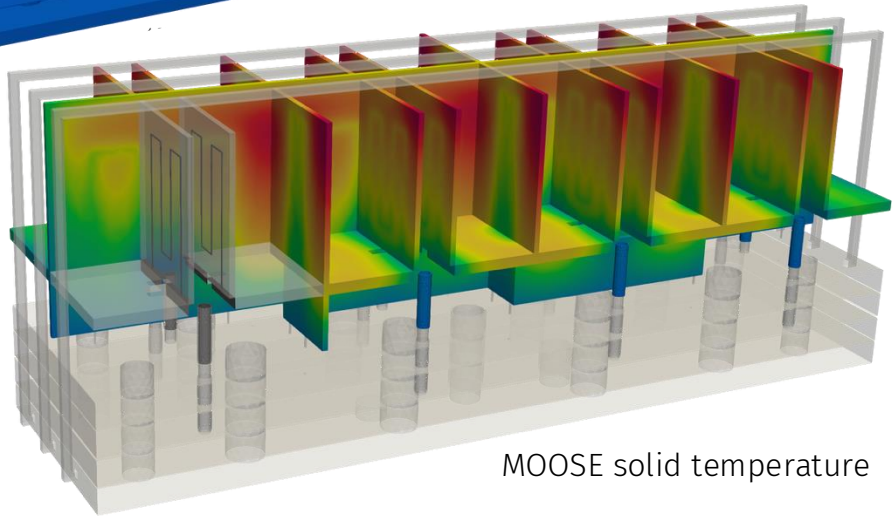




OpenMC + MOOSE
heat conduction

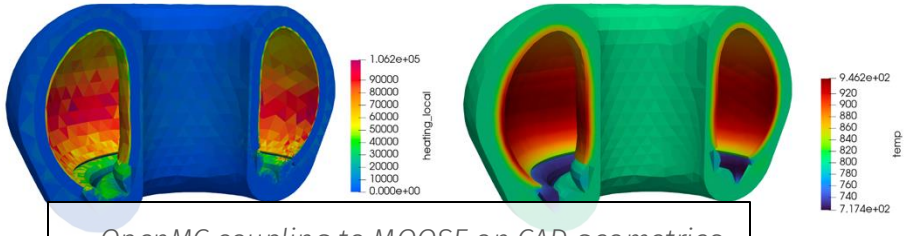


OpenMC tritium production rate



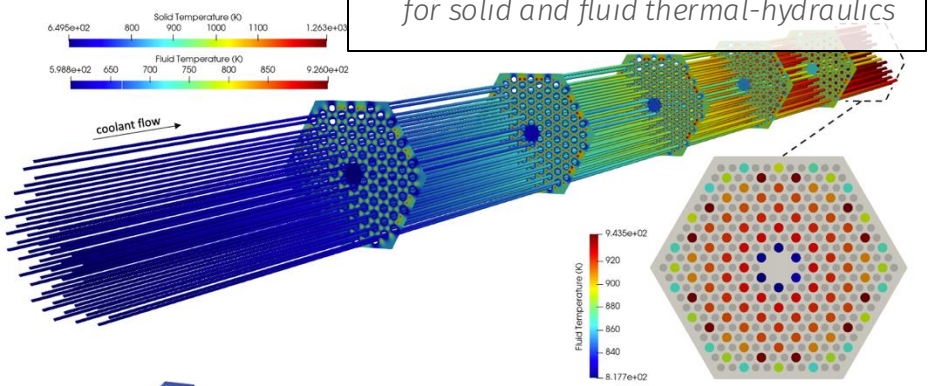
MOOSE solid temperature

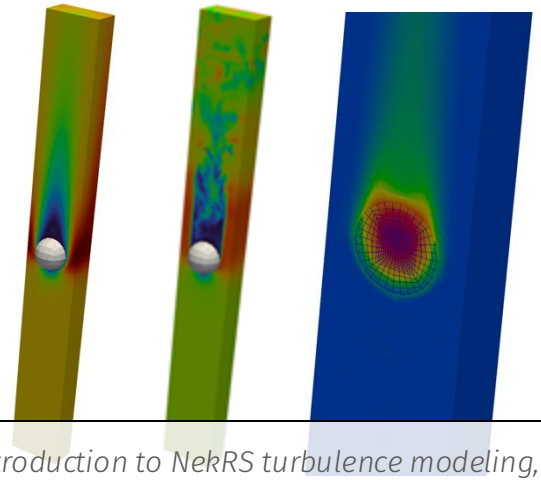
25 Tutorials on the Cardinal Website: https://cardinal.cels.anl.gov



OpenMC coupling to MOOSE on CAD geometries

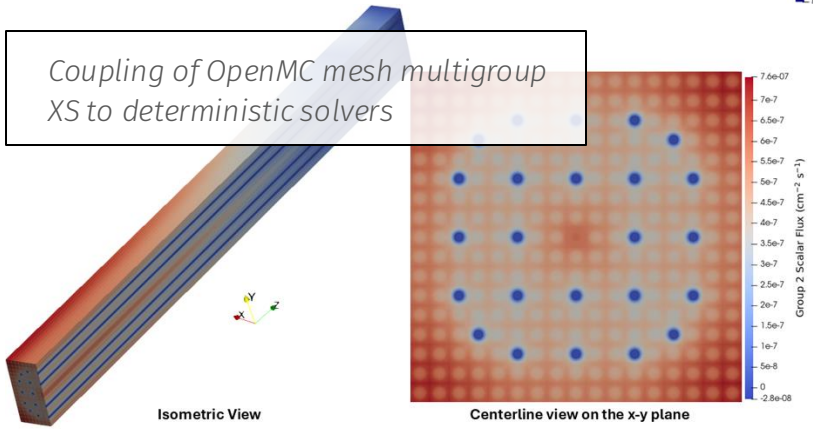
OpenMC coupling to two codes solving for solid and fluid thermal-hydraulics





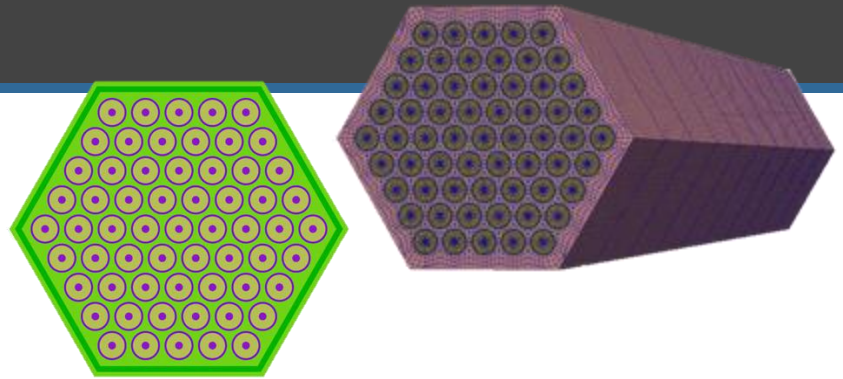
Introduction to NekRS turbulence modeling, conjugate heat transfer coupling to MOOSE

Coupling of OpenMC mesh multigroup XS to deterministic solvers

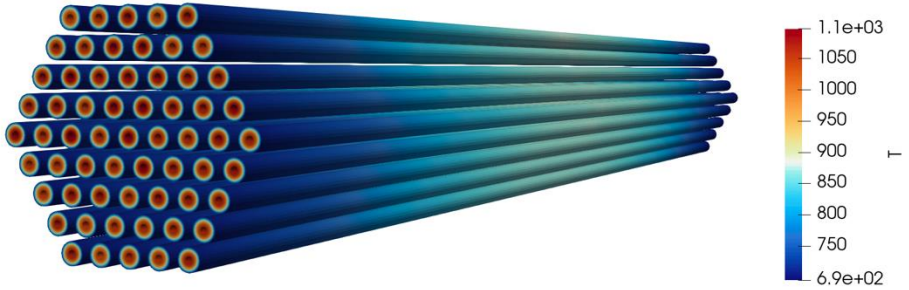


Workshop Schedule

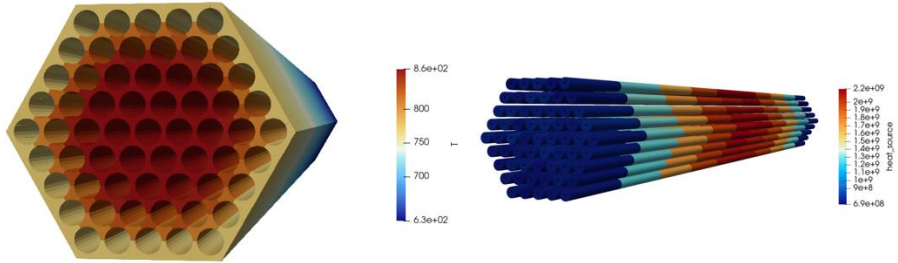
cardinal.cels.anl.gov/tutorials/subchannel.html



- **Step 1:** Build OpenMC and MOOSE heat conduction model of CEFR fuel assembly



- **Step 2:** Multiphysics coupling of OpenMC and MOOSE heat conduction



- **(time permitting) Step 3:** Coupled OpenMC, heat conduction, and a subchannel solver

Take-Home Activity: `all_coupled` folder

- Vary the number of axial layers in the mesh (10, 20, 30 layers)
  - Plot the temperature in the center fuel pin as a function of z as the mesh is refined (plot the data in `openmc_out_conduction0_T_0005.csv`)
  - How many axial layers would you recommend for use in this model?

- Change the thermal conductivity of the fuel (k from 1.0 to 10.0 W/m/K)
  - Plot the maximum fuel temperature and the multiplication factor as the thermal conductivity is varied and explain the trends you see (these values are printed to the screen as postprocessors)

- Vary the power level (power from 500 KWth to 1000 KWth)
  - Compute a power reactivity coefficient as a function of power (be sure to increase the number of particles and inactive batches to have sufficiently low statistical noise and a converged source)
  - What important physical process is missing from this model? Explain what effect you think including it will have on the power reactivity coefficient

Questions?

ajnovak2@illinois.edu

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