NEUP Integrated Research Project Workshop 2:
FHR Benchmarking and VVUQ

Session 2.4: Multiphysics discussion

April 14, 2016

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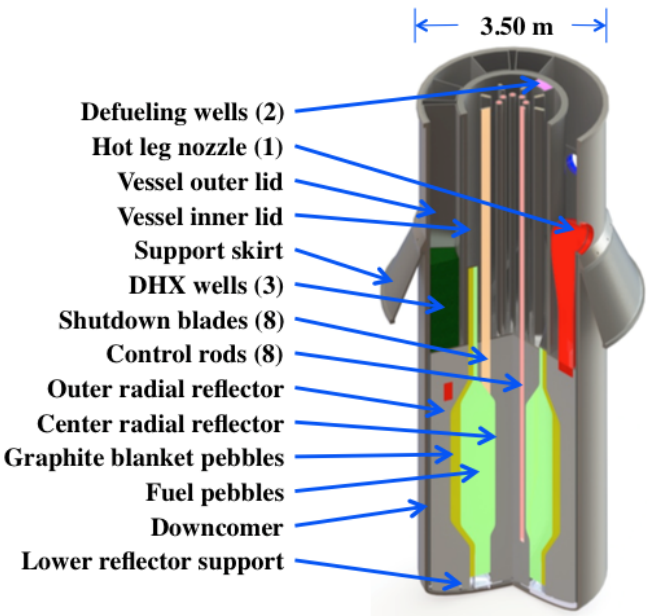
Content

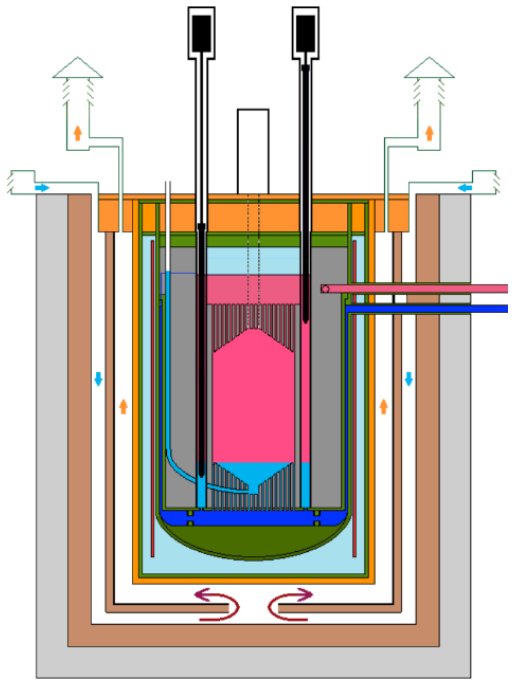
- Overview of FHR core and fuel designs
- Important thermal-hydraulic and neutronic phenomena
- Available thermal-hydraulic and neutronic numerical tools
- Materials multiphysics
- Available experimental facilities

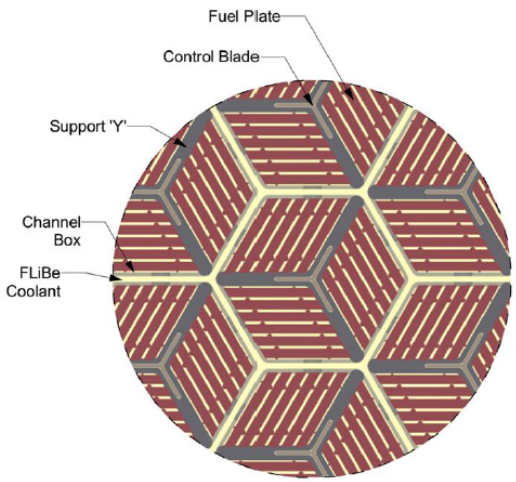
OVERVIEW OF FHRS

FHR Overview

Mk 1 Pebble-Bed FHR	Thorium Molten Salt Reactor – Solid Fuel 1 (TMSR-SF1)	Advanced High Temperature Reactor
236 MWth	10 MWth test reactor	3400 MWth, plate fuel







IMPORTANT PHENOMENA

What are the important parameters?

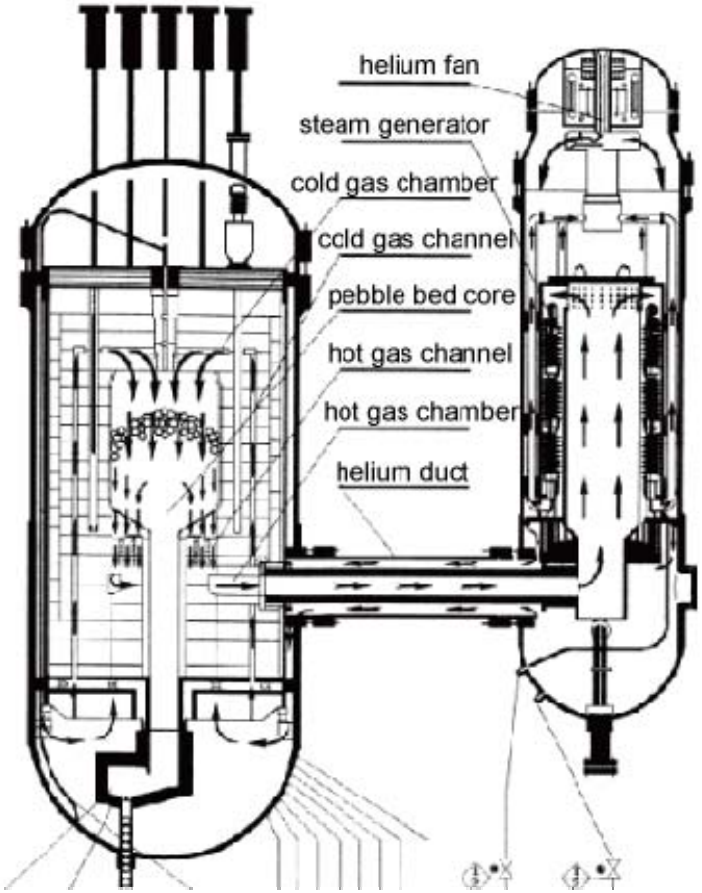
- **For multiphysics coupling, which parameters may be needed from each domain as input to the other?**

- **Neutronics**
  - Global
    - » Criticality
    - » Reactivity feedback from temperature and void
    - » Power peaking factor
  - Local
    - » Power distribution
- **Thermal-hydraulics**
  - Global
    - » Maximum temperature
    - » Time scale (time for heat generated in fuel to reach coolant)
  - Local
    - » Temperature profile
    - » Flow distribution

Important Phenomena: Case Study

- **HTR-10 is a 10 MWth test reactor located at Tsinghua University**
  - 6 cm diameter pebble fuel
  - Helium-cooled, 250-700 ^{o}C core ΔT
  - Cylindrical core with graphite reflector and carbon brick insulation

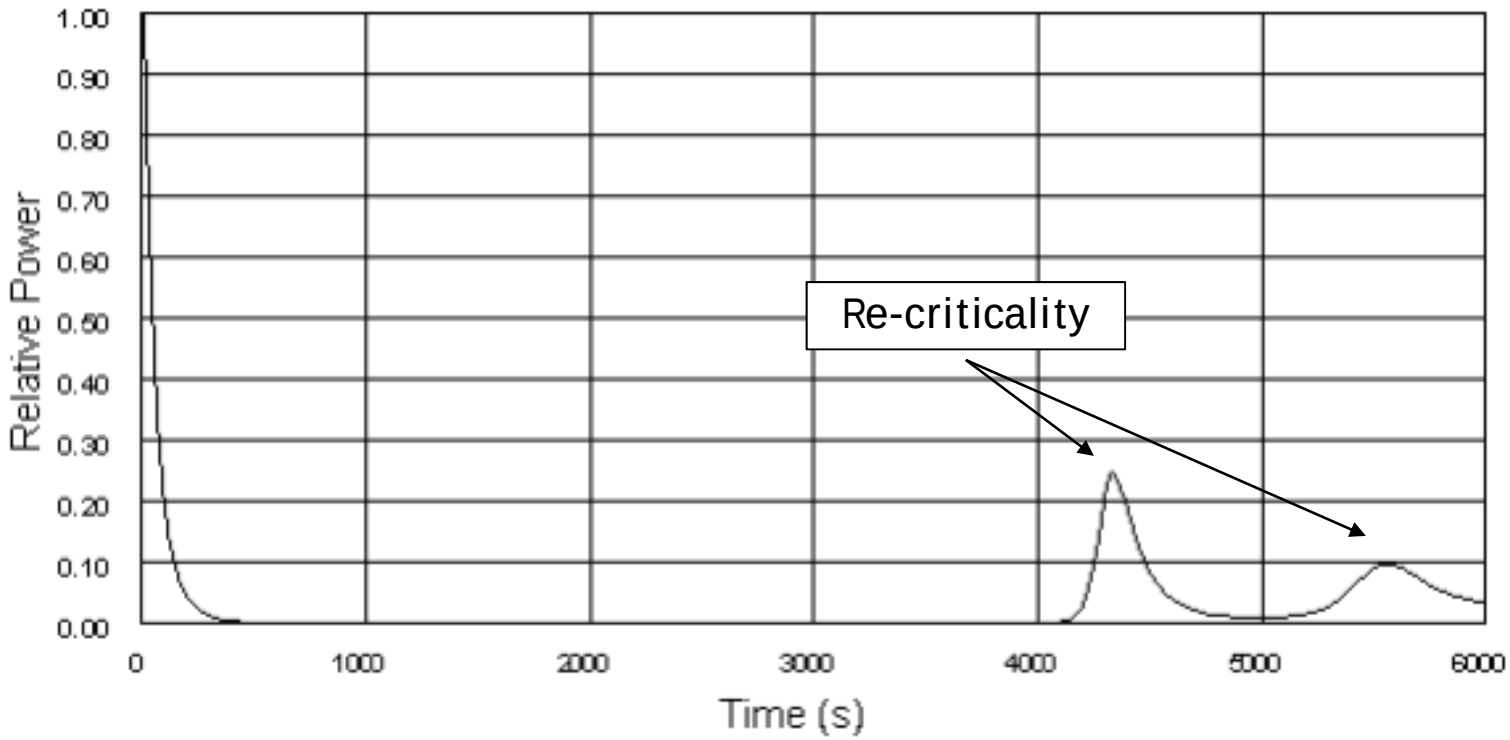
- **Experimental tests:**
  - LOFC at 30% power
  - LOFC at 30% power and ejection of one control rod



http://www.jsm.or.jp/ejam/Vol.2.No.1/GA/12/article.html

Important Phenomena: Case Study

- **Loss of Forced Circulation (LOFC) experiment:**
  - Helium blower is turned off (no forced circulation)
  - Primary system isolated from water cooling (no cooling)
  - No control rod insertion (ATWS)

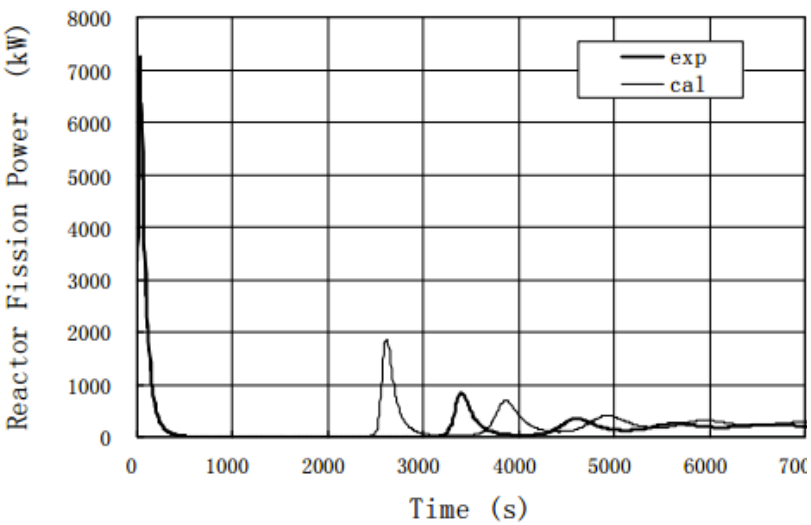


HTR-10 experimental data for the LOFC experiment [1].

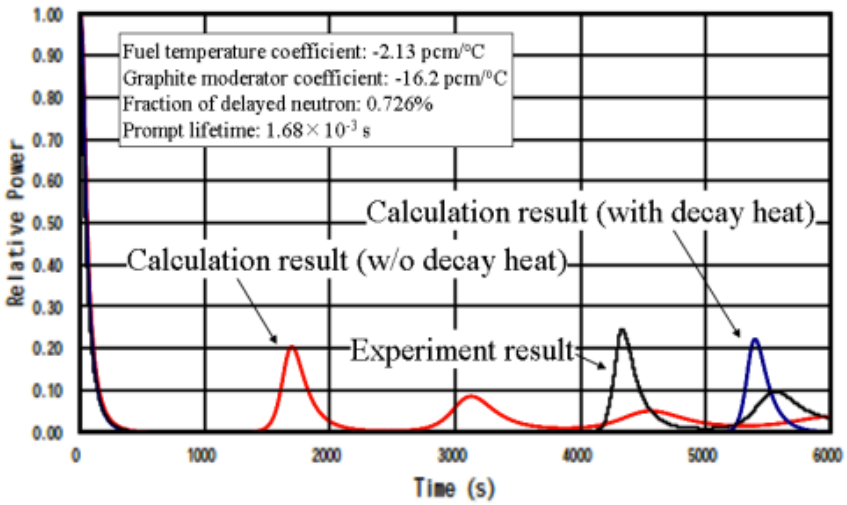
[1] *Evaluation of High Temperature Gas Cooled Reactor Performance*. Rept. no. TECDOC 1694. Vienna: IAEA, 2013. Print.

Important Phenomena: Case Study

- **Sensitivity studies [2] showed high dependence on:**
  - Effective core thermal conductivity
  - Decay heat
  - Overall core heat capacity



China's benchmark results using THERMIX, KONVEK, and KINEX for the LOFC + control rod withdrawal test [1].



Japan's benchmark results using TAC-NC for the LOFC test [1].

[2] BALL, S., CRP-5 Benchmark Calculations for INET HTR-10 Loss Of Forced Cooling (LOFC) ATWS Accidents, Nuclear Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN, United States of America (December 13, 2006).

Important TH Phenomena

- **What are the thermal-hydraulic phenomena that have the biggest impact on neutronics in salt reactors?**
  - Heat transfer
  - Bypass flows
  - Materials thermal properties
  - Time delay from heat generation in fuel to heat transfer to coolant
  - Others

Important Neutronics Phenomena

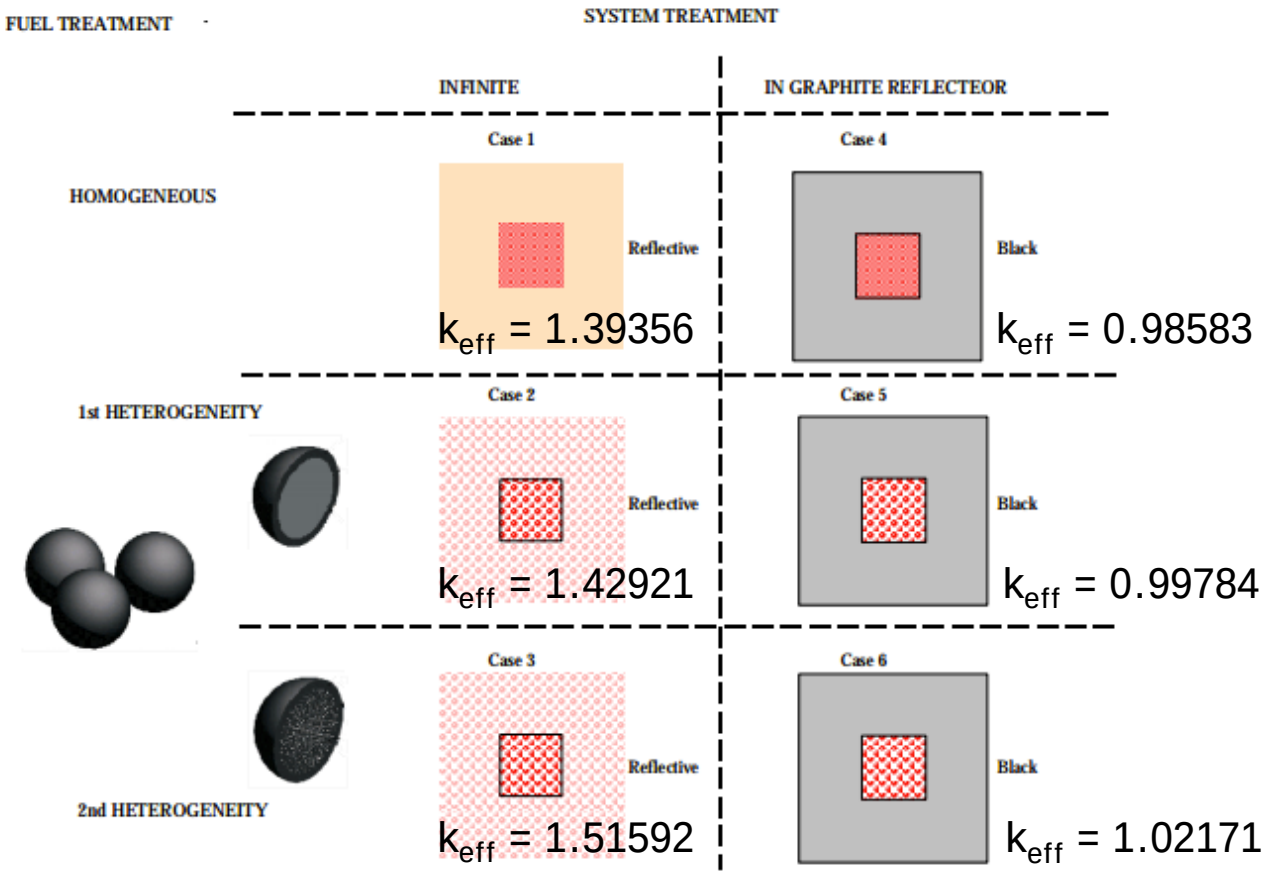
- **What neutronics phenomena/considerations have the largest impact on thermal-hydraulics in salt reactors?**
  - Multiscale approximations (double heterogeneity)
  - Impact of pebble movement and (random) distribution
  - Uncertainty in nuclear data
  - Decay heat for transients
  - Others

Order of Importance for Modeling

- **What are the scenarios for which coupled TH/N is most important?**
  - Steady-state
  - Reactivity insertions (global and localized)
  - Flow blockages (freezing transients)
  - LOFC (Loss of Forced Circulation without Scram)
  - LOHS (Loss of Heat Sink)
  - Depletion
  - Start-up
  - Others

Multiscale: Case Study

- **Double heterogeneity leads to increase in k_{eff} due to increase in resonance escape probability**



South Africa results using VSOP99 [1].

Multiscale

- **Fully resolving TRISO particles in large models may be computationally expensive**
  - 4,730 TRISO particles/pebble
  - 470,000 pebbles/core

- **To what level of accuracy are certain variables needed for particular modeling scenarios?**
  - When do we need to retain double heterogeneity in fuel?

Multiscale

- **What multiscale approximations are acceptable in the neutronics analysis to simplify whole-core analysis?**
  - Unit cell results → Whole core extrapolations
  - Other

- **How to capture temperature profile in the pebbles and TRISO particles for reactivity feedback?**
  - Discretization along radius
  - Function decomposition
  - Other

Combine core with other components

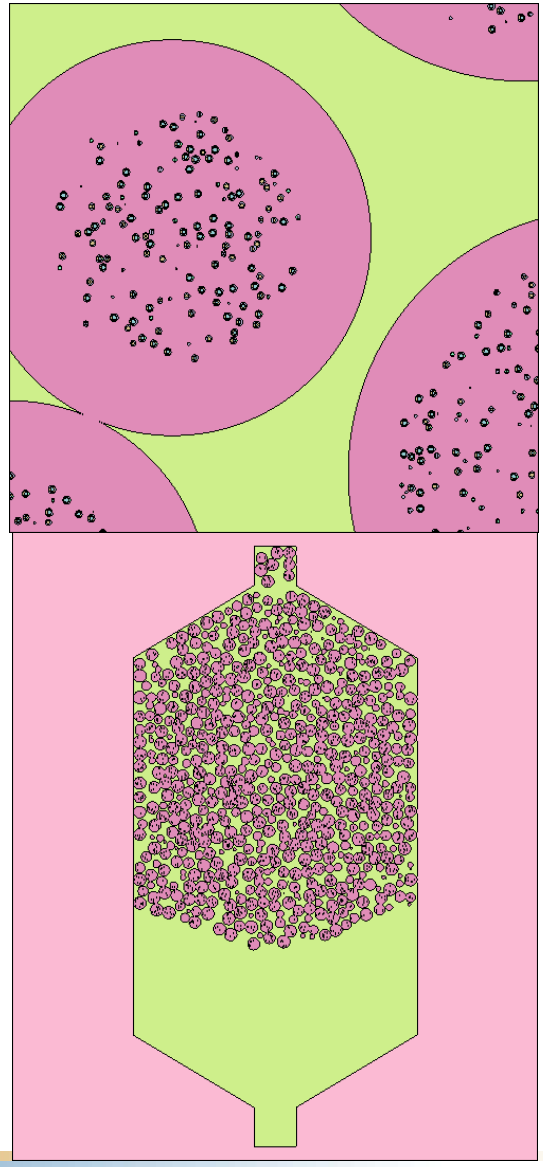
- **Which transients need systems code vs. core models?**
  - Steady-state
  - Reactivity insertions (global and localized)
  - Flow blockages (freezing transients)
  - LOFC (Loss of Forced Circulation without Scram)
  - LOHS (Loss of Heat Sink)
  - Others

- **Which transients need thermal-mechanical (conjugate heat transfer) study?**

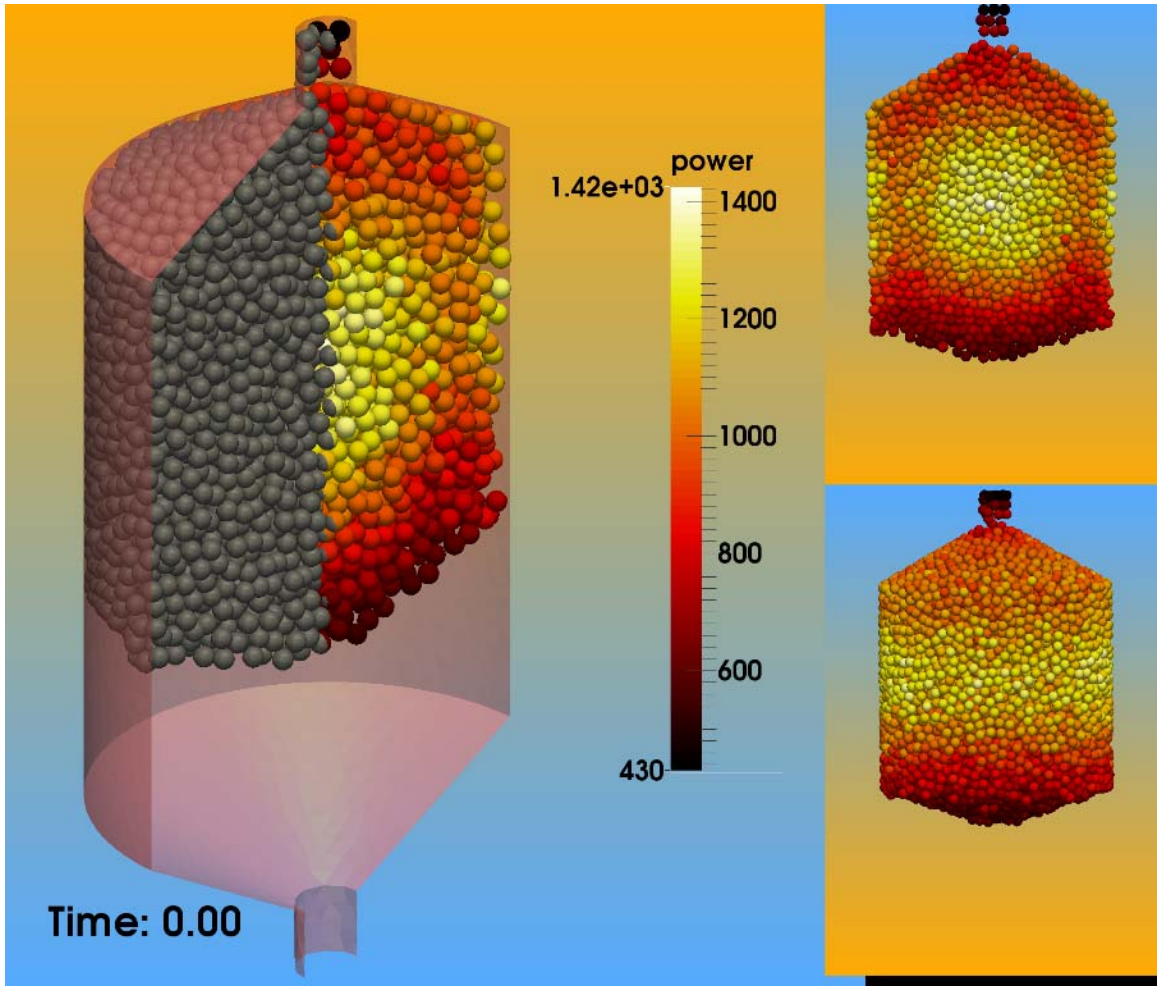
AVAILABLE NUMERICAL TOOLS

Serpent/OpenFOAM model

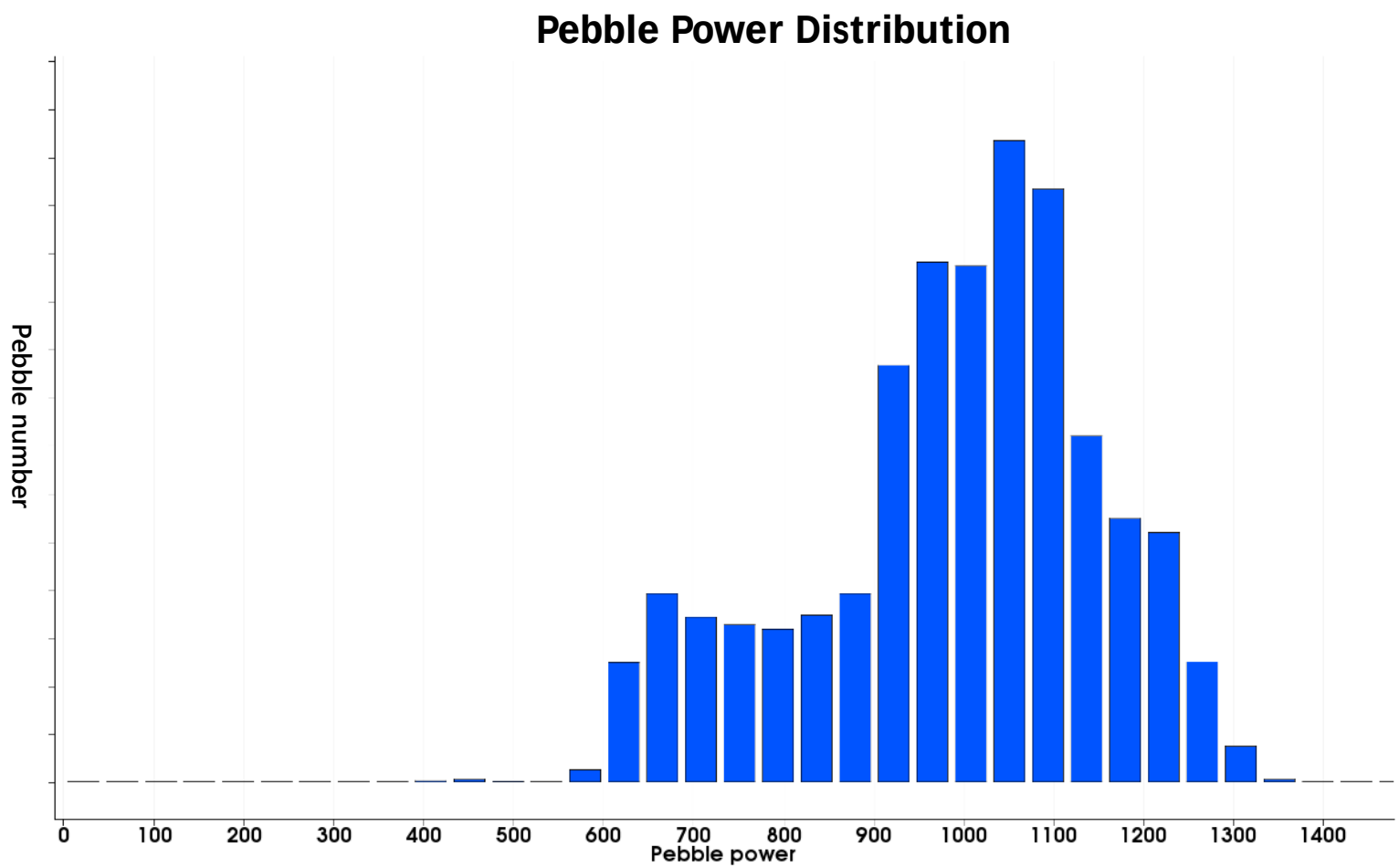
- **Fuel pebbles and individual TRISO particles are modeled explicitly**
- **Direct coupling between neutronics(Serpent) and thermal-hydraulics(OpenFOAM)**
- **Accurate but computationally expensive**
- **Used for optimization and benchmark**



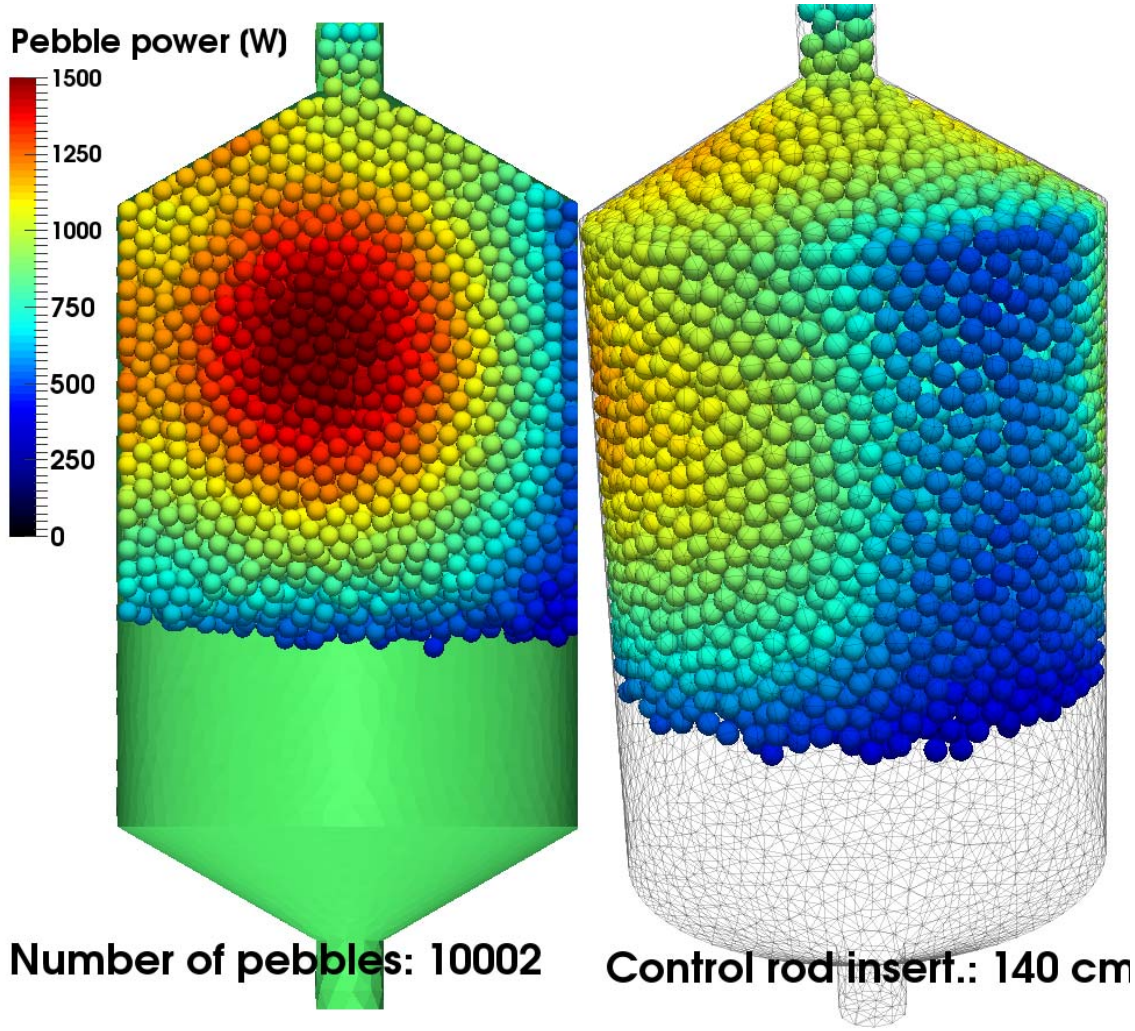
Result: power distribution



Result: power distribution

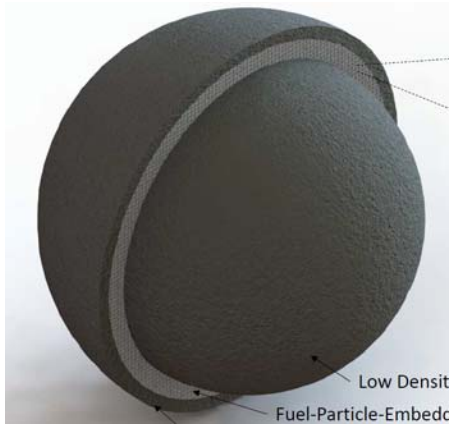


Control Rod Insertion Results



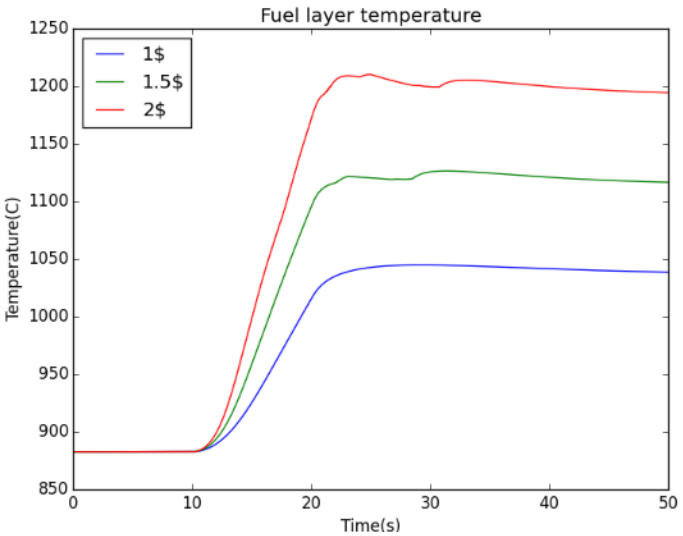
Unit cell model

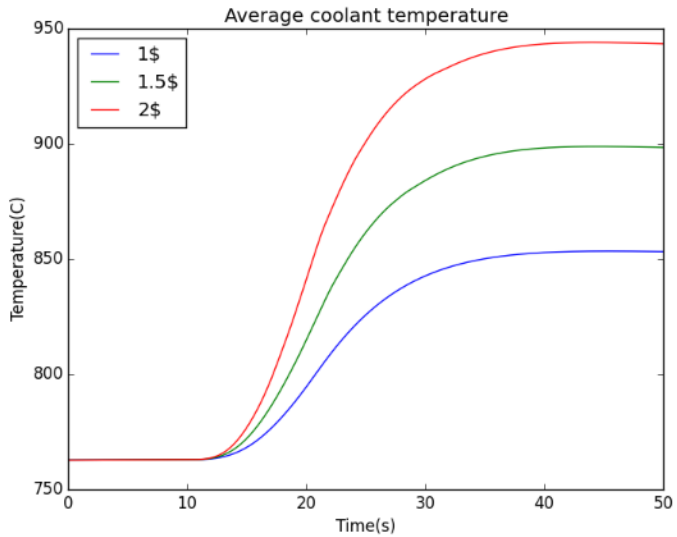
- **One average fuel pebble**
- **Average behavior, quick**
- **Used for scoping analysis, sensitivity and uncertainty study**
- **Open source Python package(Pyrk)**
  - **https://github.com/pyrk/pyrk**

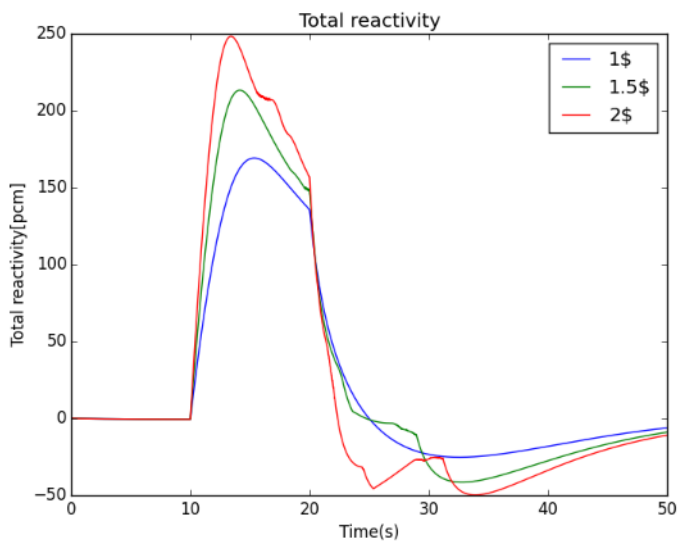


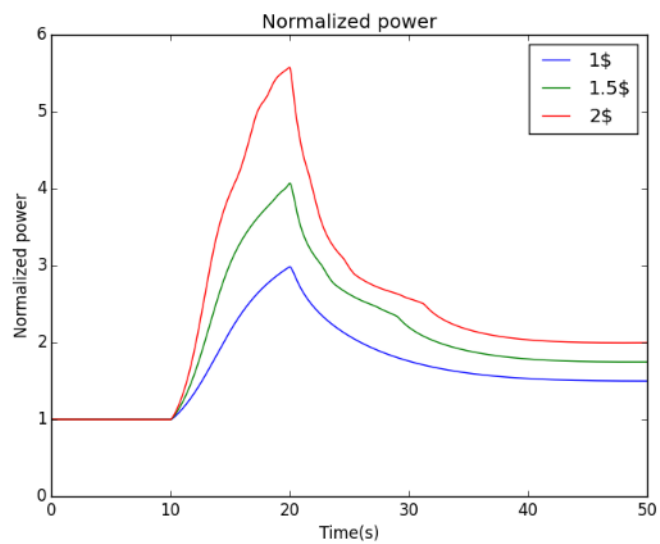
Schematic of the unit cell model geometry

Reactivity insertion results



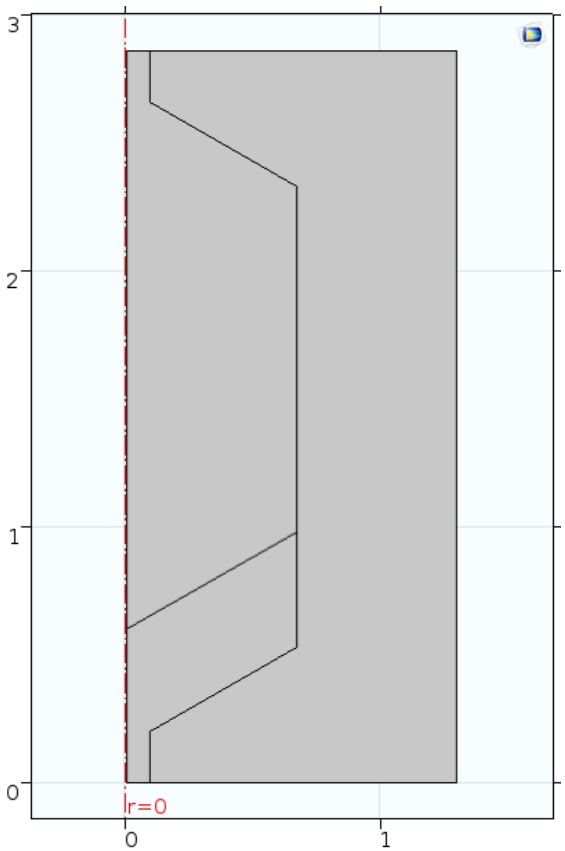






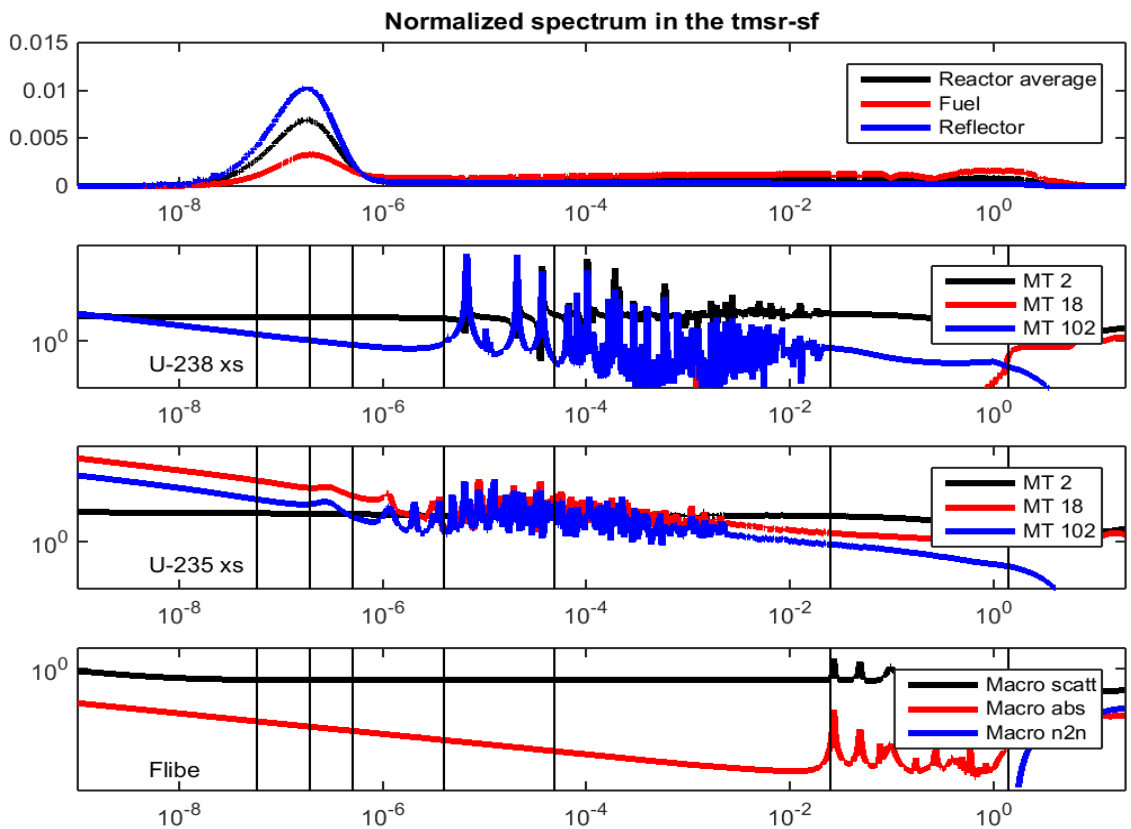
COMSOL model

- **2-D axisymmetric geometry**
- **Multi-group neutron diffusion model**
  - Cross-sections from Serpent full core model
- **Porous media thermal-hydraulics model**
  - Convective heat transfer coefficient from Wakao correlation
  - Uniform velocity
  - Adiabatic boundary condition
- **Multi-scale temperature profiles in the fuel pebbles and in the TRISO particles**
- **Less flexible but quick**
- **For production calculations, scoping analysis**

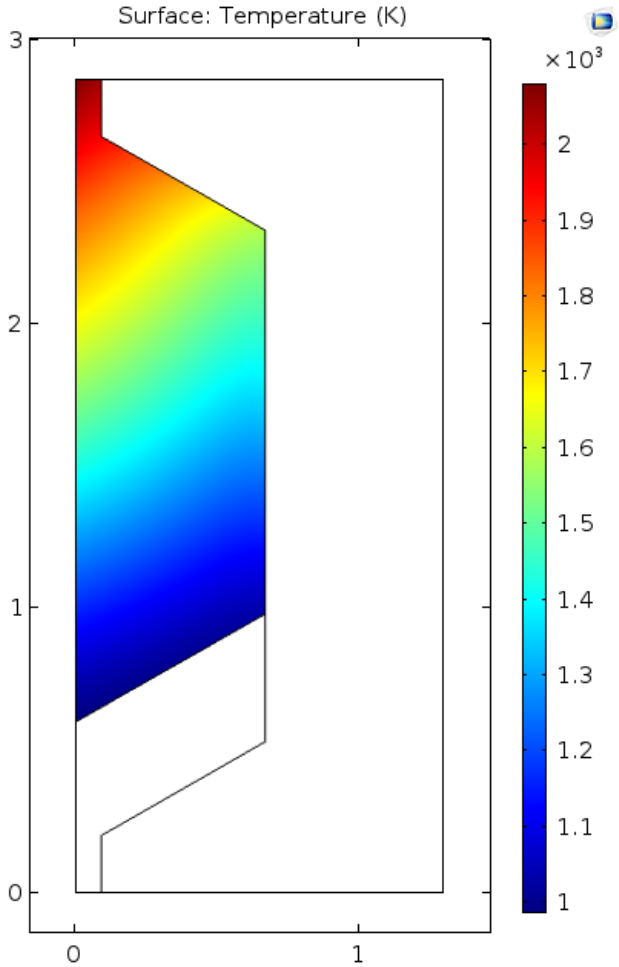


Multi-group structure

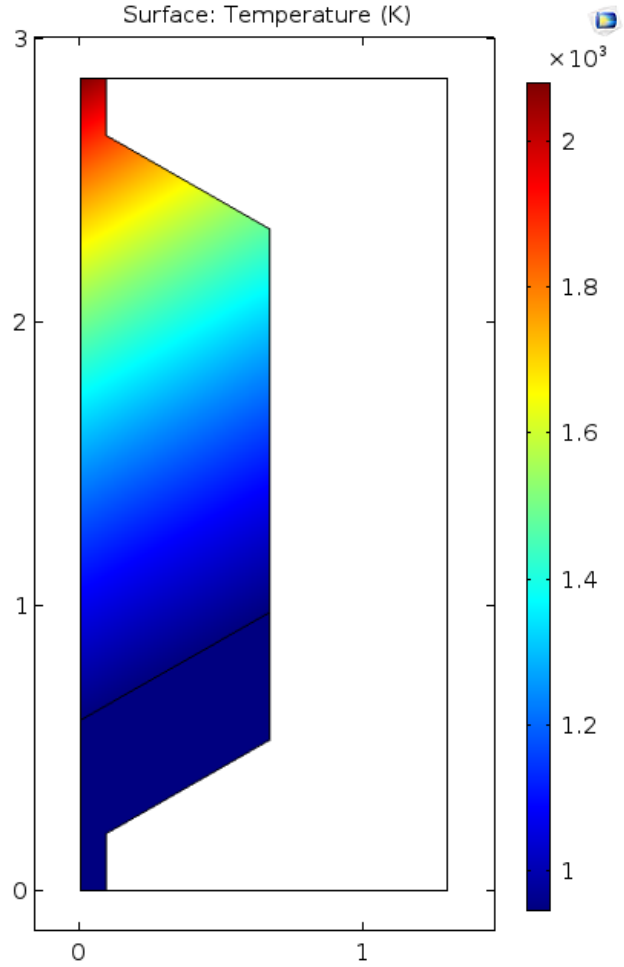
Group	Lower bound [MeV]
1	1.40E+00
2	2.50E-02
3	4.80E-05
4	4.00E-06
5	5.00E-07
6	1.90E-07
7	5.80E-08
8	0.00E+00



Temperature profile

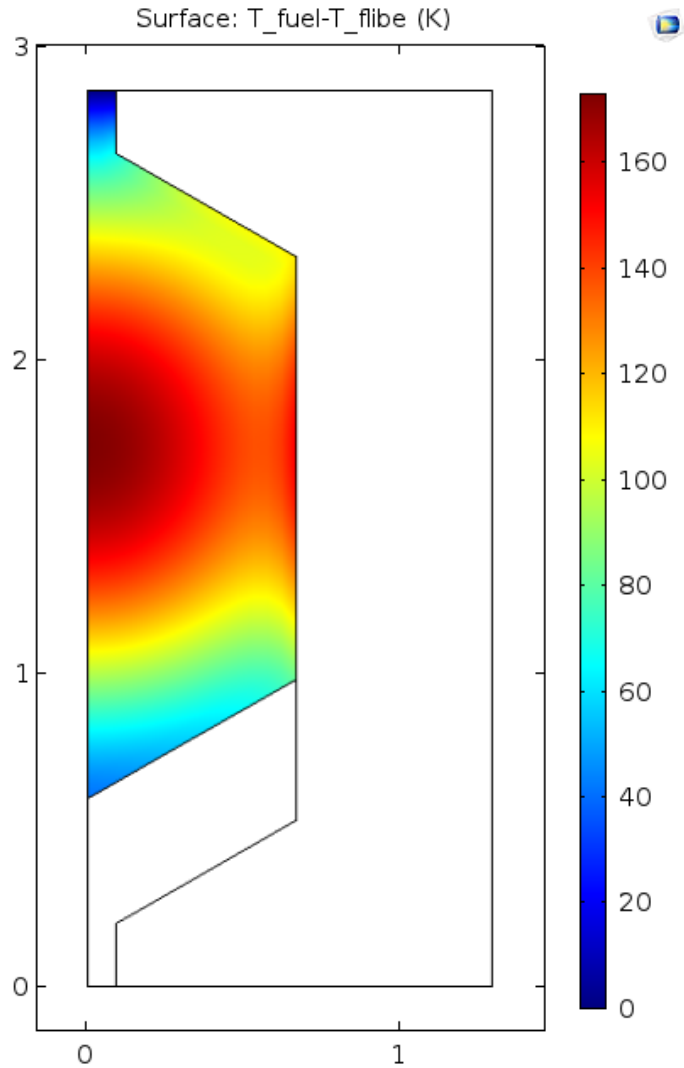


Average pebble temperature



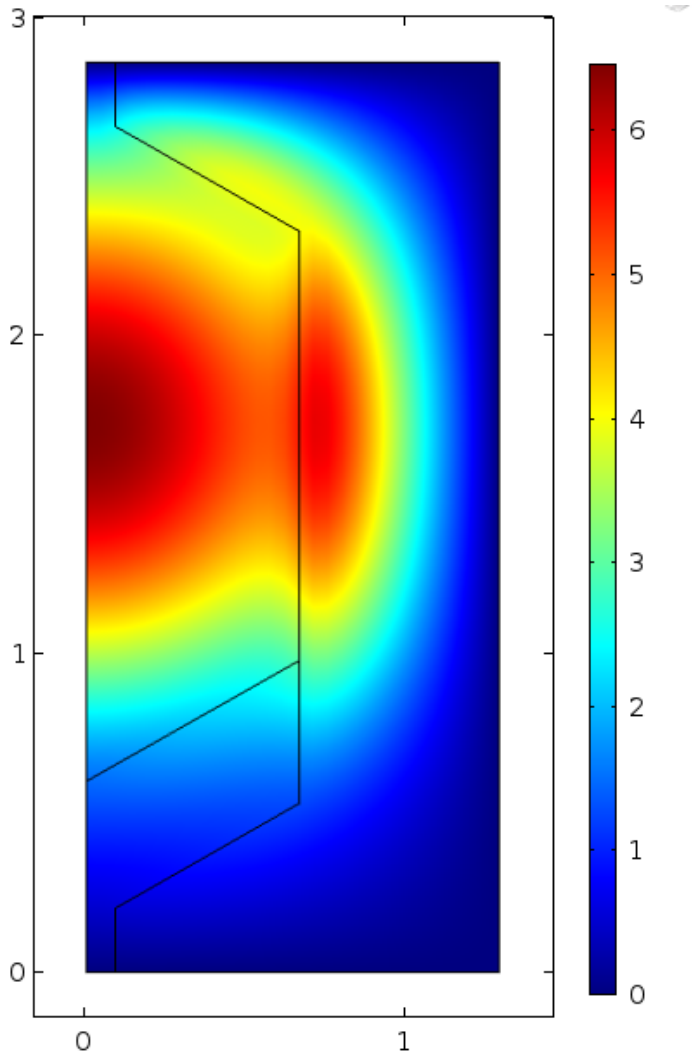
Coolant temperature

Temperature profile

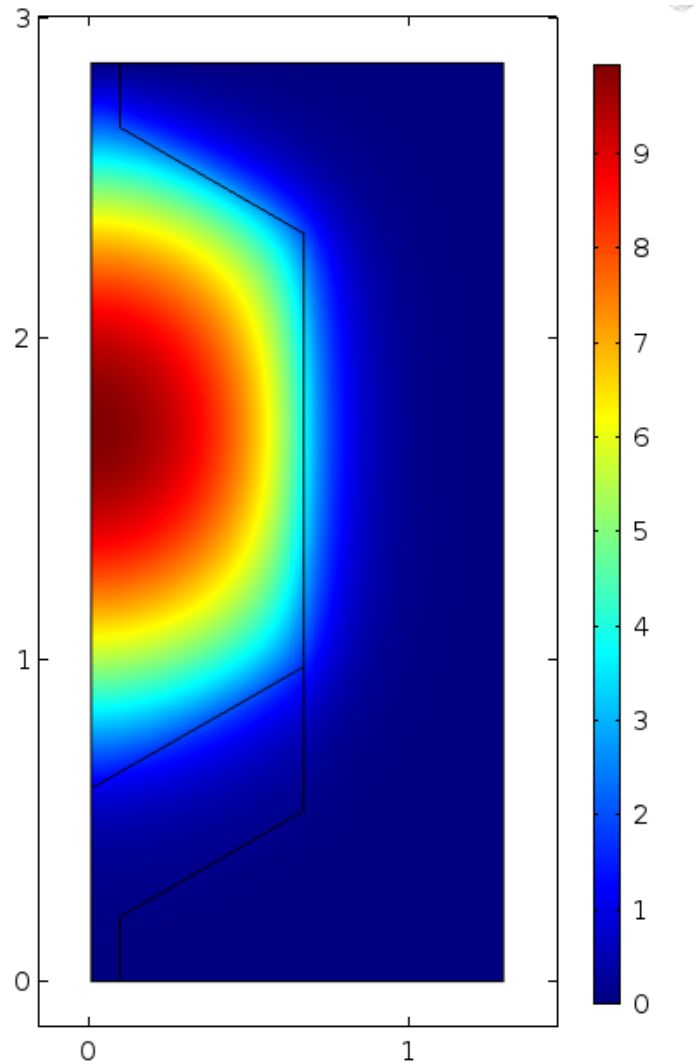


Difference between fuel temperature and coolant temperature

Neutron flux

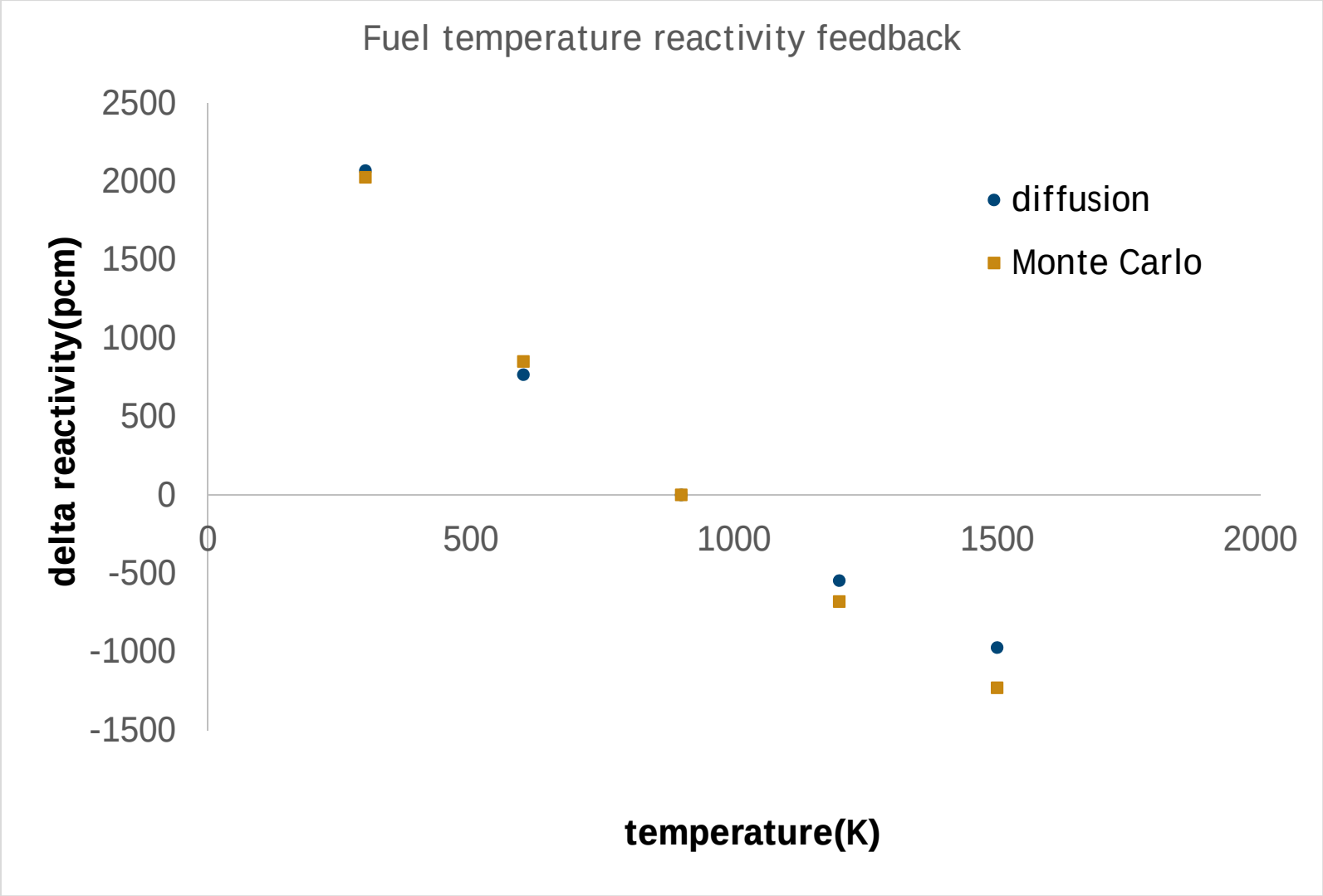


Thermal neutron flux

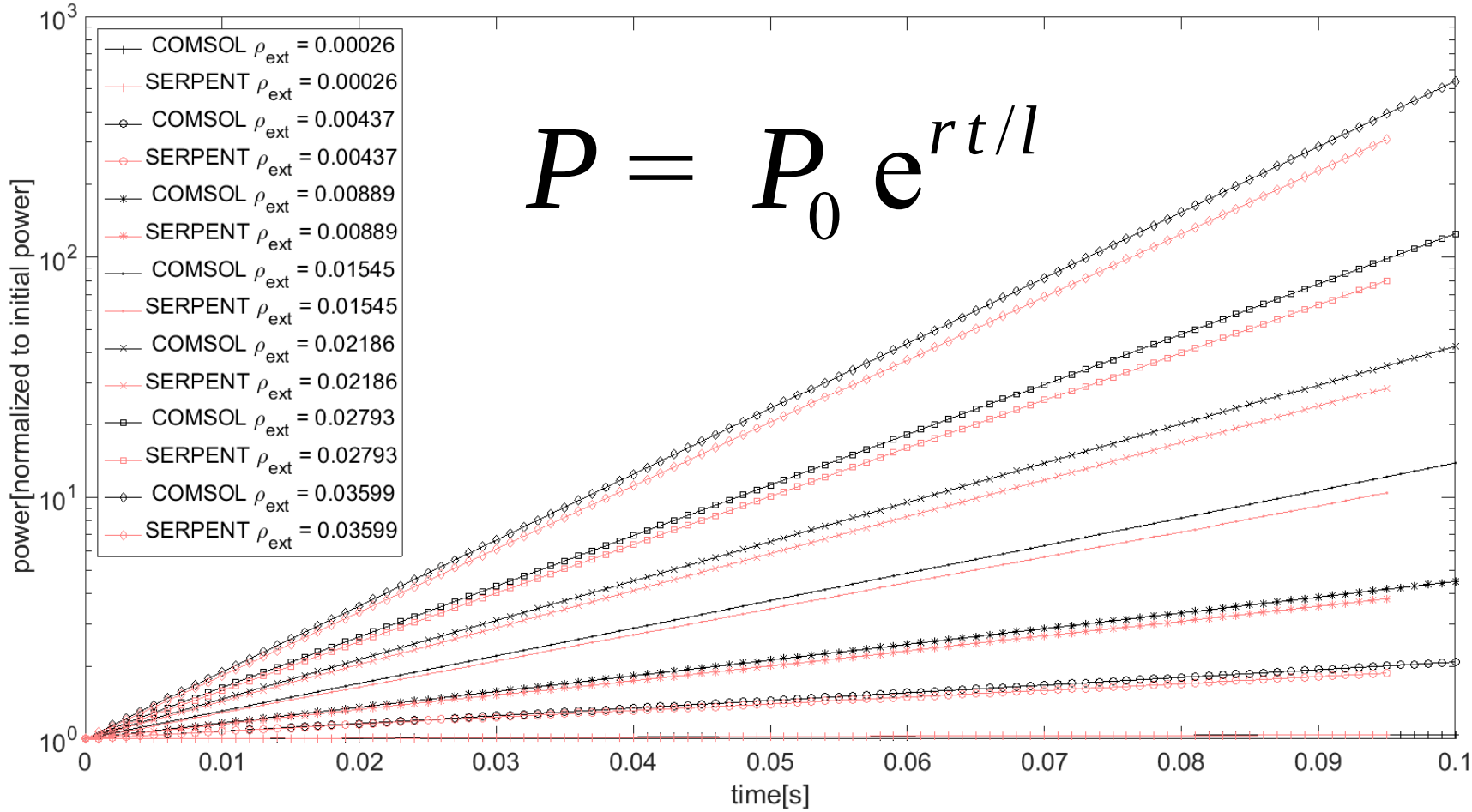


Fast neutron flux

Validation-Temperature feedback

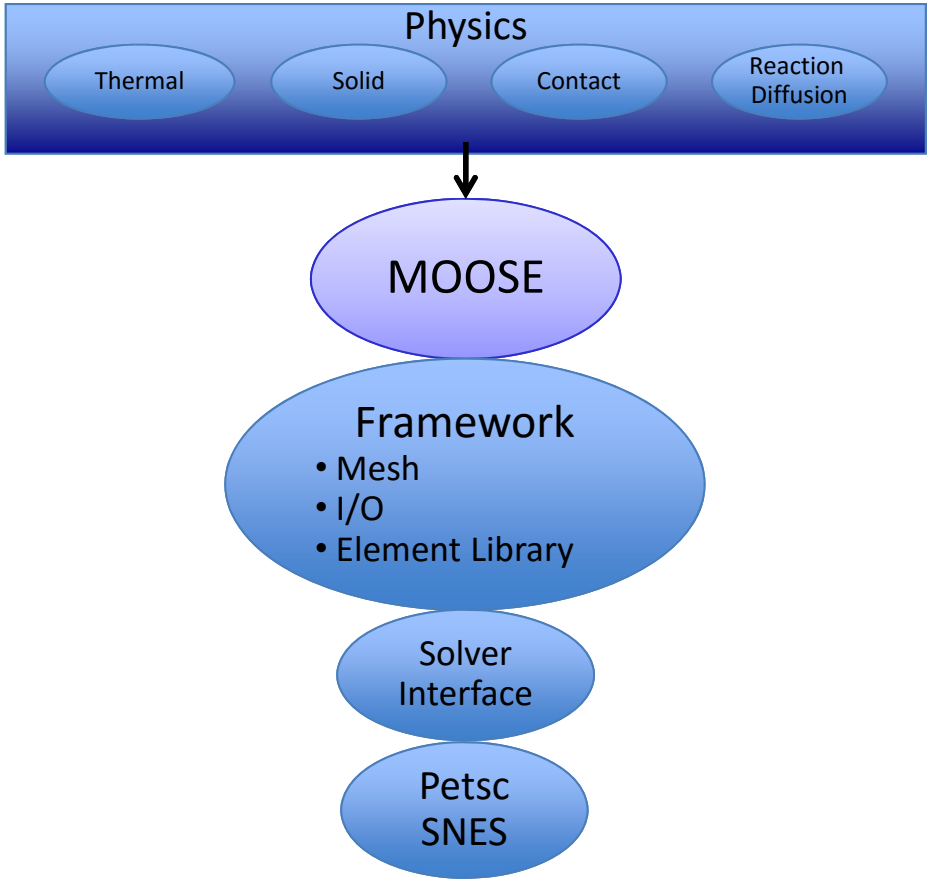


Validation-Reactivity insertion



MOOSE

- **Multiphyscis Object-Oriented Simulation Environment**
- **Modern software framework to allow rapid development of simulation tools**
  - Minimal external dependencies
  - Modular design



[5] Martineau, R. "INL's Advanced Modeling & Simulation Capability for Nuclear Applications." University of California. Berkeley. Oct. 2015. Lecture.

MOOSE Eco-system

- **RELAP7 – plant-scale thermal-hydraulics**
- **PRONGHORN – Gas-cooled pebble bed reactors**
  - Diffusion neutronics, porous media flow, and conjugate heat transfer
  - Being modified for salts (incompressible, thermally expandable, porous medium flow)
- **BISON – fuel performance**
- **Rattle$S_N$ake – multigroup diffusion, P_N, and 2nd-order S_N**
- **UW would be interested in creating a MOOSE animal for tritium transport**

[5] Martineau, R. "INL's Advanced Modeling & Simulation Capability for Nuclear Applications." University of California. Berkeley. Oct. 2015. Lecture.

Selected Tools

- **To study FHR transients, different approaches are adopted for coupled thermal-hydraulic and neutronics modeling:**
  - Coupled Monte Carlo/CFD/DEM model
    - » Accurate but computationally expensive
    - » For optimization and benchmarking
  - Point kinetics/unit cell heat transfer model
    - » Quick
    - » For uncertainty study
  - Deterministic/CFD model
    - » Less flexible but quick
    - » For production calculations, scoping analysis

Modeling Considerations

- **What tools should be used for which phenomena?**
- **What additional models should be developed?**
- **Are there other important phenomena to consider?**

MATERIALS MULTIPHYSICS

Numerical tools MATT

- **TRIDENT – system-level tritium transport modelling**
- **COMSOL – core-level tritium transport model**
  - More of a TH problem, since the core temperature rise does not dramatically affect diffusion
- **HSC (chemical reaction and equilibrium software) - calculate $\Delta G_{reaction}$ for corrosion modelling**
- **No current models for coupled TH/Materials**
  - Have time-based curve fits for static corrosion
  - Corrosion of materials under irradiation is still an open question

What are the important parameters?

- **For multiphysics coupling, what are the most important parameters for material and tritium transport modeling?**
  - Global
    - » Redox potential
    - » Impurity species and concentrations
    - » Tritium concentrations
  - Local
    - » Microstructure
    - » Radiation damage (dpa)

What information does MATT need?

- **What information is needed from other physics as input to materials models?**

- **Neutron flux**
  - Radiation damage
  - Isotopic production (tritium)
- **Temperature**
  - Creep and thermal stress
  - Impurities solubilities and diffusion constants
  - Corrosion
  - Freezing
- **Flow velocities**
  - System level corrosion products transport
  - Affects rate of corrosion and plate-out
  - Erosion might be a concern, still to be studied

Important MATT Phenomena

- **What materials phenomena/considerations have the largest impact on TH/neutronics in salt reactors?**
  - Salt freezing
  - Corrosion
  - Structural changes
  - Tritium transport
  - Degradation in thermal-physical properties

- **Is microstructure important for neutronics?**

Order of Importance for Modeling

- **What are the scenarios for which integration between TH/N and MATT is most important?**
  - Tritium transport
  - Corrosion product transport and activation
  - Salt Freezing
  - Others

- **Which of these scenarios are approximately 1-way couplings?**

BENCHMARK WITH EXPERIMENTS

Experimental Facility for Benchmark

- **Forced Fluoride Flow for Experimental Research**

Experimental Design

- **What types of experiments should be designed to benchmark multiphysics models?**
  - Implementing temperature feedback into the CIET heat supply to simulate Doppler feedback of fuel

- **Considerations in experimental design:**
  - Time lag between neutronics and thermal-hydraulics
  - Accurate determination of reactivity coefficients