Deep dive into Moose-based Micro-reactor Simulations

GAIN Micro-reactor Workshop

June 19th, 2019

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Where does this work come from?

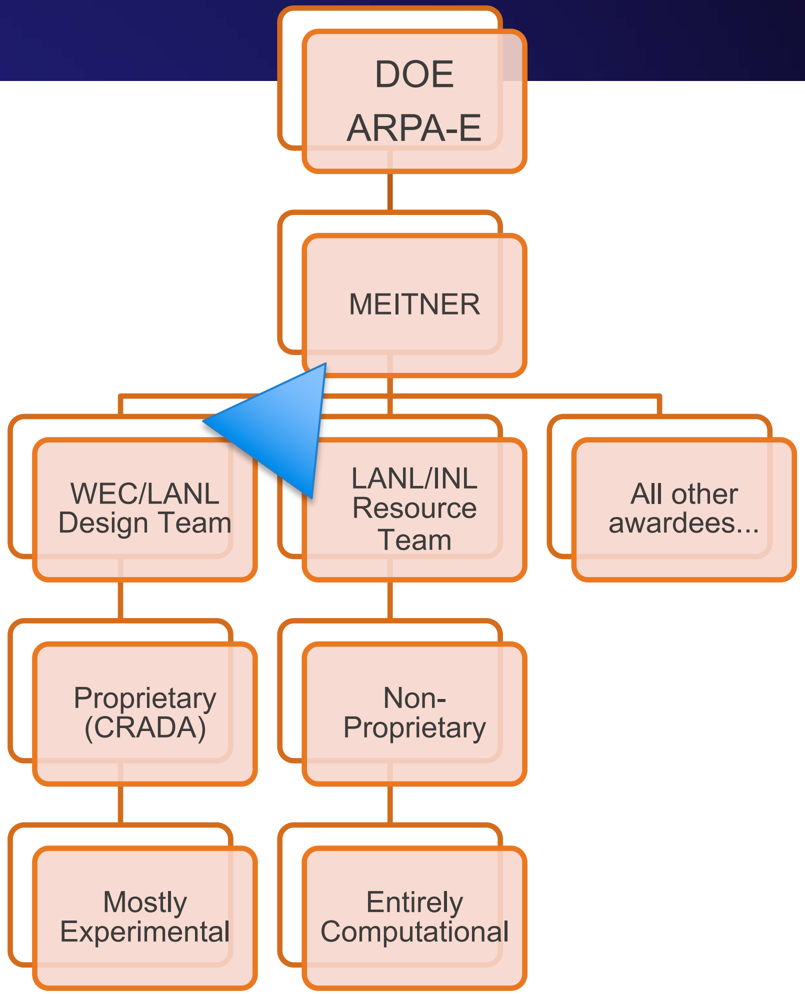
- MEITNER “Resource Team” is supporting computational design of Westinghouse/LANL “Design Team”

- Code down-selection part of Resource Team tasks:

  – Task 1: Identify problems, potential toolsets, and metrics for success
    → “Evaluation of M&S tools for micro-reactor concepts” LA-UR-19-22263

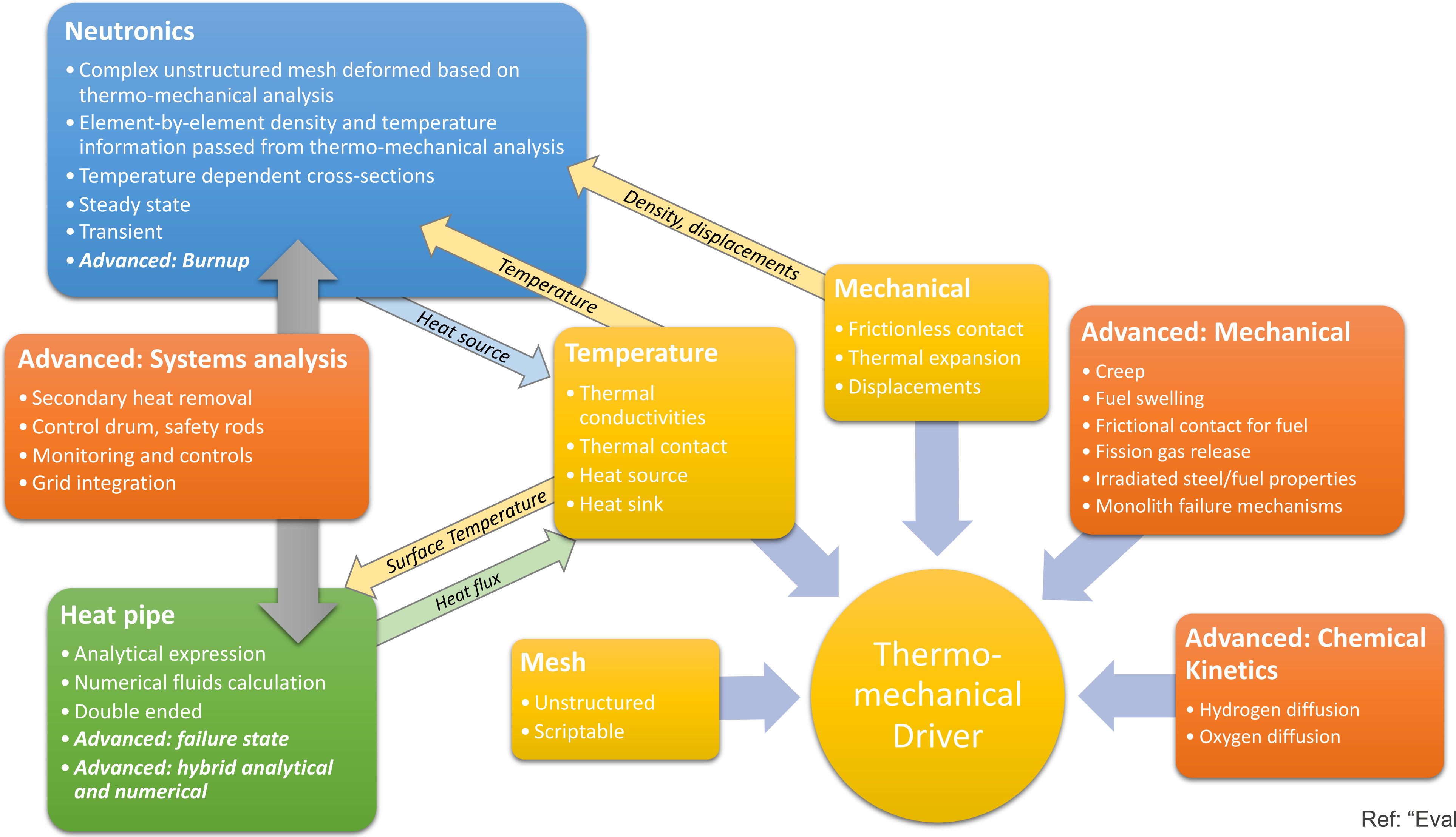
  – Task 2: Compare toolsets to an example problem to identify successes and risks
    → TBD

  – Task 3 and beyond: Provide support to MEITNER WEC Design Team



Analysis done here focused on heat pipe cooled micro-reactors…
But really the toolsets apply to any reactor design

Task 1: What do we care about, and what can be done about it



Ref: "Evaluation of M&S tools for micro-reactor concepts" LA-UR-19-22263

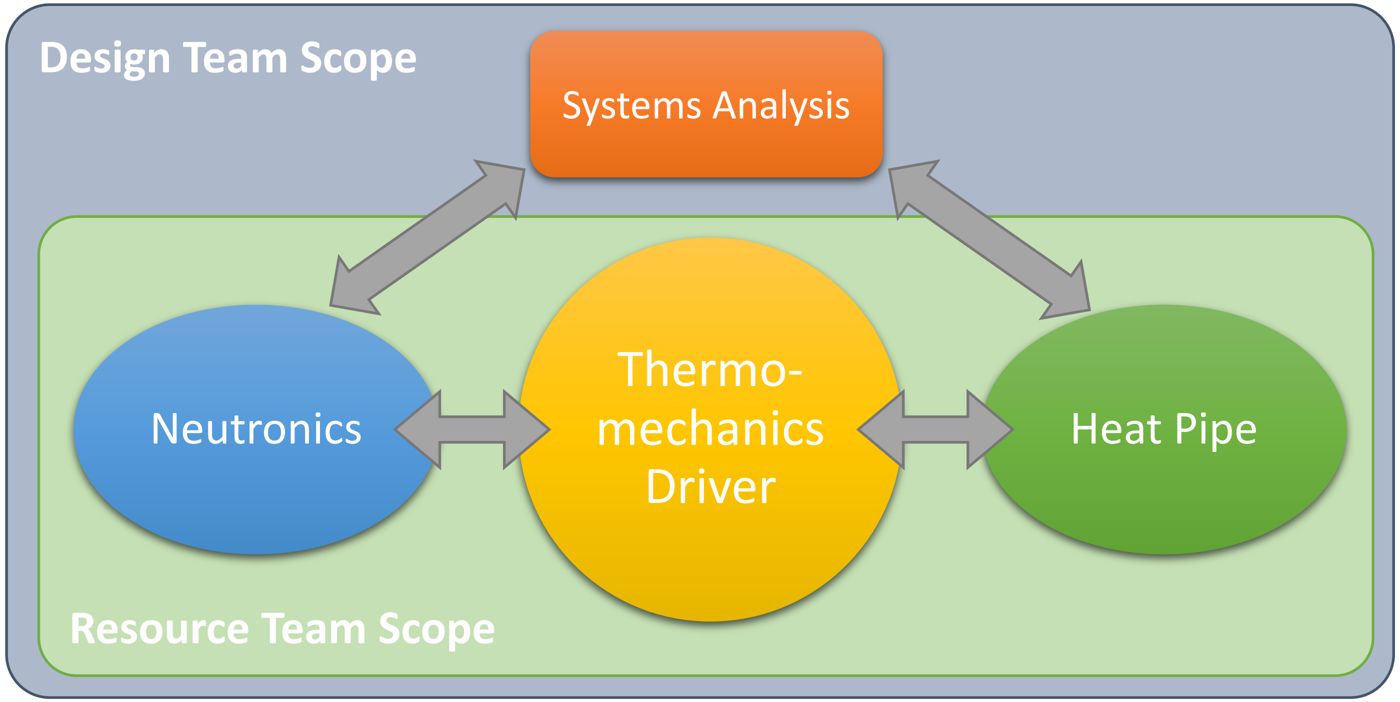
Task 1: What do we care about, and what can be done about it

Focus of RT is showing Self-Regulation:
Fundamental aspect of micro-reactor heat pipe design

Thermo-
- Heat generation
- Heat conduction

Mechanical-
- Thermal expansion
- Displacement

Neutronics
- Cross section creation
- eigenvalue solution,
- transient analysis



MAMMOTH

BISON

Ref: "Evaluation of M&S tools for micro-reactor concepts" LA-UR-19-22263

Task 1: What do we care about, and what can be done about it

Potential tool-sets:

ABAQUS – MCNP – Sockeye (LANL)
- Clunky and expensive due to input/output ascii parsing
- No transient capability

DireWolf: MAMMOTH – Bison – Sockeye
- Built to couple using Moose framework, but relatively unfamiliar
- Cross-section generation from Serpent or MCNP

Ansys – Proteus – Sockeye (ANL)
- Coupling framework still TBD
- Familiarity at Westinghouse

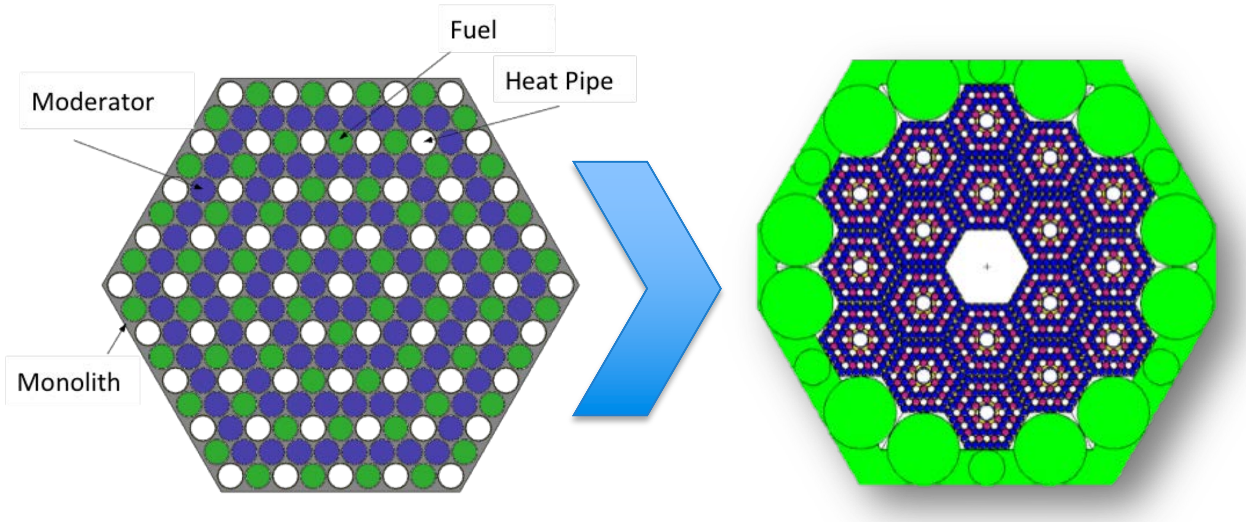
Metric	MOOSE	ANSYS	ABAQUS
Mechanical contact	◐	●	●
Thermal contact	●	●	●
Creep	●	●	●
Code Maturity	◐	●	●
Code Flexibility	●	○	○
Coupling Interface	●	○	○
Ease of use	●	●	●
Source code	●	●	●
Cost	●	○	○
Developer interaction	●	○	○
Massively Parallelizable	●	◐	◐
Run time	◐	◐	◐
Advanced capability implementation	●	◐	◐

Metric	SOCKEYE	HTPIPE	HTApprox
Double-ended heat pipe	◐	○	○
Analytical solution	●	●	●
Numerical solution	◐	◐	○
Code Maturity	◐	●	○
Code Flexibility	●	◐	○
Coupling Interface	●	○	○
Ease of use	◐	●	◐
Source code	●	●	●
Cost	●	●	●
Developer interaction	●	○	●
Massively Parallelizable	●	○	○
Run time	◐	●	●

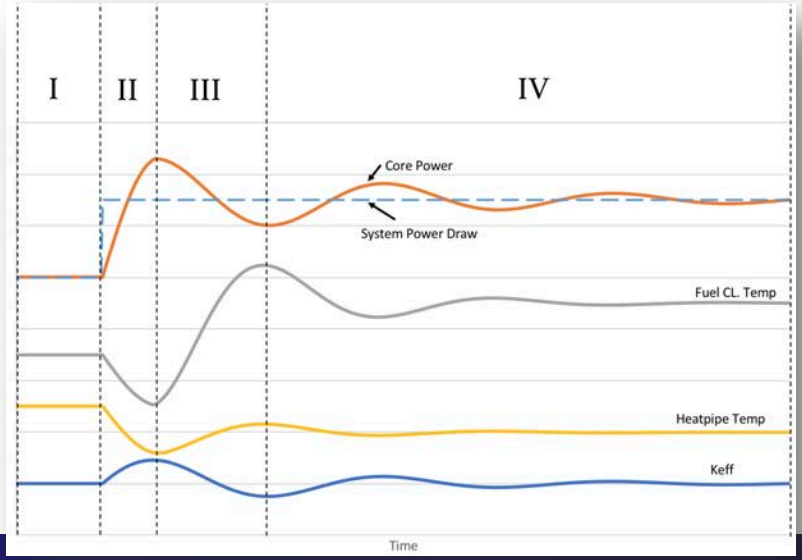
Ref: "Evaluation of M&S tools for micro-reactor concepts" LA-UR-19-22263

Task 1: What do we care about, and what can be done about it

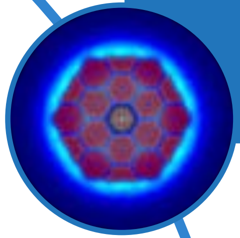
- How will we know it works?
  - Test against non-proprietary design
  - “Empire” Assessment problem
  - Test power draws, temperatures, failure modes, etc



- How do we guard against a “null” result
  - Focus on thermo-mechanical-neutronics *only*
  - Incremental problem growth
  - No contact
  - Approximate heat pipes as boundary conditions
    - 1) Constant temperature at surface
    - 2) Constant heat flux at surface



Task 2: Assessment problem



Cross-section generation

- Serpent → ISOXML → .XML
- Adding unstructured mesh capability with MCNP

Mesh

- Unstructured mesh for thermo-mechanical
- CSG or unstructured for cross-section generation

Steady state simulation

- Eigenvalue calculation to determine the initial conditions for transient simulations

Transient state simulation

- Diffusion or Sn simulation tightly, strongly, or loosely coupled to other physics

Coupling terminology:

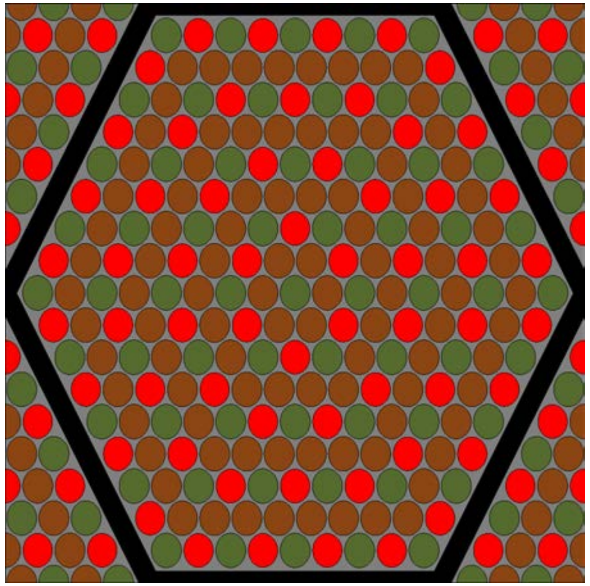
Strongly: Single non-linear solve with a single PDE matrix

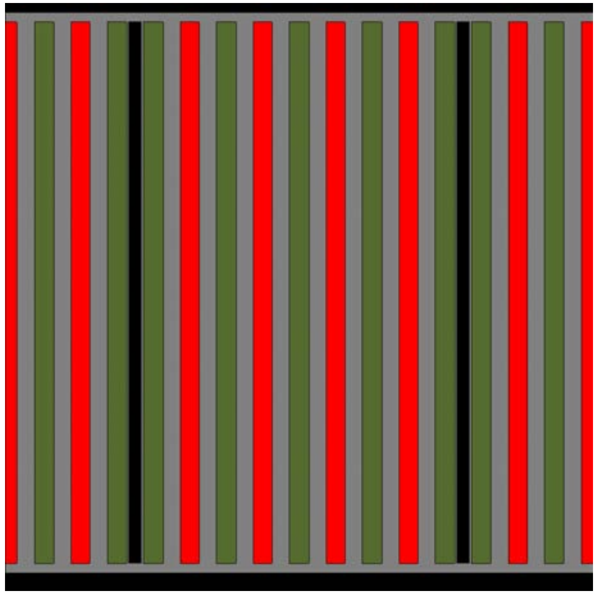
Tightly: Picard iteration between two or more non-linear solves

Loosely: Time-step information passing with no iteration between two or more non-linear solves

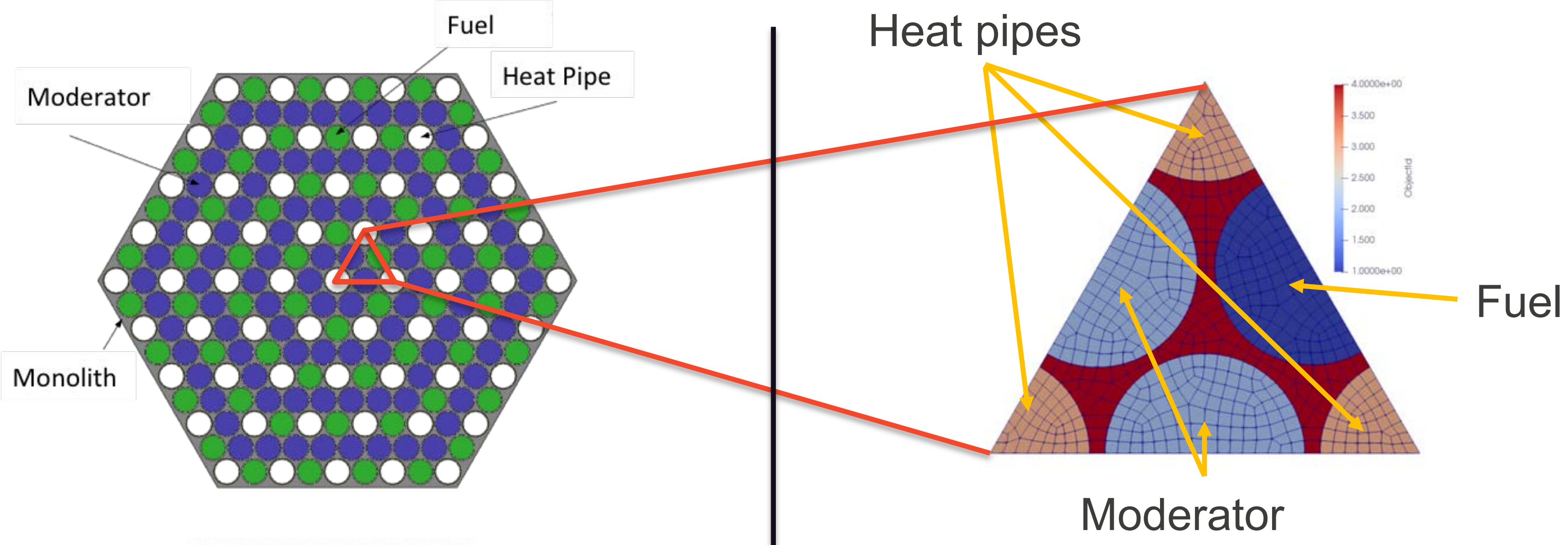
Assessment Problem: Cross-section generation

- Serpent model includes small axial reflector (1 cm).
- 6 energy groups from TRIPOLI (based on the 33 ECCO structure)
- 3 pins: fuel, heat pipe and moderator.
- 5 XS regions: fuel, heat pipe, moderator, monolith and axial reflector.
- XS functionalization: Tfuel (400, 600, 900, 1200 K).

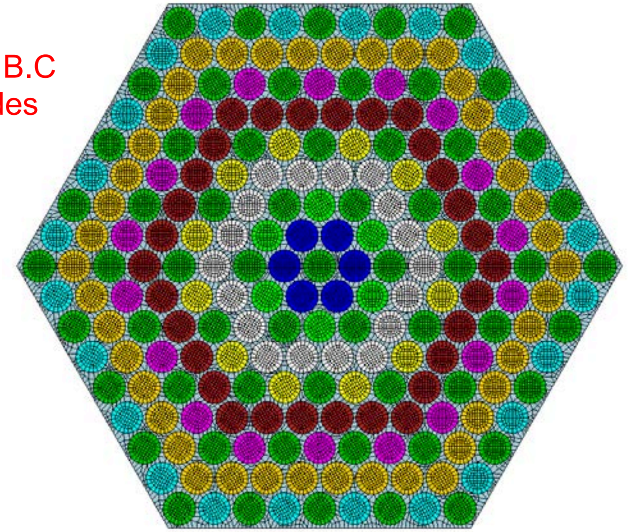


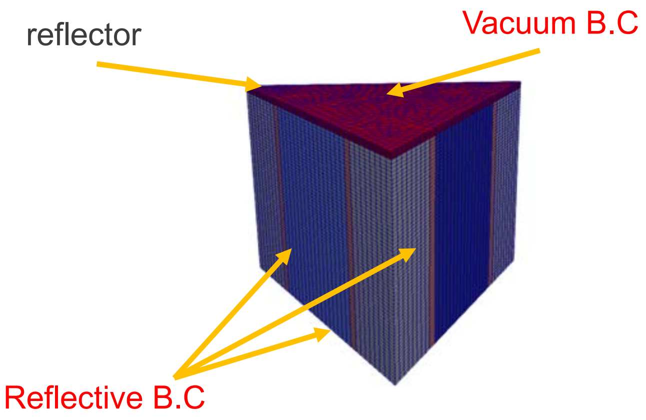


Assessment Problem: Mesh generation



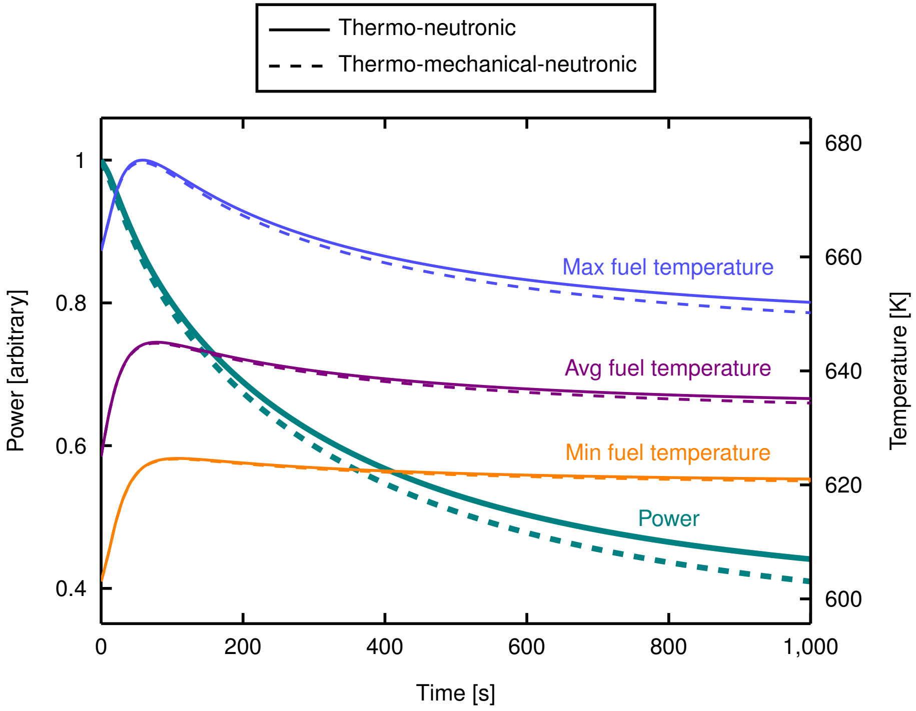
Vacuum B.C
on all sides



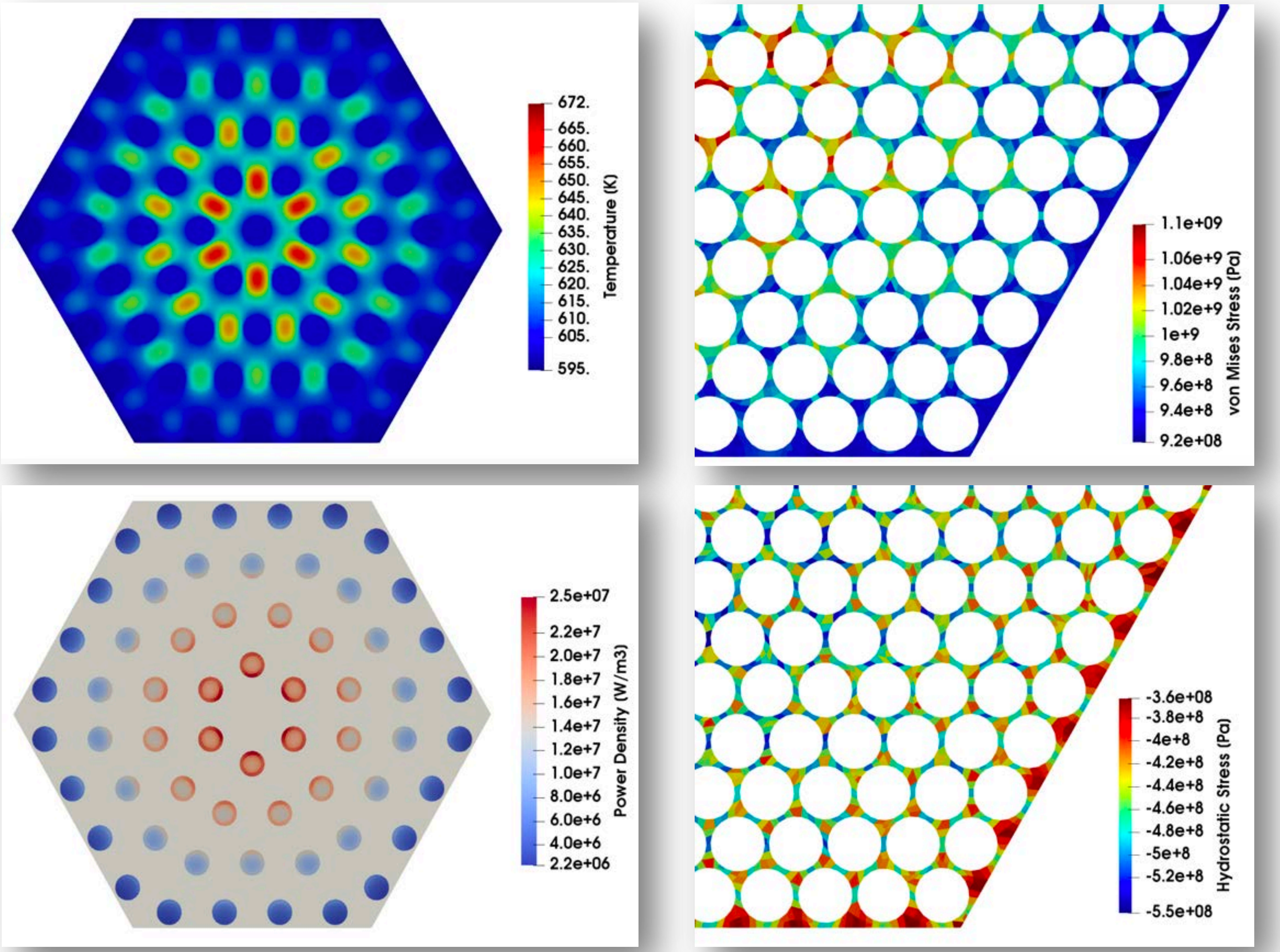


Assessment problem: Unit Assembly
Constant heat pipe temperature BC

- Steady state: Temperature BC = 600 K
- Transient initiation: Temperature BC = 625 K
- Temperature dependent cross-sections only
- Feedback from cross-section and density

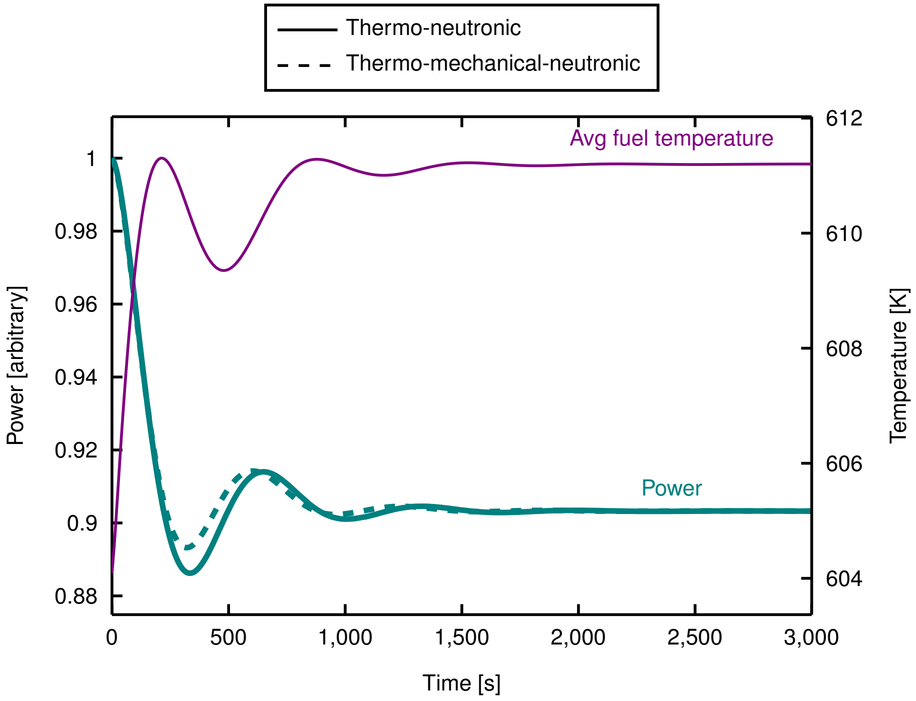


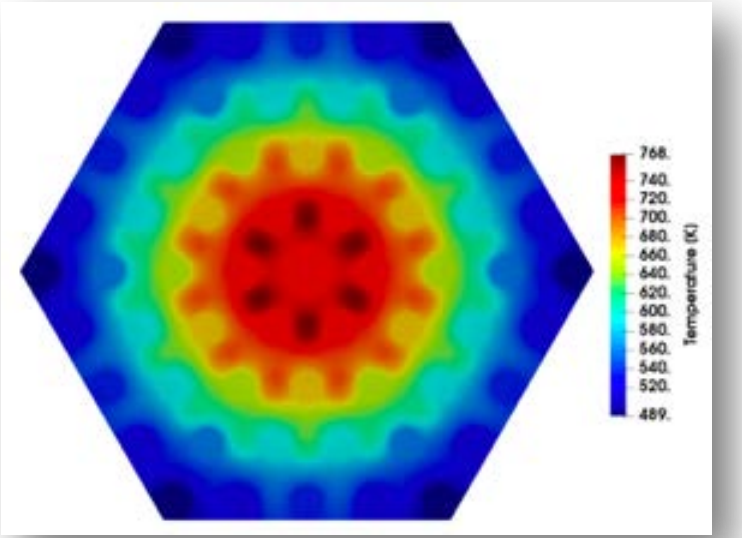
Fuel temperature increase = Power decrease

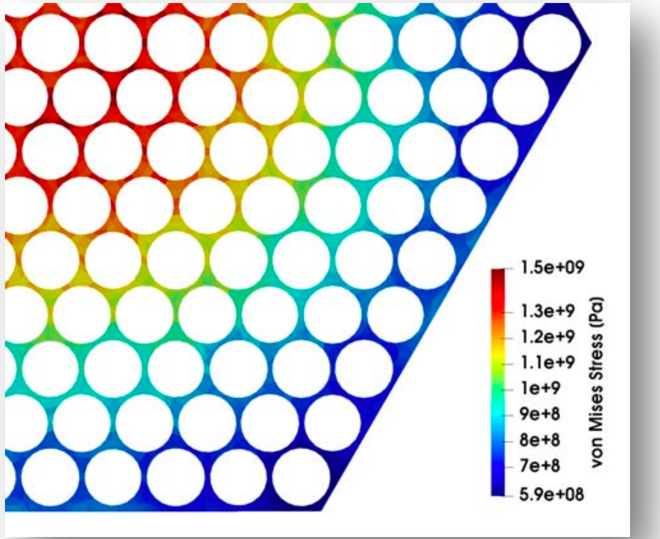


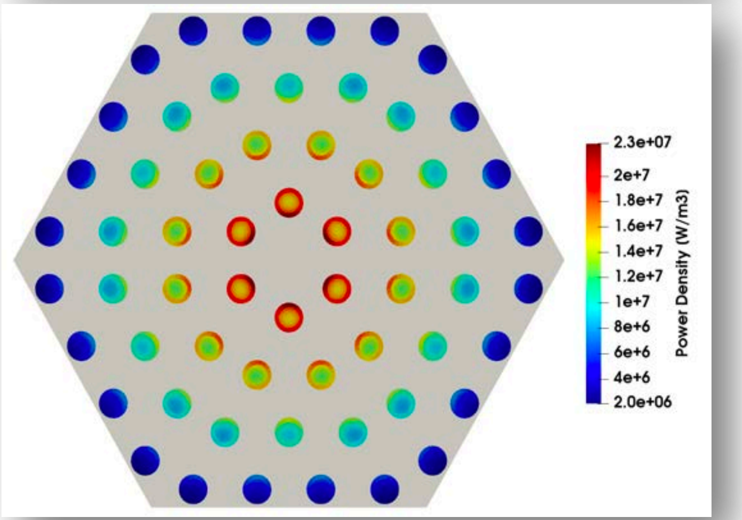
Assessment problem: Unit Assembly Constant heat pipe flux BC

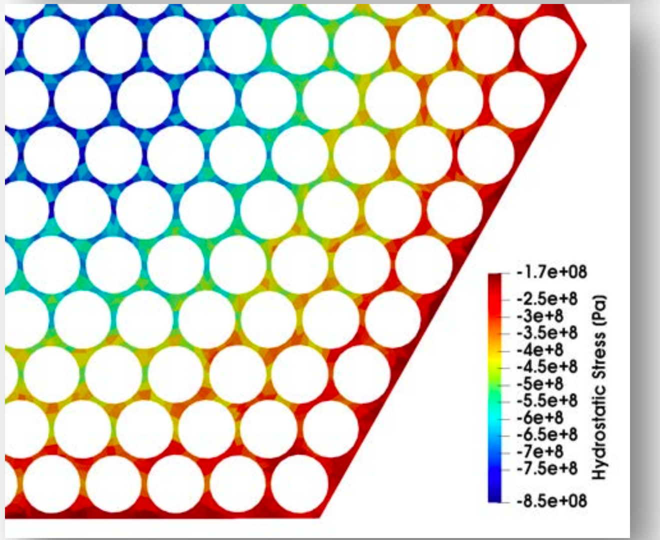
- Steady state: Heat Flux BC = 100% SS power
- Transient initiation: Heat Flux = 90% SS power
- Temperature dependent cross-sections only
- Feedback from cross-section and density









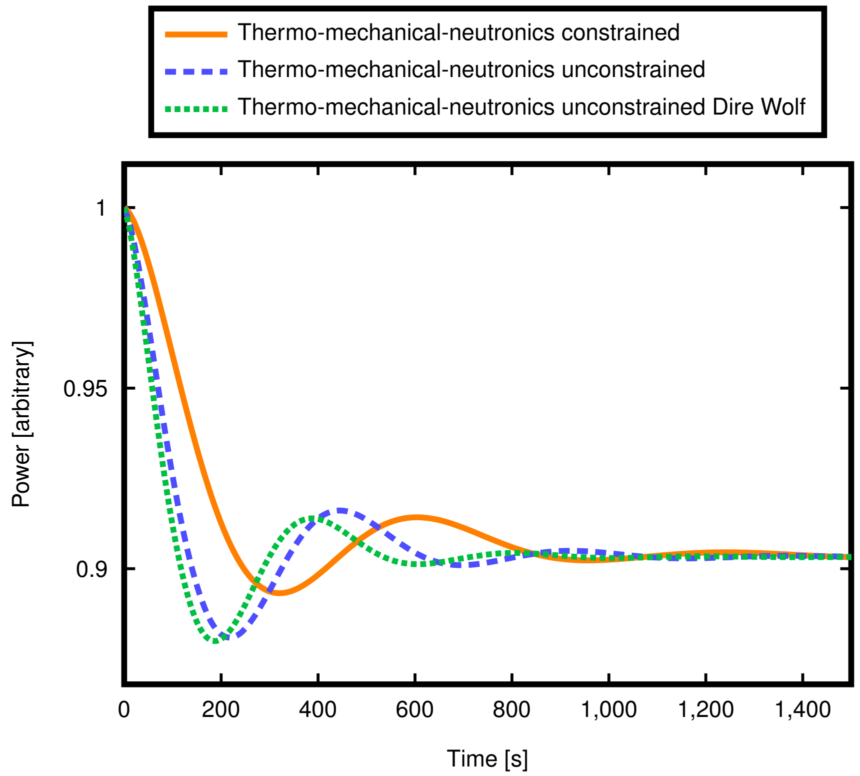


Coupling = Self-regulation

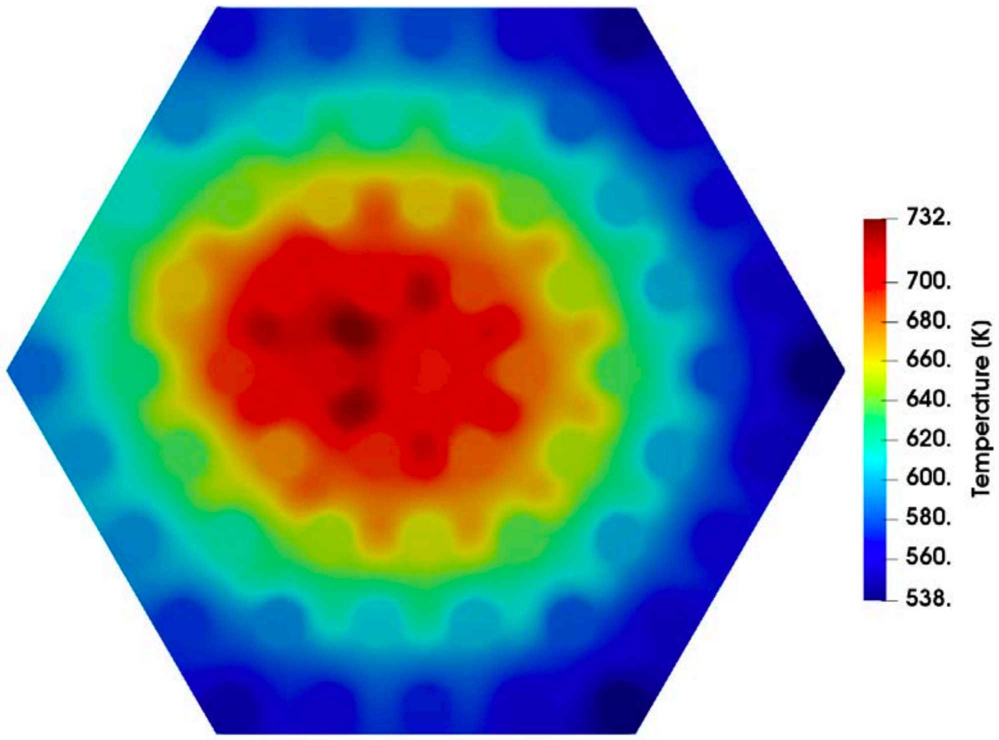
Assessment problem: Unit Assembly

Rapid comparison possible via input file manipulation

Boundary Conditions & Properties

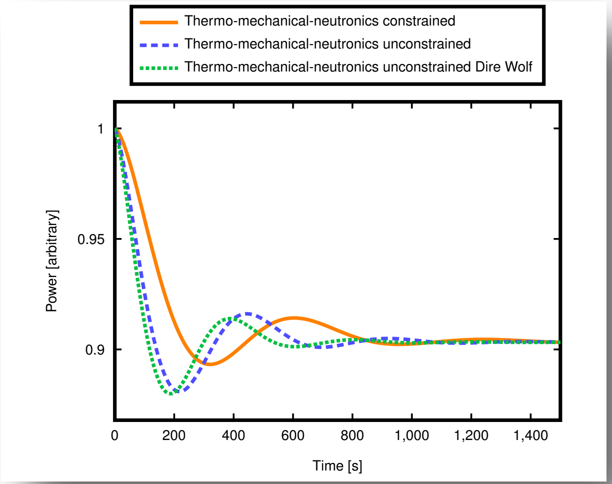


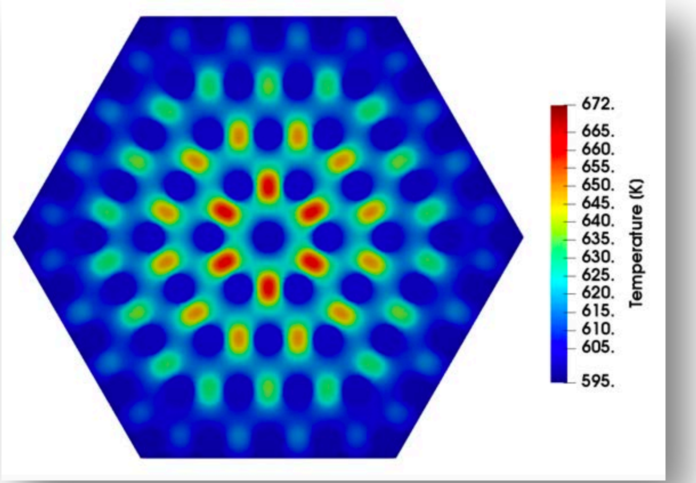
Heat pipe "Failures"

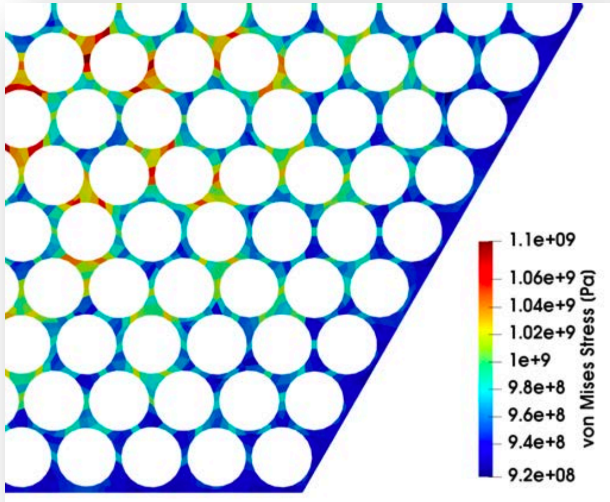


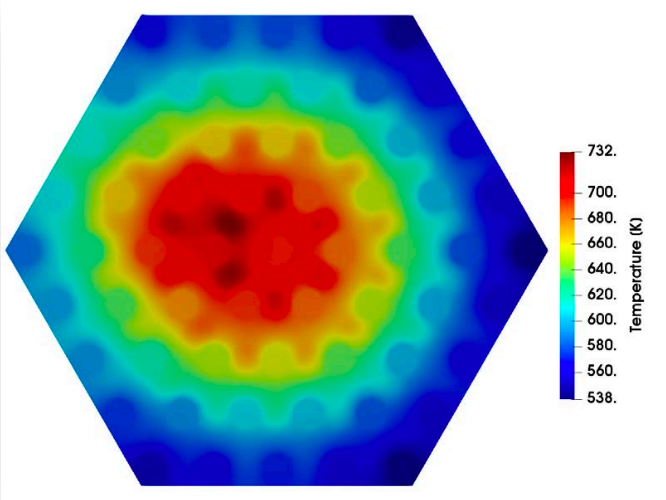
DireWolf is ready to show self-regulation through thermo-mechanical-neutronics coupling

- Computer science heavy-lifting has been completed → Focus on physics
- Still much more work to be done
  - Sockeye coupling
  - Contact
  - Convergence studies



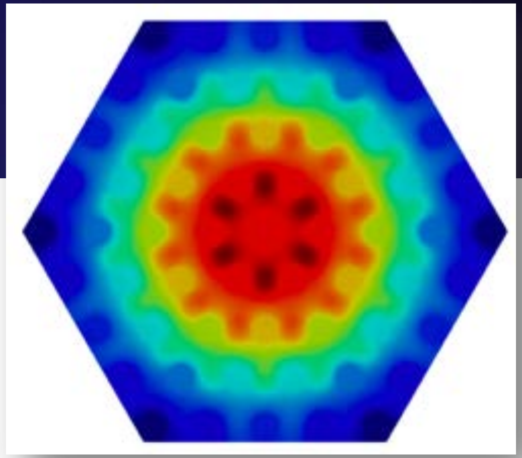




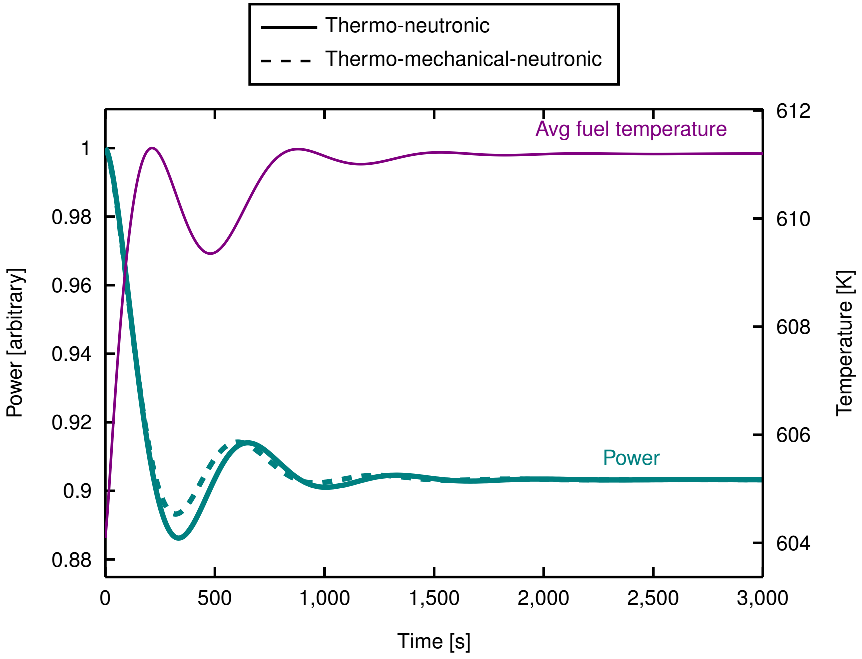


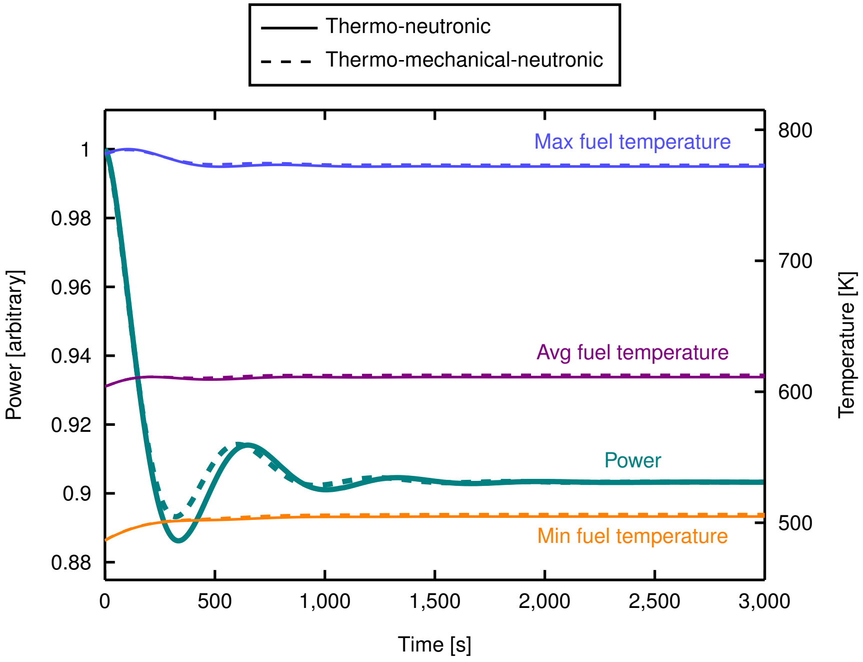
Backup slides

Assessment problem: Unit Assembly
Constant heat pipe flux BC 100% to 90% load



- Steady state: Heat Flux BC = 100% SS power
- Transient initiation: Heat Flux = 90% SS power
- Temperature dependent cross-sections only
- Feedback from cross-section and density

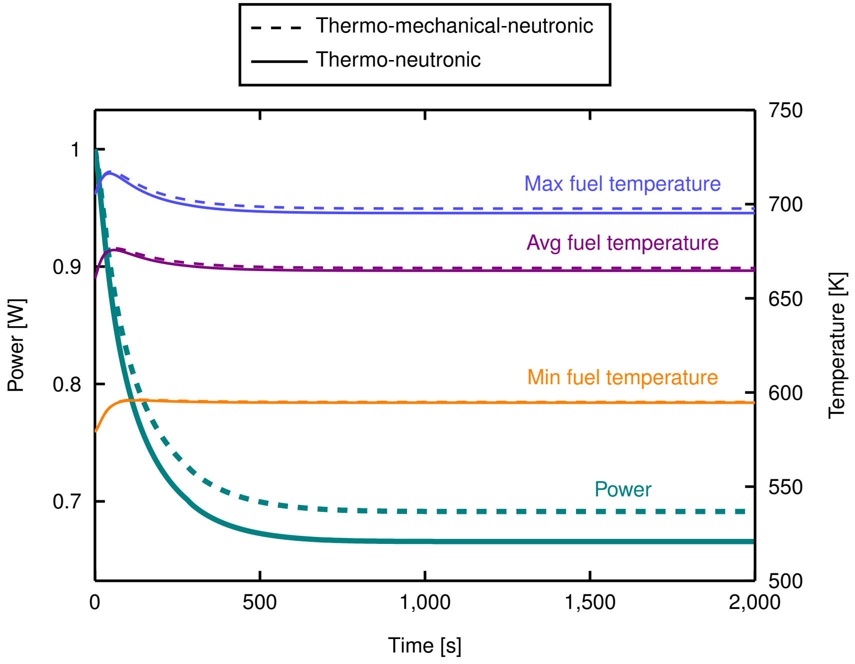


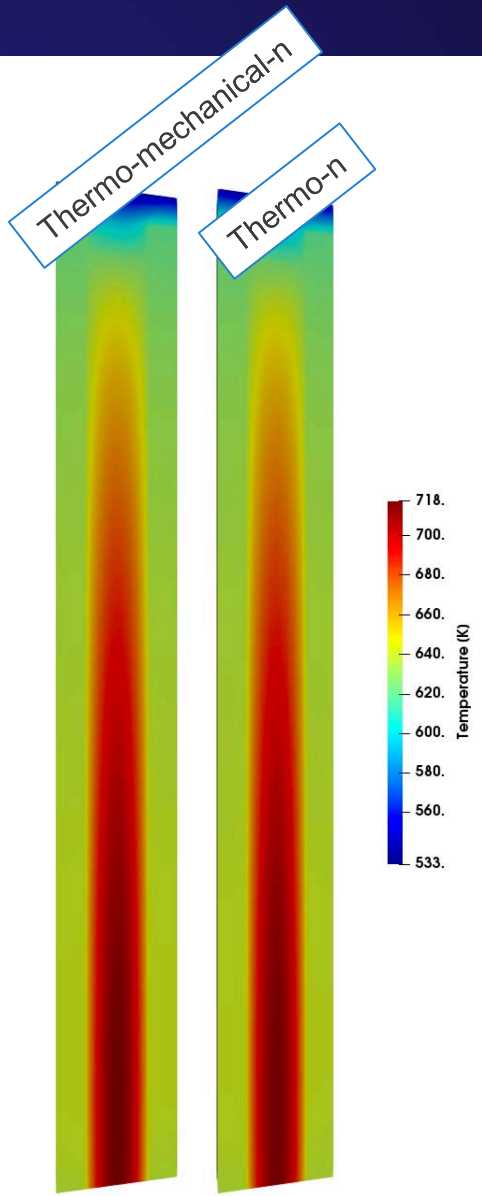


Average fuel temperature stays relatively constant
Transient marked by gradient

Assessment problem: Unit Cell
Constant heat pipe temperature

- Steady state: Temperature BC = 600 K
- Transient initiation: Temperature BC = 625 K
- Temperature dependent cross-sections only
- Feedback from cross-section and density

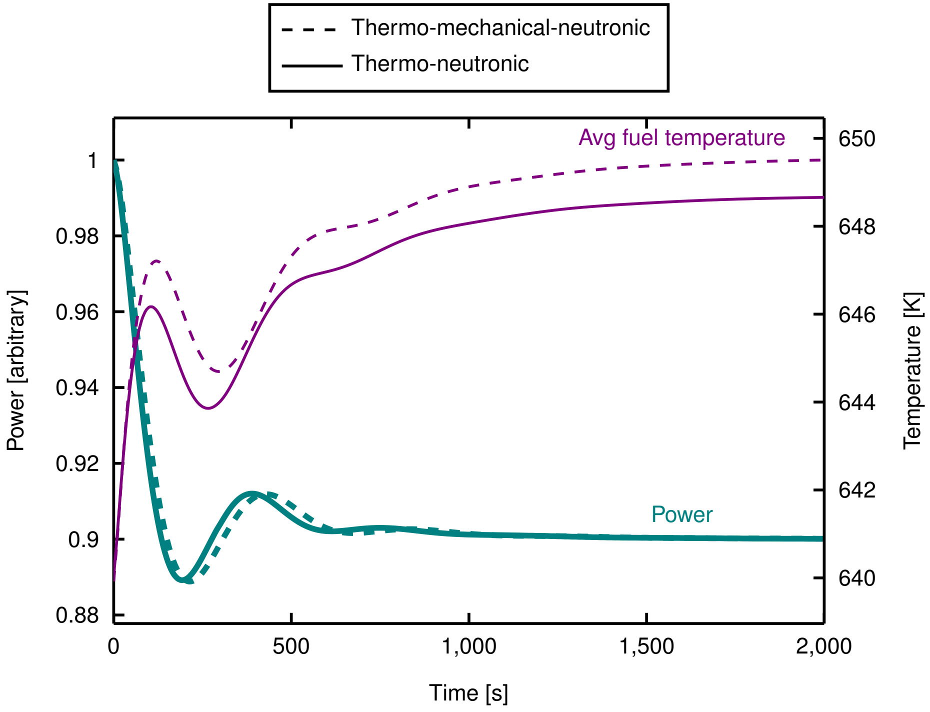


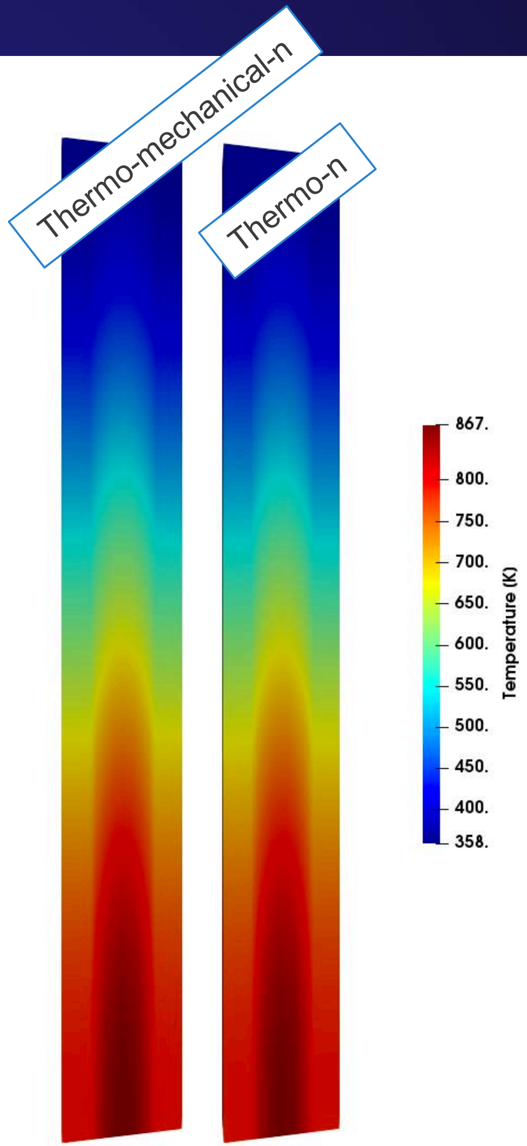


Coupling clearly captured, but…
Unit cell is simple to capture expected physics

Assessment problem: Unit Cell
Constant heat flux heat pipe BC

- Steady state: Power draw = 1 kW
- Transient initiation: Power draw = 0.9 kW
- Temperature dependent cross-sections only
- Feedback from cross-section and density changes





Coupling clearly captured, but again…
Unit cell is too simple to capture expected physics

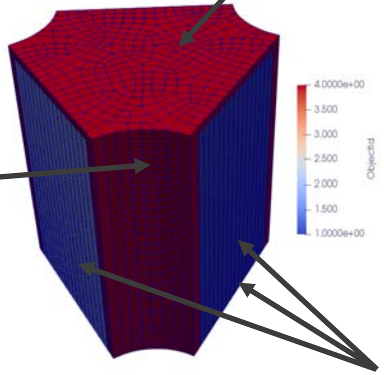
Assessment Problem: Heat pipe approximations

Focus of RT is showing Self-Regulation:
Fundamental aspect of micro-reactor heat pipe design

- Need to show coupling of thermo-mechanical-neutronics for core

- Approximated heat pipe behavior via BC
  - 1) Surface temperature: time dependent heat pipe surface temperature
  - 2) Surface heat flux: time dependent heat pipe surface heat flux

Robin B.C: $h = 10^3 \frac{W}{m^2 - K}$
$T_{ext} = 450K$



HP surfaces - Robin B.C.:

$$h = 10^3 - 10^5 \frac{W}{m^2 - K}$$

$$T_{ext} = 600 \rightarrow 575 - 625K$$

Neumann B.C