The Scalability of Heat-Pipe cooled Reactors

for Remote and Autonomous Applications

15th Nordic Meeting on Nuclear Physics

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University of Oslo

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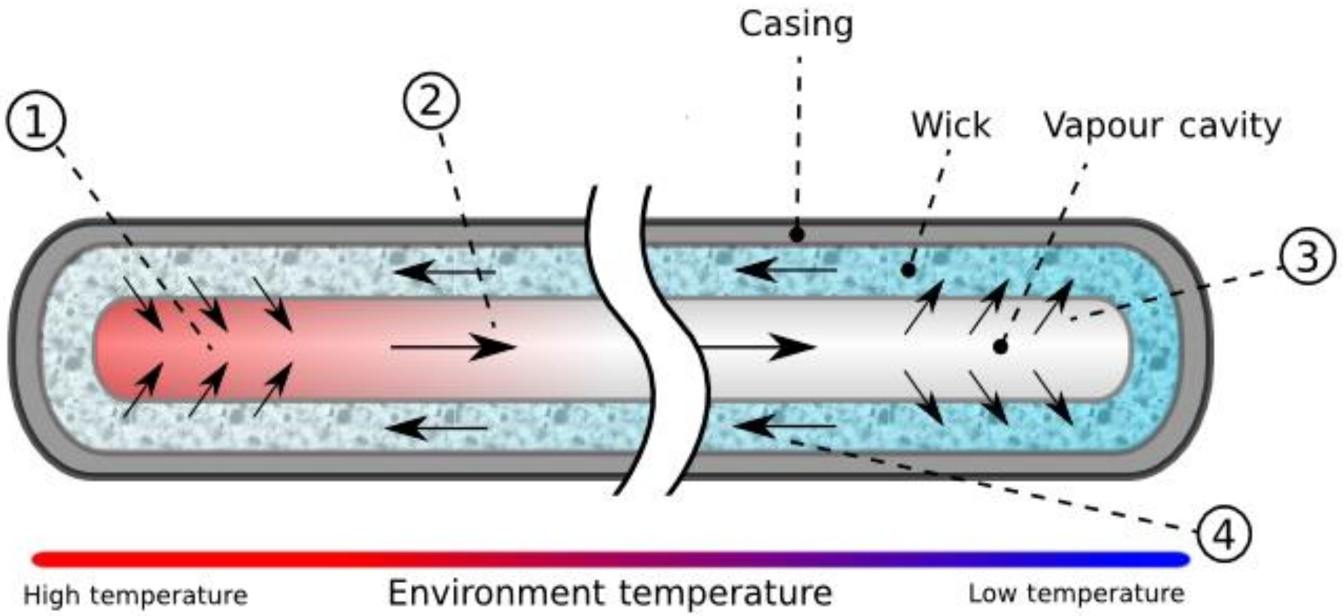
Agenda

1. Introduction to heat pipes and HPRs
2. Motivation and aim
3. Methodology
4. Results
5. Limitations

Heat Pipes

Type of thermosiphon

- **Passive heat transport**
- **Continuous evaporation/condensation of a working fluid**



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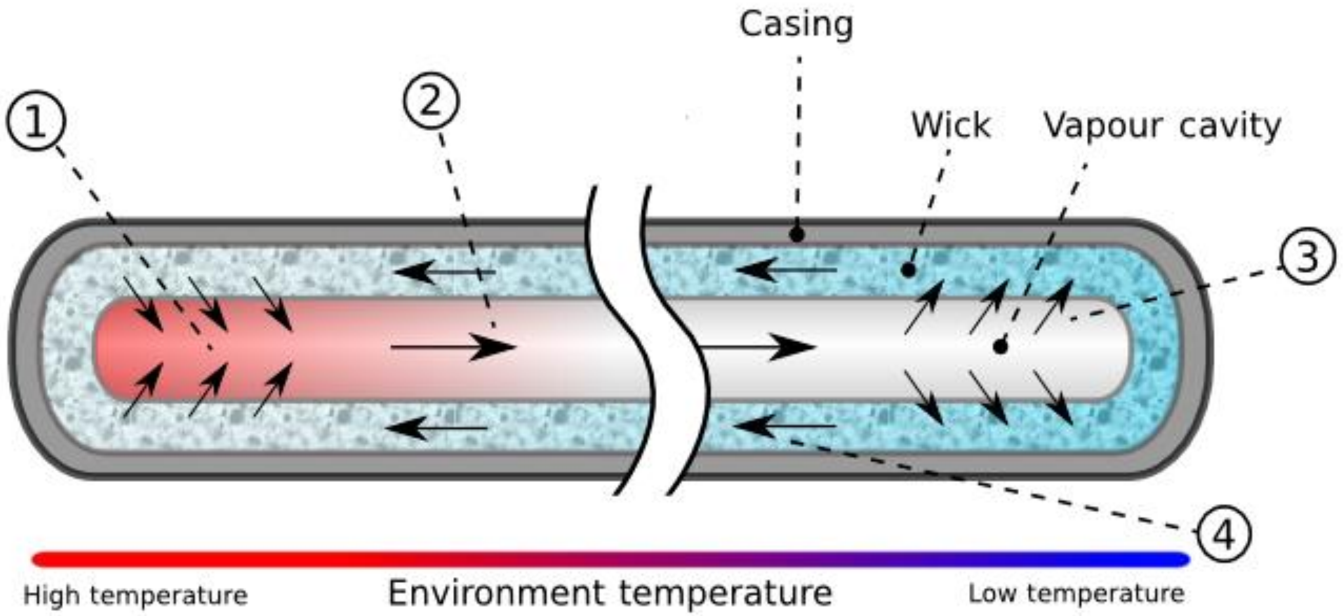

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Heat Pipes

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  - Passive heat transport
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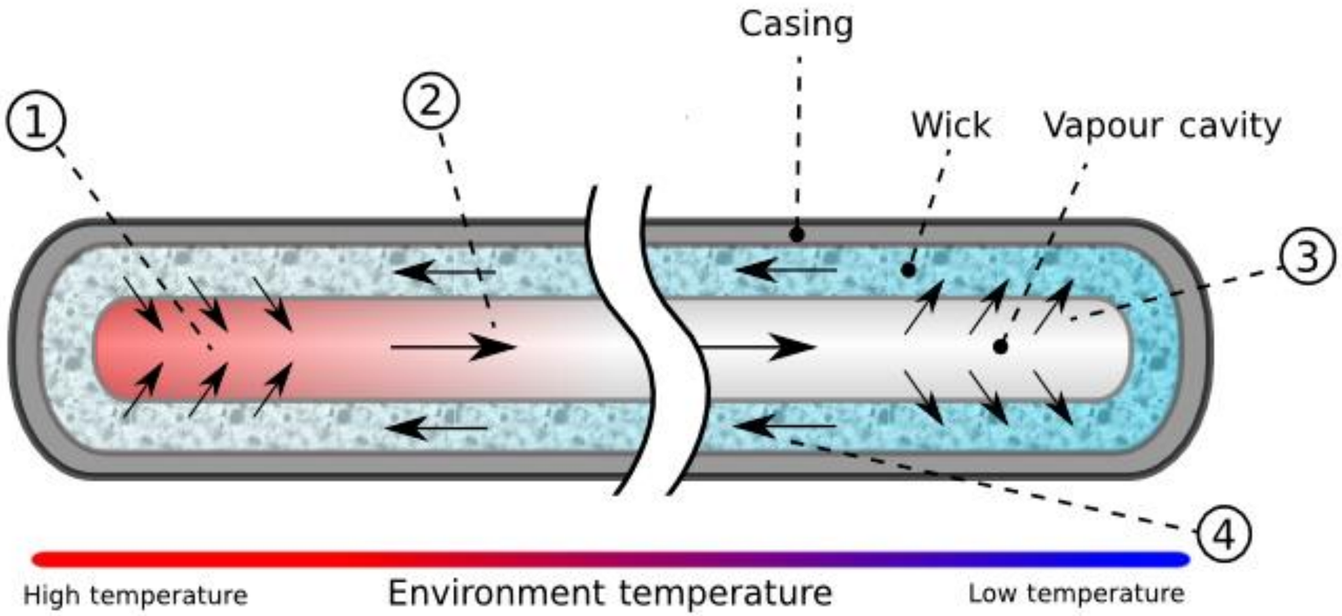
- **Between 0.6 and 20 kW per heat pipe, depending on:**
  - **Working fluid**
  - **Wick structure**
  - **Dimensions**



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Heat-Pipe Reactors (HPRs)

Designs originate from the 60s and 70s

Originally envisioned for space-power applications (electrical power, propulsion)

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Key design features:

- **Epithermal/fast neutron spectra**
- **Heat removed from core using heat pipes**
- **Heat pipes and fuel connected directly or arranged in solid matrix**
- **Historically lower power: 100s of kW**
- **Current designs: 1-15 MW (proposed)**

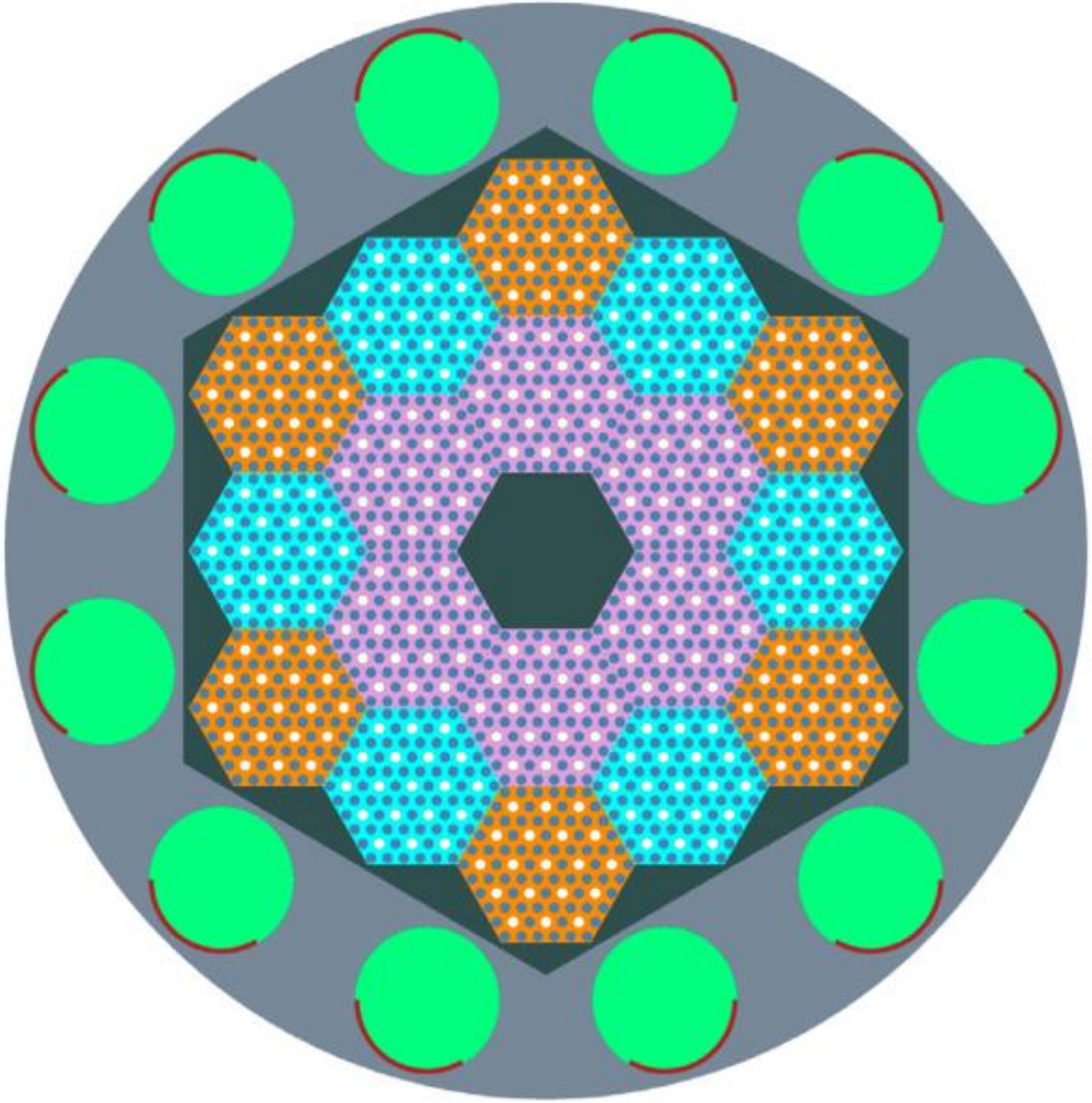
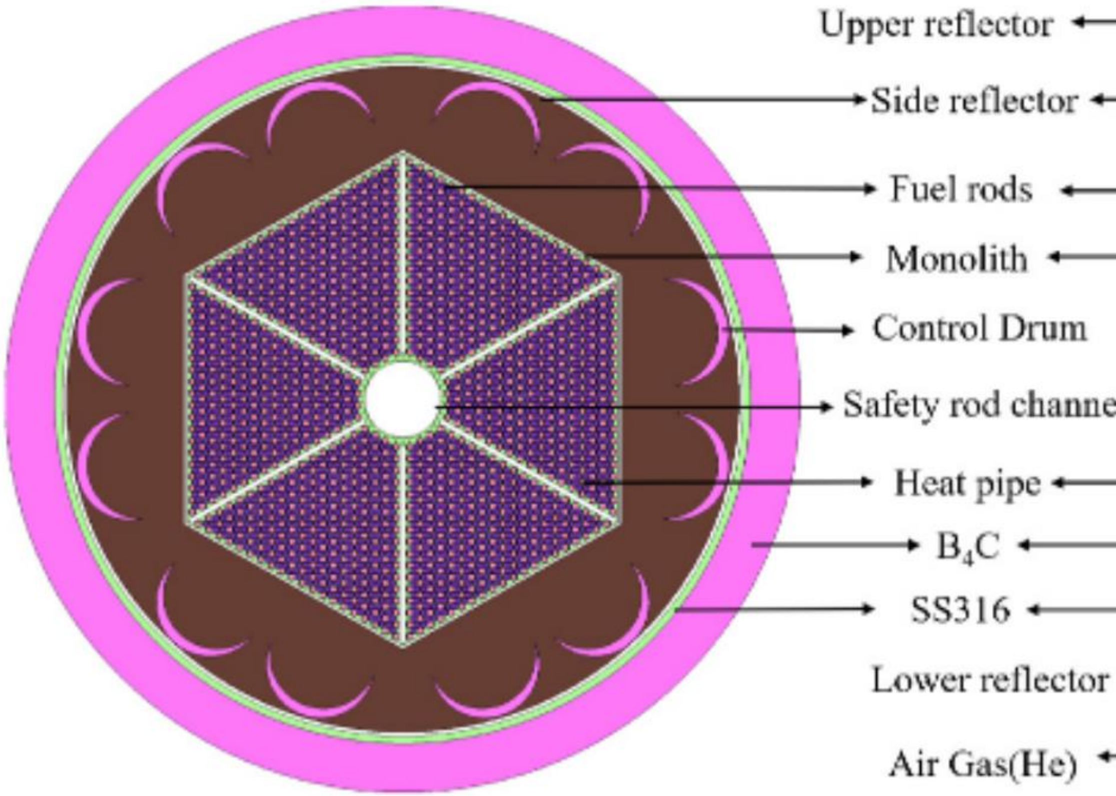
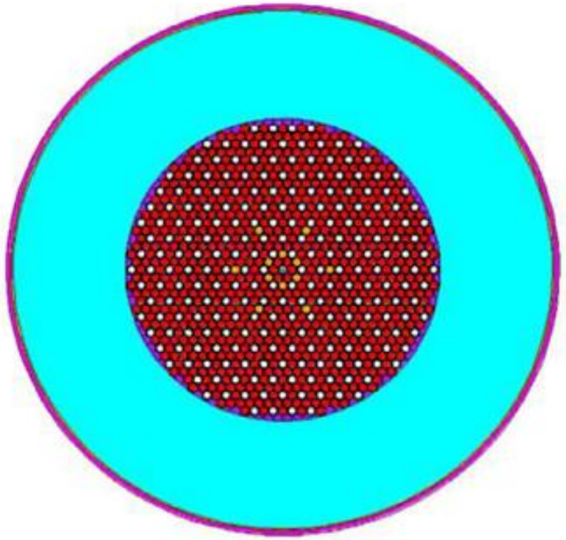


Fig. 1. Mid-plane view of the reference reactor model developed by OpenMC.





Clockwise from top-left:
snowflake design
triangular monolith design
single-block design

Motivation and Aim

Current interest in micro-reactors and SMRs

- **Distributed and remote energy applications (mini-grids, mining centers, data-centers)**
- **Maritime propulsion/floating power plants**

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  - Maritime propulsion/floating power plants
- **Focus of existing literature:**
  - **Neutronics and thermal-hydraulics of specific designs**
  - **Some work on fuel performance and load-following/start-up performance**

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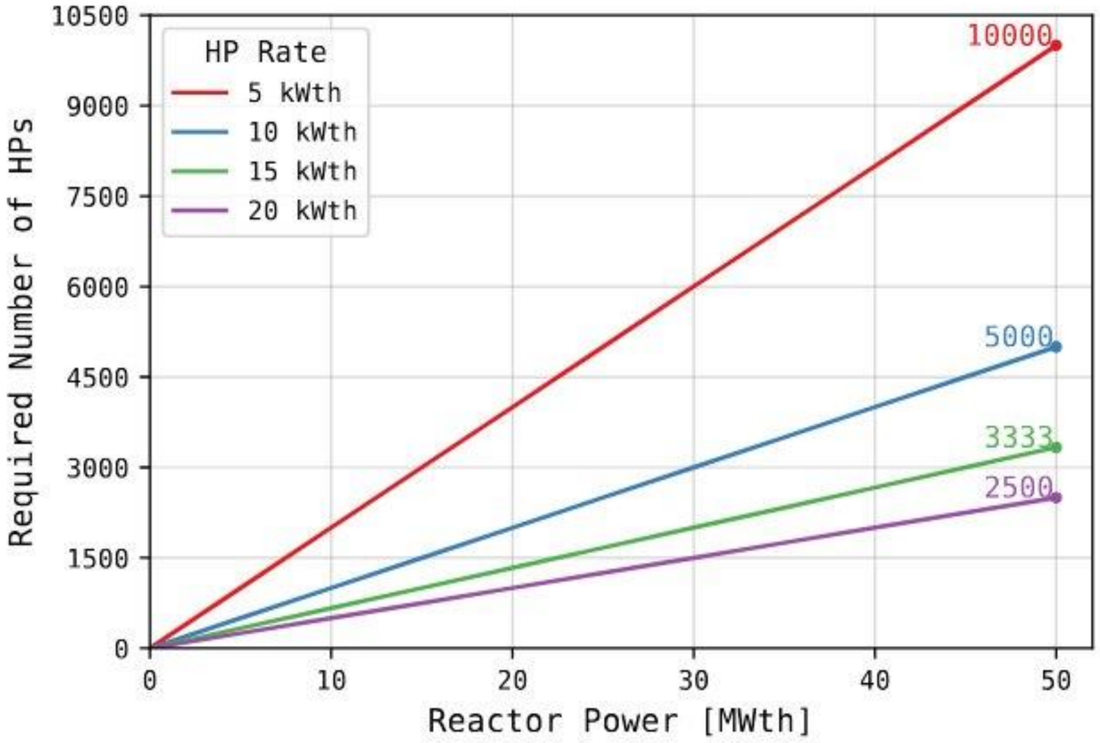
- Focus of existing literature:
  - Neutronics and thermal-hydraulics of specific designs
  - Some work on fuel performance and load-following/start-up performance
- **Research gap: scalability of HPRs, from kW to MW**

Motivation and Aim

Key concerns for scalability:

- **Number of heat pipes**
- **Individual heat pipe performance**
- **Accident considerations (single/multiple HP failure)**
- **Thermal/mechanical limitations of the core matrix, fuel rods, and heat-pipes**



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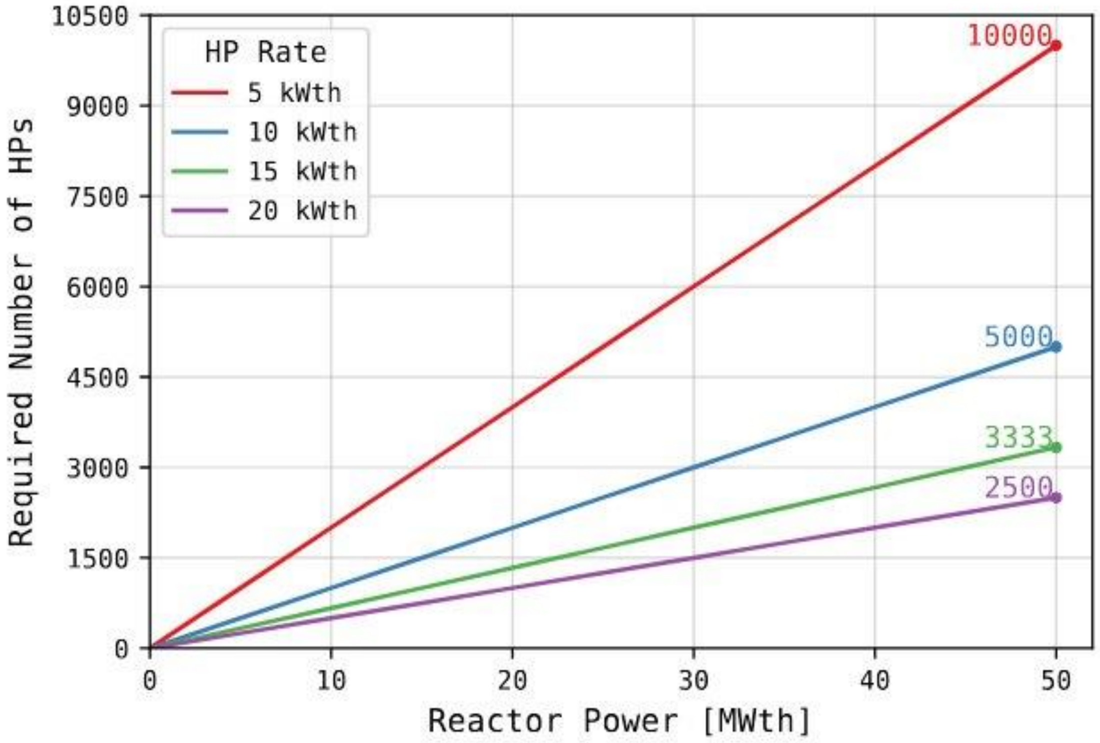
Research questions:

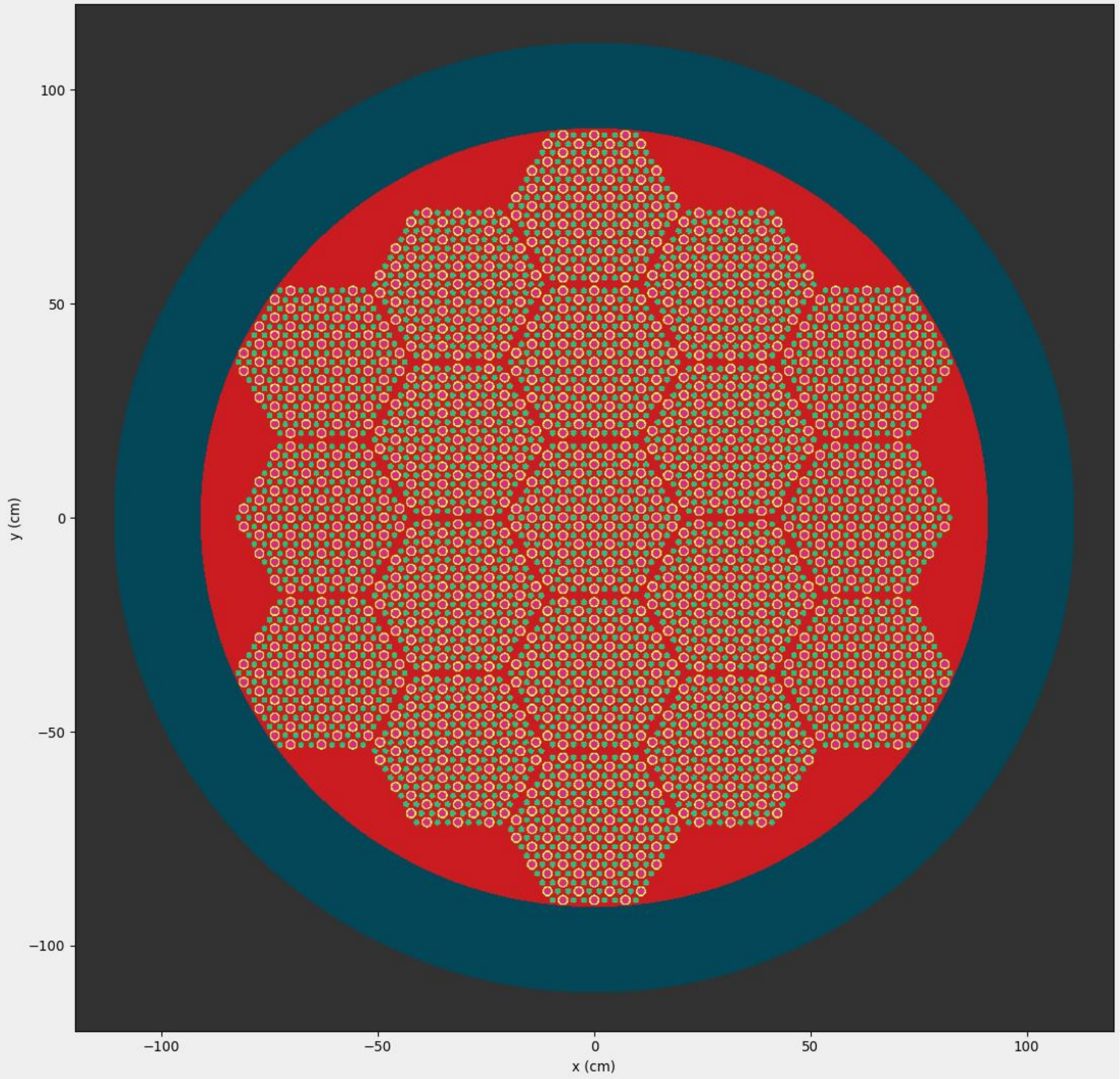
- **What is the maximum nominal power a generic HPR can operate at without exceeding critical material temperature limits in steady-state beginning-of-life conditions?**
- **What sort of neutronic properties does the scaled-up HPR have?**



Methodology

Model a "generic" HPR:

- **19 graphite block assemblies**
- **73 HP and 144 fuel rods per assembly**
- **Active core height: 175 cm**
- **BeO reflectors (20 cm radial, 15 cm axial)**
- **HP operating temperature of 900 K**



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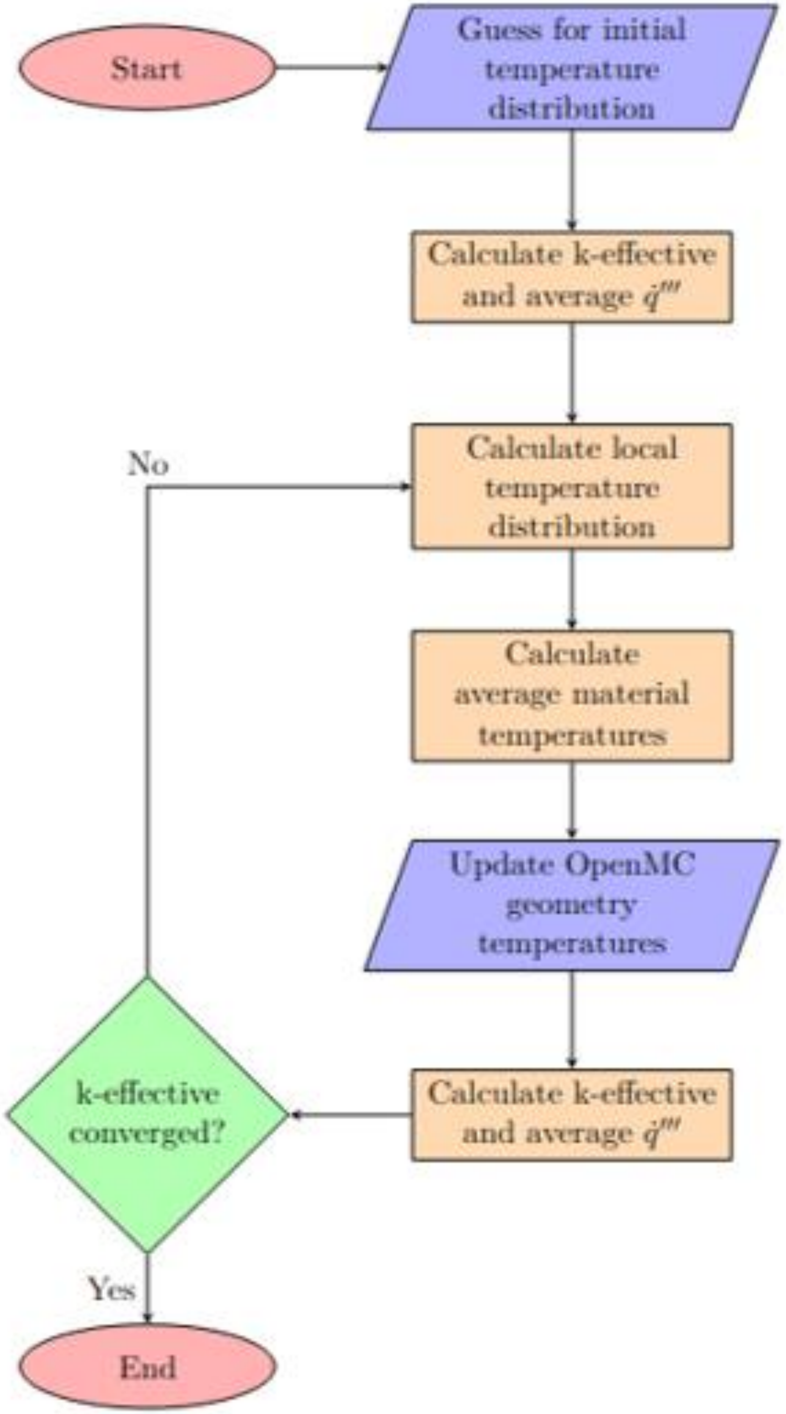
Iteratively calculate the average volumetric heat rate of the fuel pins and use it to calculate the temperature distribution of the core for 5, 10, and 15 MWth



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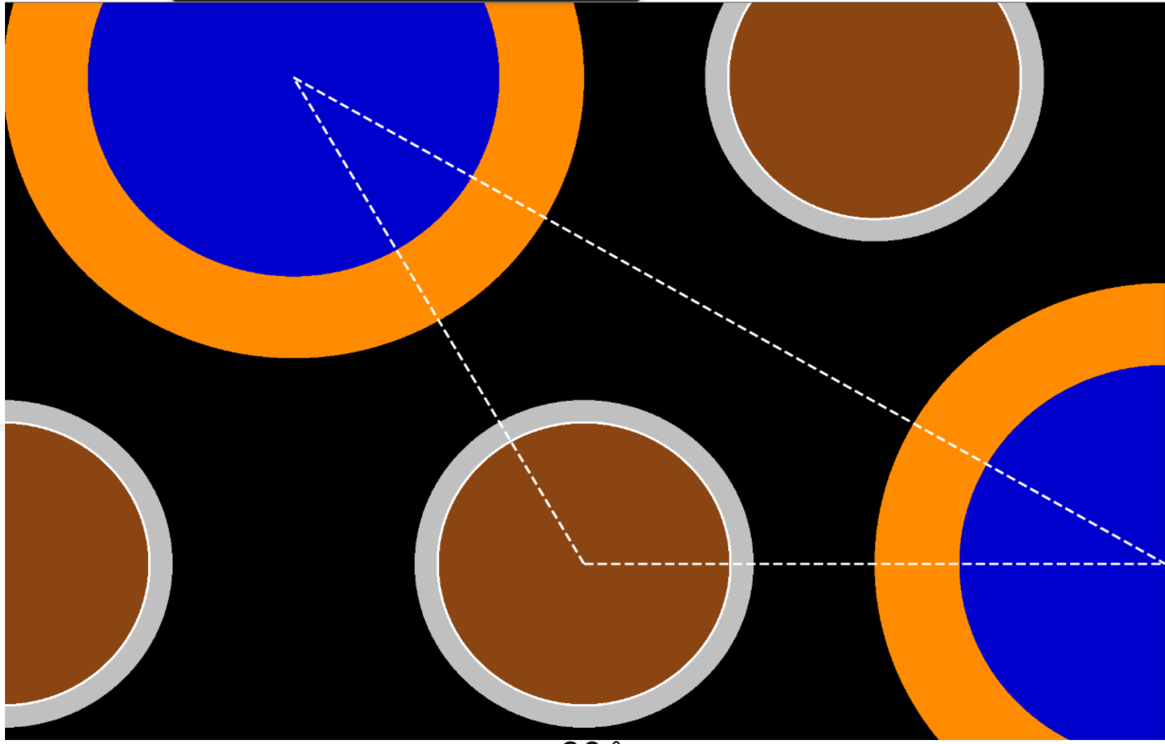
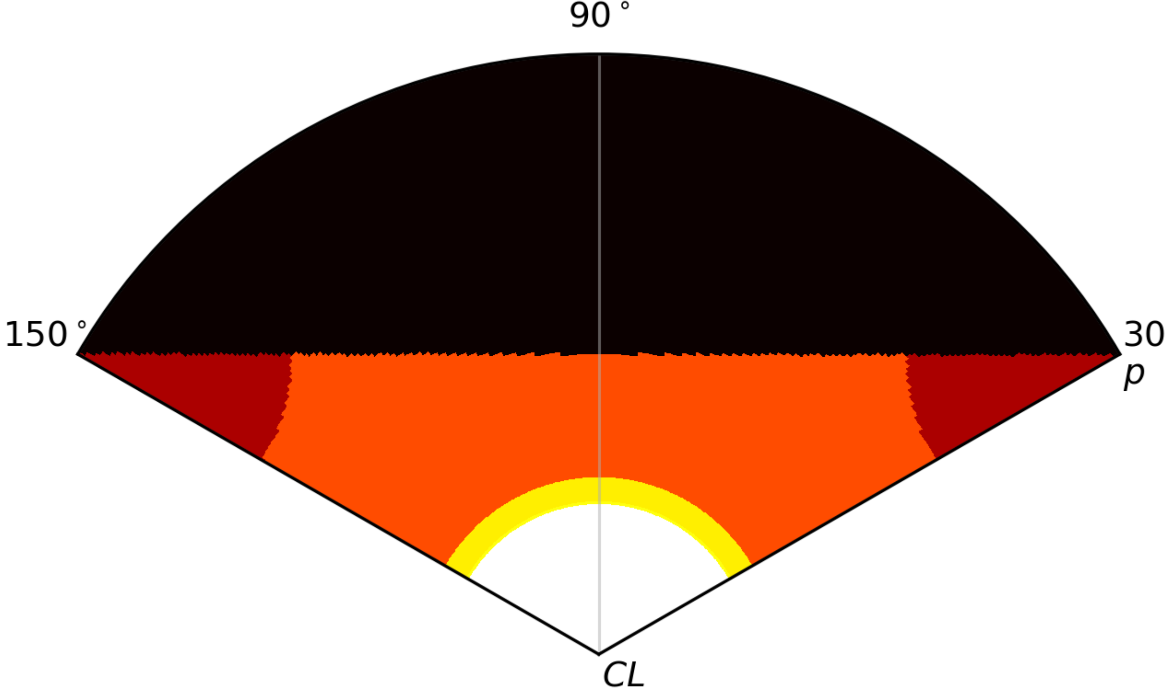
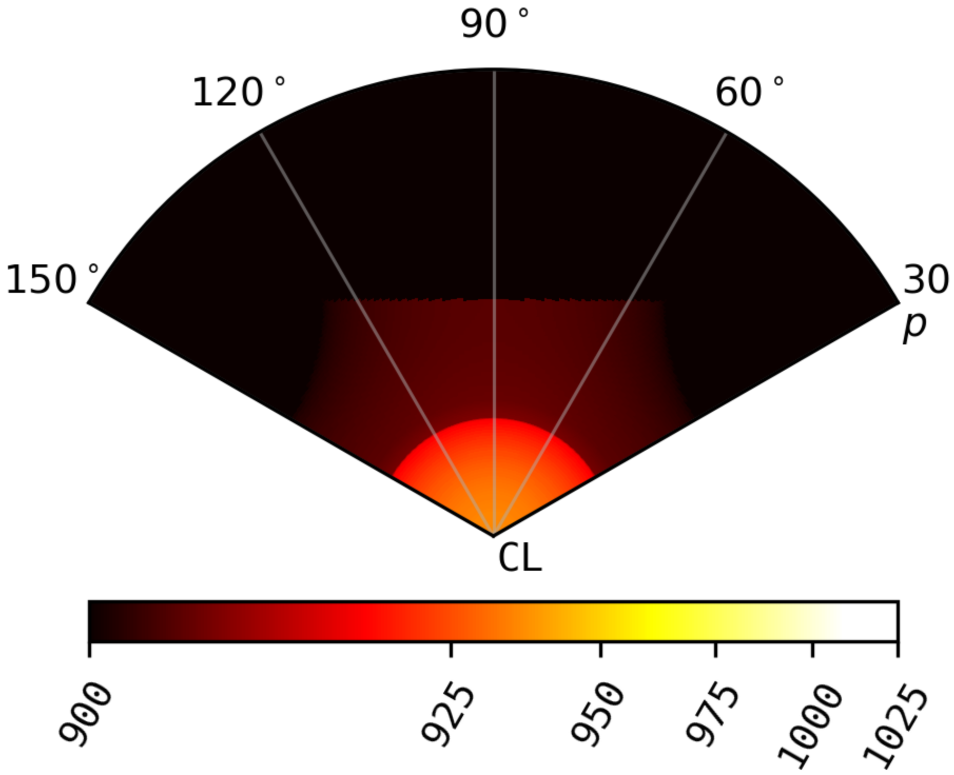
Two models:

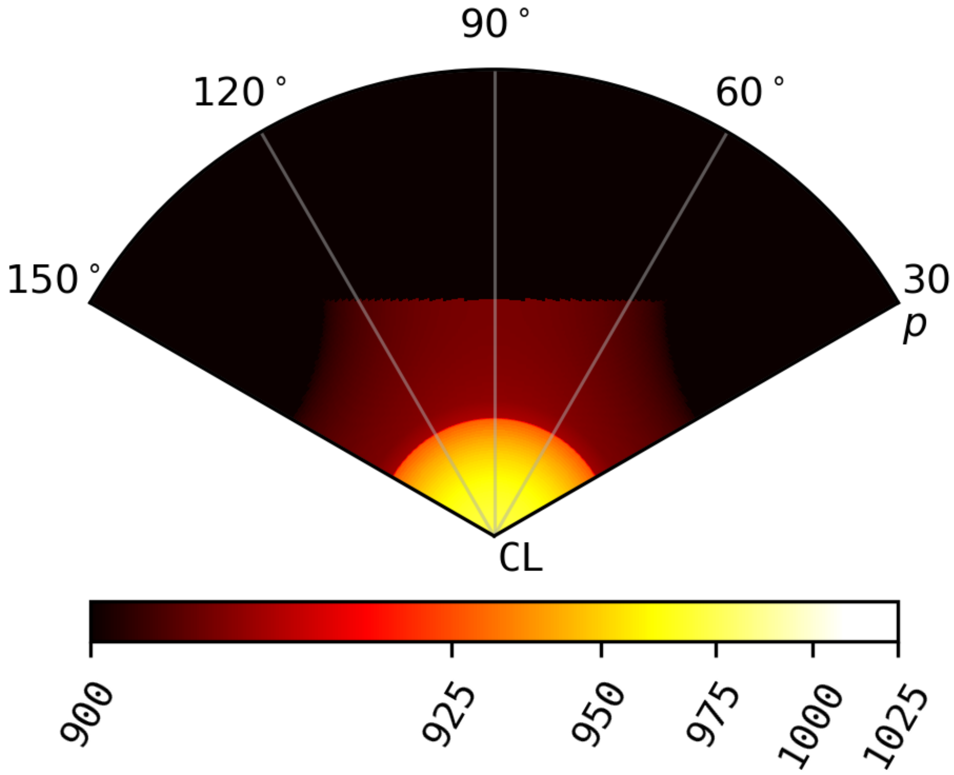
- **Neutronics model: calculate k-eff (convergence check) and average fuel pin power (W/cm3)**
- **Thermal model: calculates temperature distribution and calculates average temperatures for updating the neutronics model**



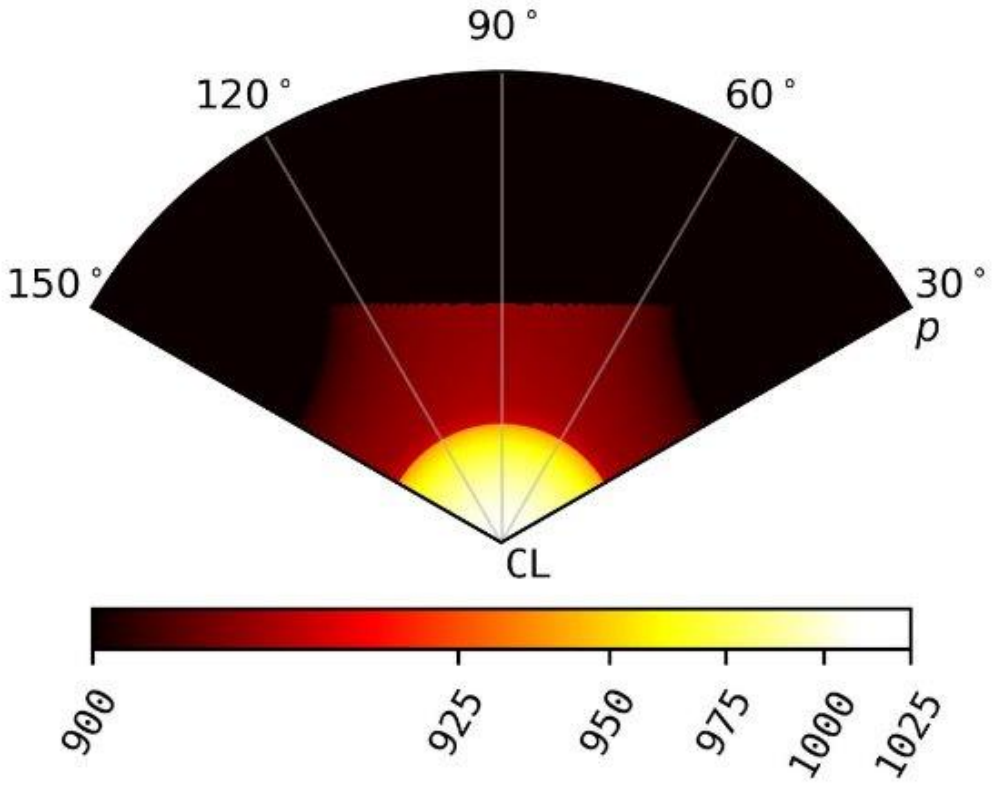


Thermal Results – 5 and 10 MWth

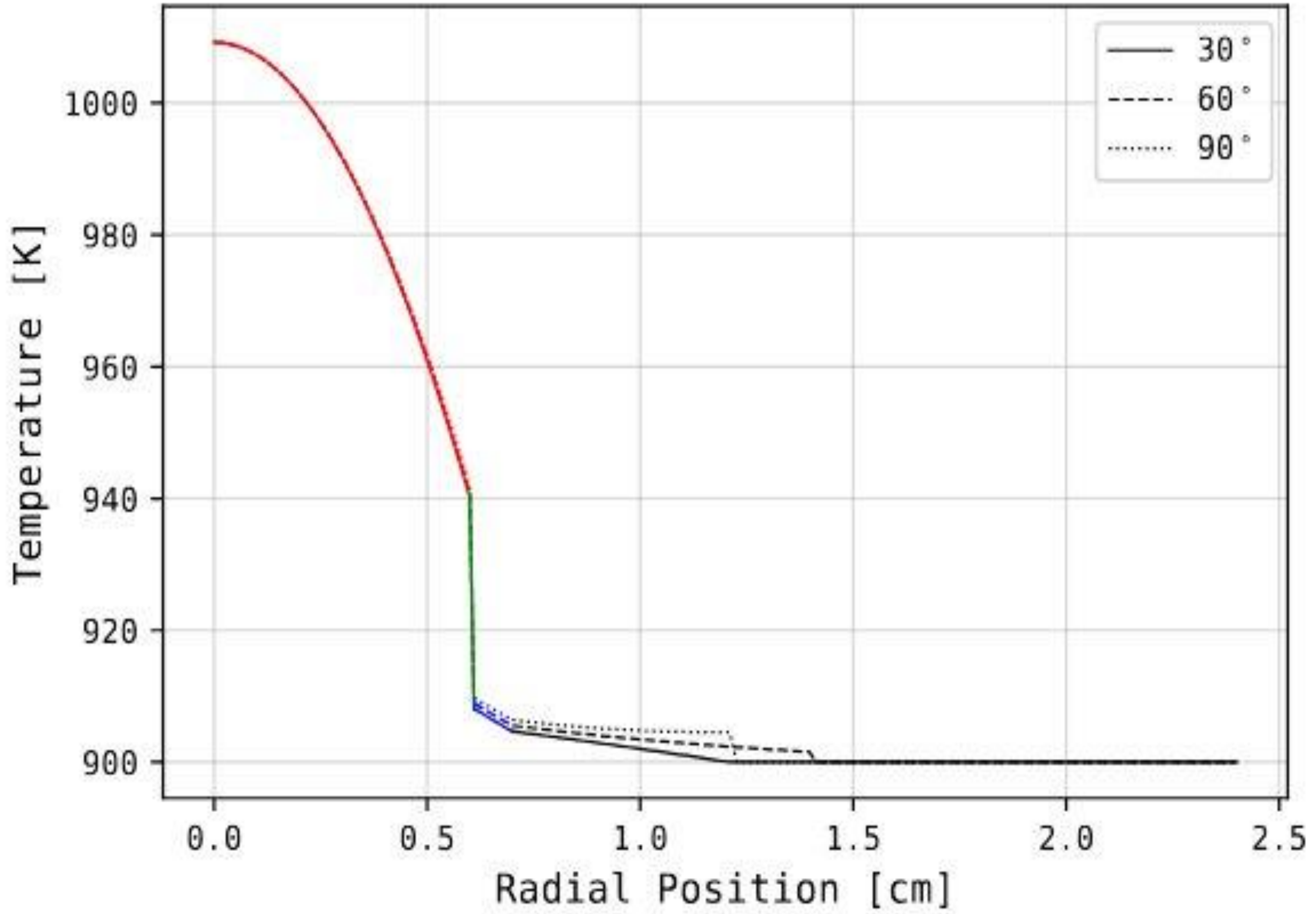




Thermal Results – 15 MWth



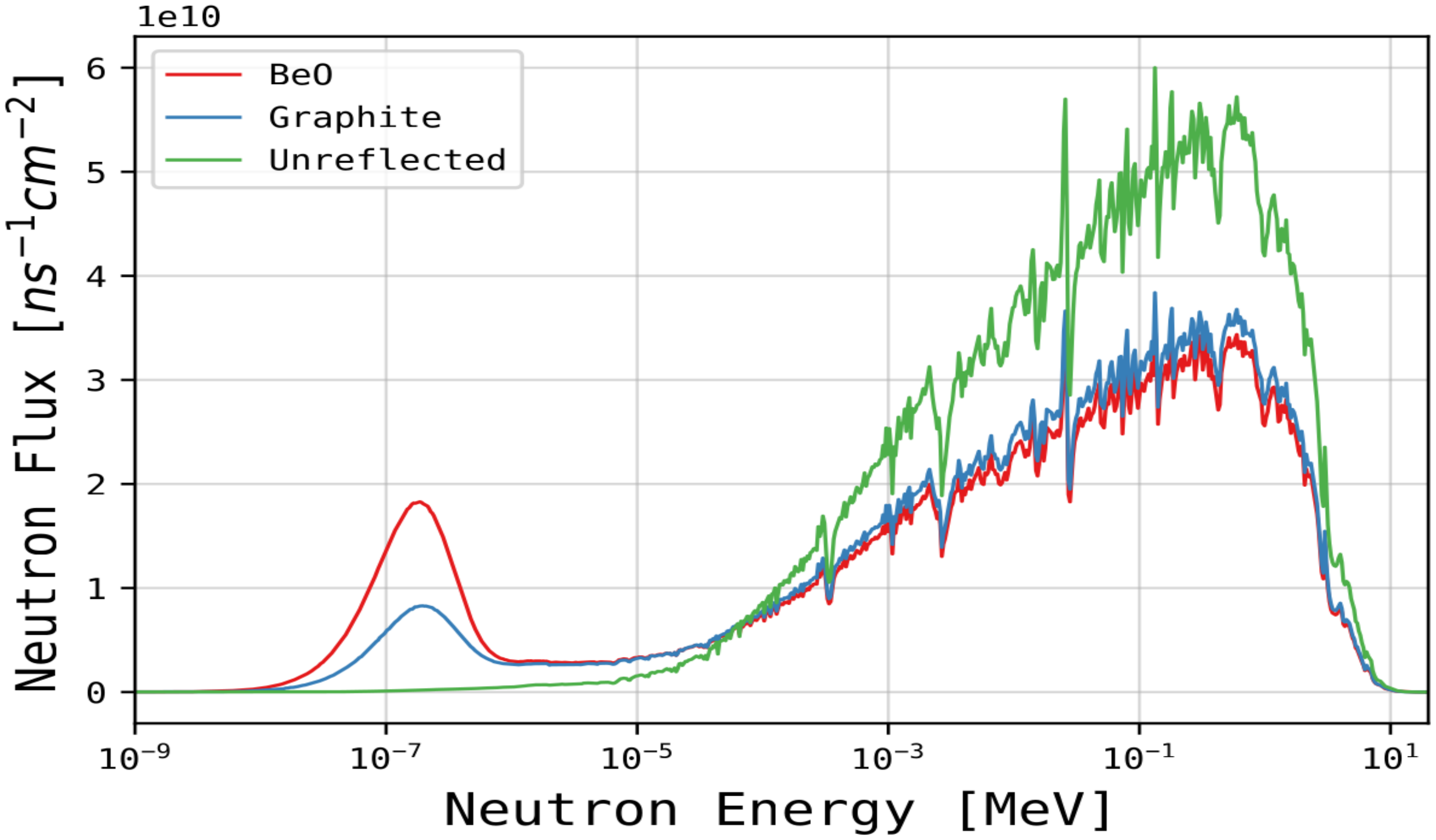
Critical material temperatures (melting points) **not exceeded**



Temperature asymmetry present in the materials closer to the heat-pipes (block, cladding)

Neutronic Properties

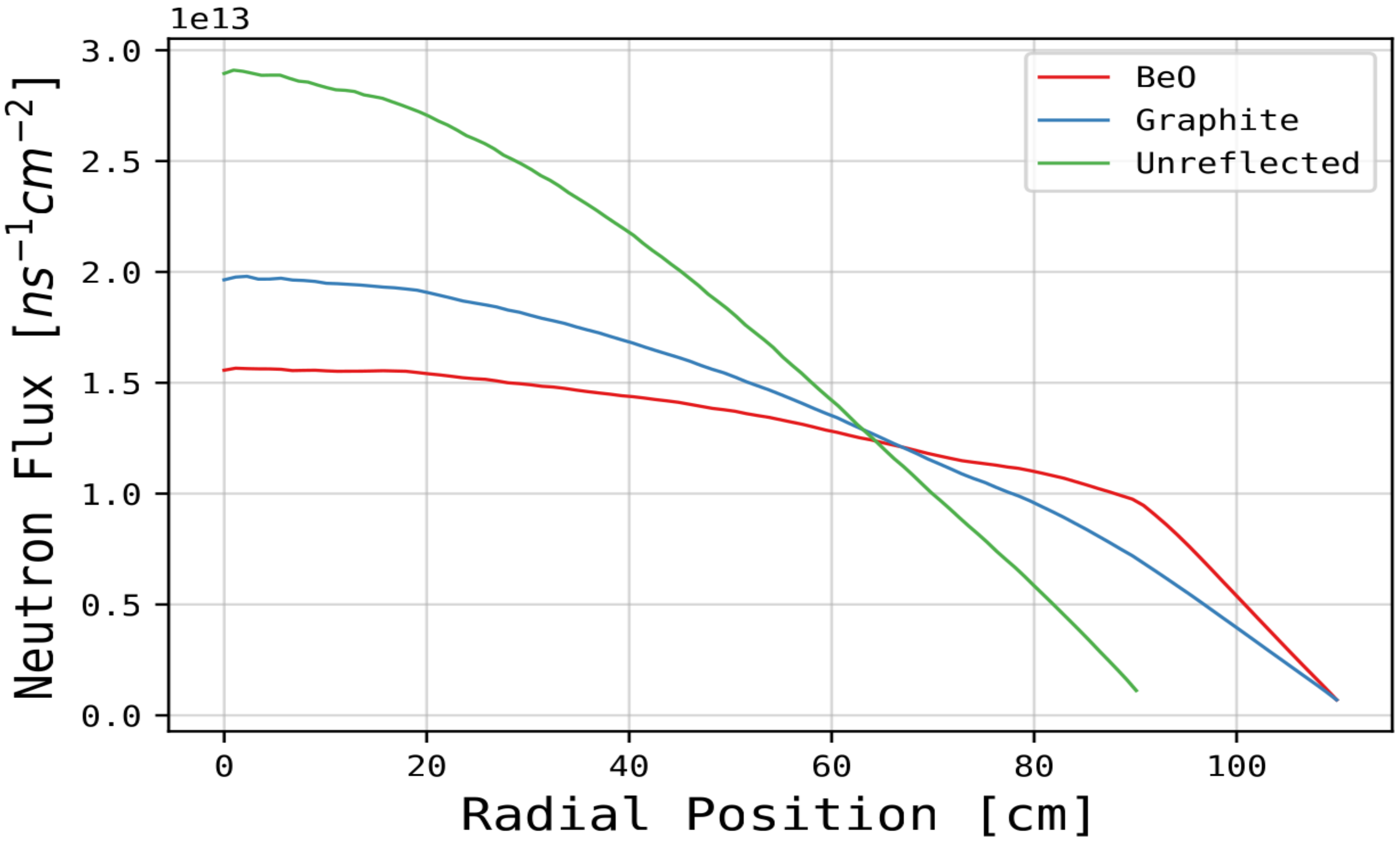
Epithermal spectrum



Neutronic Properties

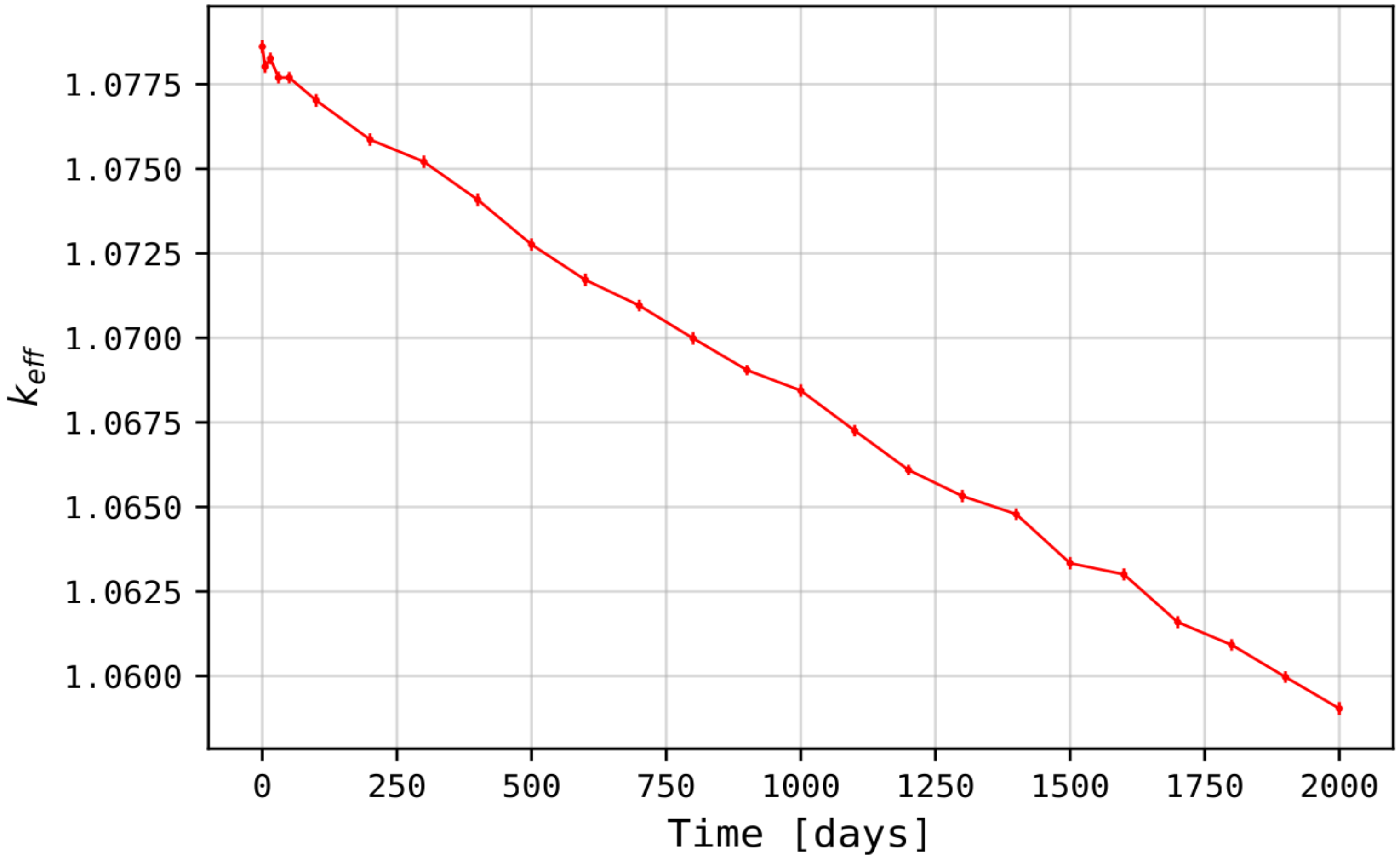
Epithermal spectrum

Relatively flat radial spectrum



Neutronic Properties

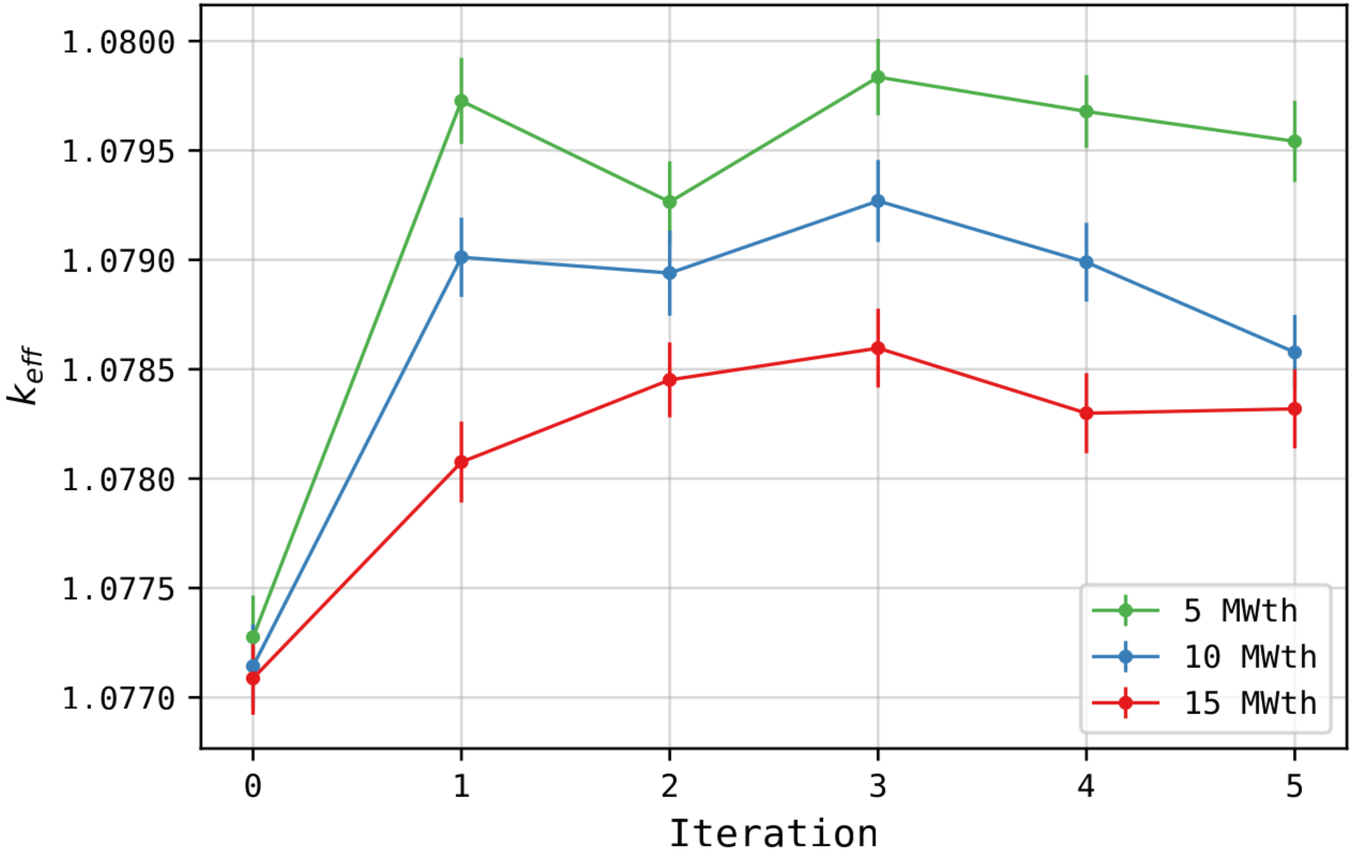
- Epithermal spectrum
- Relatively flat radial spectrum
- **Excessive excess-reactivity**
  - **Depending on desired operational period, reactor design could be modified**
  - **For example: reducing fuel enrichment or changing fuel rod-dimensions**



Limitations

Methodology limitations:

- **Thermal model only considers a small region of the core**
- **Fails-to account to for the non-uniform nature of the power distribution (especially axially)**
- **Fuzziness of the thermal model space (discretization) near the HP-HP horizontal**
- **Failed to consider mechanical considerations; temperature limits weren't exceeded but the deformation of the block needs to be investigated**



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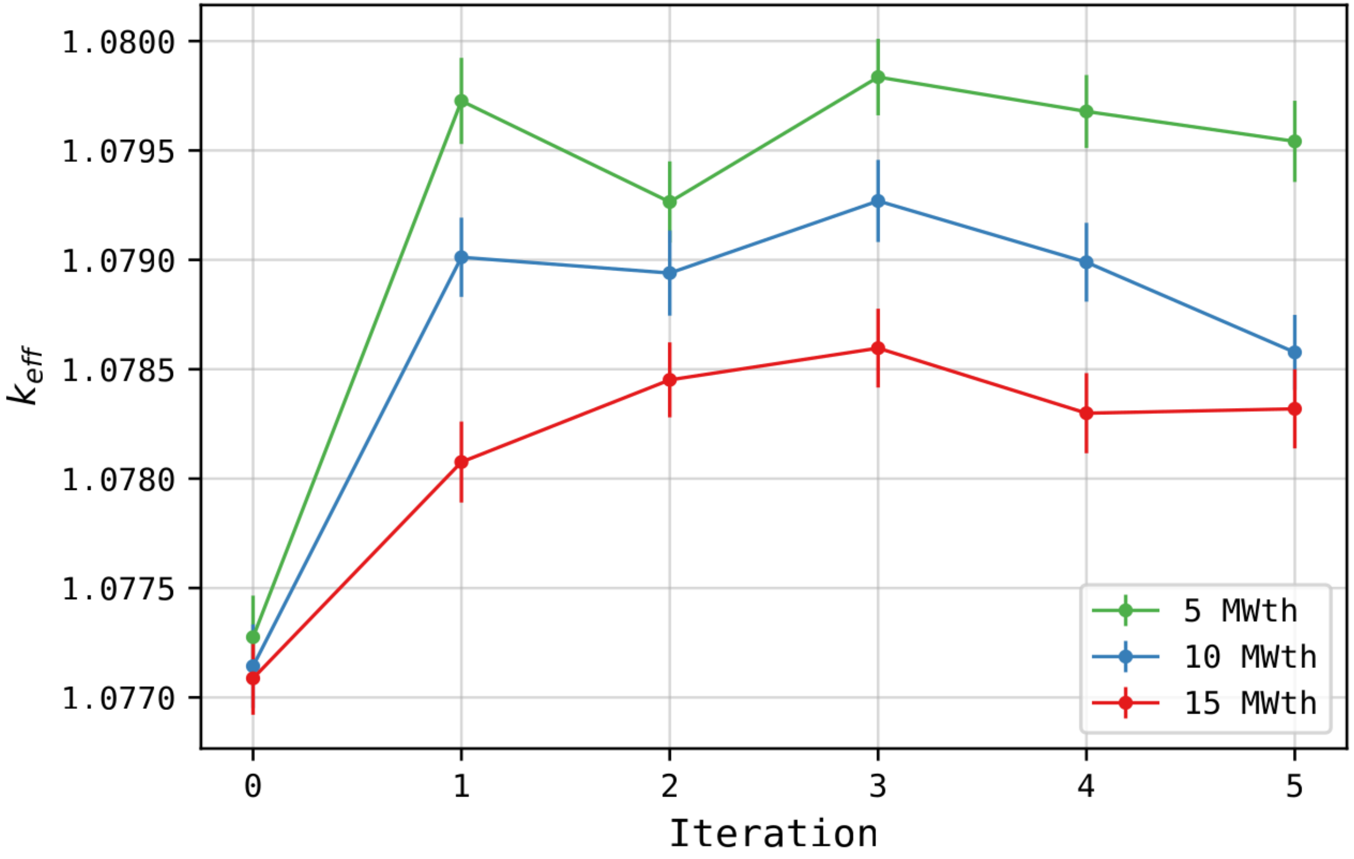
Improvements:

- **Divide fuel pins into axial zones to calculate the axial temperature distribution**
- **Treat inner and outer fuel assemblies separately**
- **Try different reactor configurations (central assembly replaced with reflector, different fuel rod dimensions)**



Summary and Outlook

Summary

Using a simple coupled neutronics-thermal model, a generic HPR was modelled at three different power levels

The design could operate at 15 MWth without exceeding material temperature limits in steady-state BOL conditions

The design is characterized by a flat radial flux profile, epithermal neutron spectrum, and excessive excess reactivity

Outlook *(master projects for other students?)*

Experiment with different design modifications (fuel enrichment, fuel material, fuel dimensions, HP dimensions, central reflector, alternative fuel assembly designs)

Improve the thermal model (larger core regions, add axial zones, more efficient solver, switch to dedicated software)

Perform similar calculations for EOL or accident conditions (single/multiple HP failure)

Thank you for listening!