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Smart solutions for complex problems

Modeling flow blockage accident in graphite-moderated MSRs

Young Molten Salt Reactor Conference
Politecnico di Milano, Lecco
08 June 2022

MMP is incubated at: POLIHUB INNOVATION DISTRICT & STARTUP ACCELERATOR BY FONDAZIONE POLITECNICO DI MILANO

Hole blockage accidents

Event initiator: a **fragment of solid material breaks apart** from a structure in the primary loop **and gets dragged in the fuelsalt flow.**

The **fragment completely obstructs the hole of a graphite brick** in the core, **stopping the axial flow.**

SOLID FUEL REACTORS (LM-FR)	LIQUID FUEL REACTORS (MSR)
Total interruption of fuel element cooling • Cladding rupture • Fuel meltdown	Partial cooling of the moderator bricks: very hard to stop gap flow. • Graphite brick cracking • Fuelsalt boiling

Method overview

The gap is not blocked: **heat generated in the blocked hole is evacuated only through radial conduction in graphite and axial flow in gap.** The thermal-hydraulics is analogous to thermal analysis of solid fuel rods up to the fuelsalt in the blocked hole:

1. Salt bulk T in gap

↓ forced convection (Dittus-Boelter)

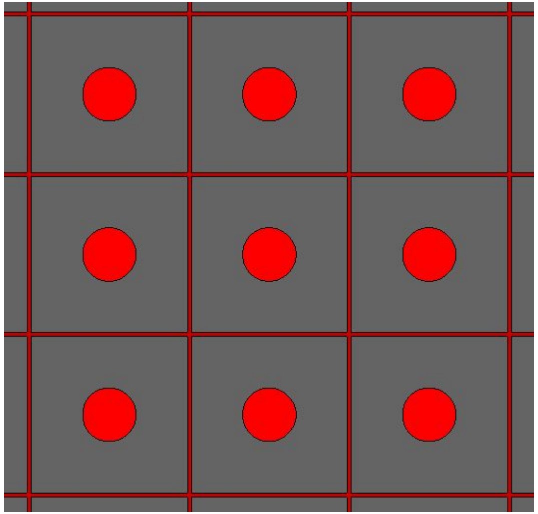
2. Graphite surface T in free gap

↓ heat conduction in graphite

3. Graphite surface T in blocked hole

↓ natural convection (CFD-derived correlation)

4. Salt bulk T, maximum T in blocked hole



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Fission power distribution (1)

First step: fission power map for each brick in the core

One Serpent fission power detector per graphite brick, divided in 40 axial bins.

Fission power is tracked **separately** for **salt in the holes** and **salt in the gaps.**

Total fission power: 2250 MW

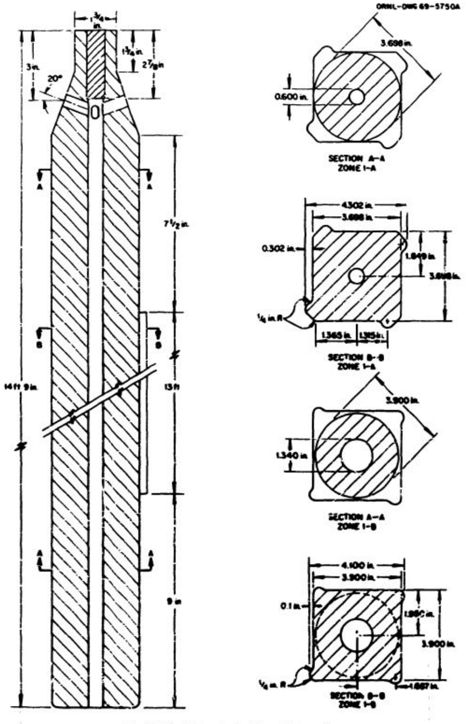
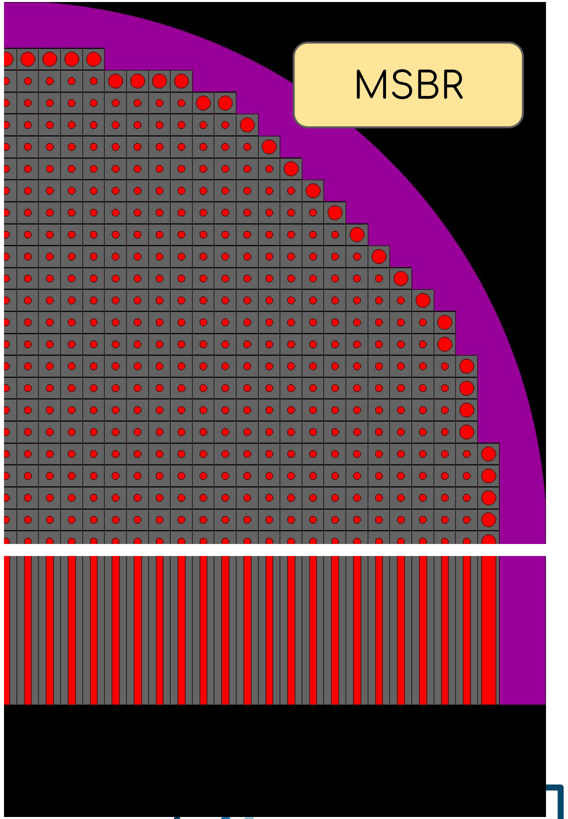
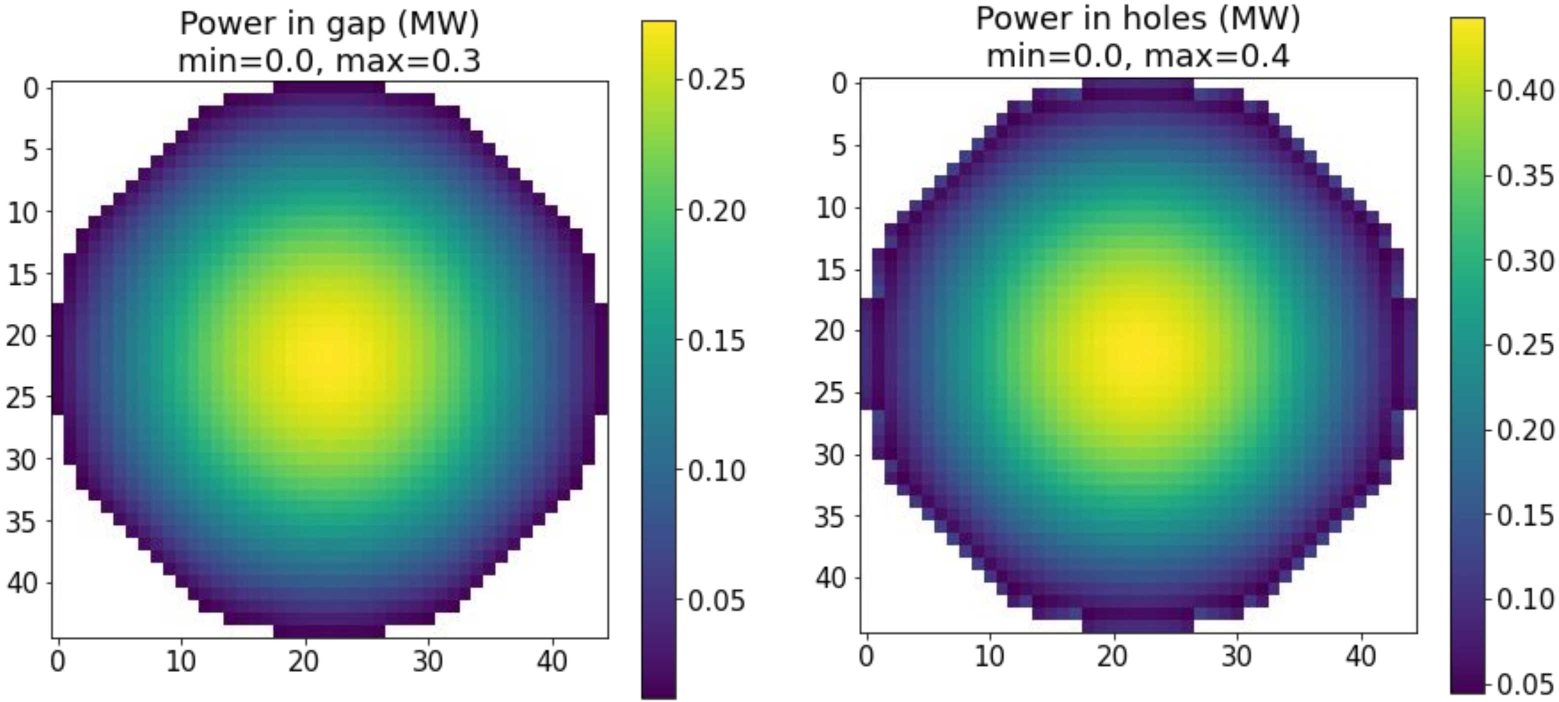


Fig. 3.4. Graphite moderator elements for zone I.



Fission power distribution (2)



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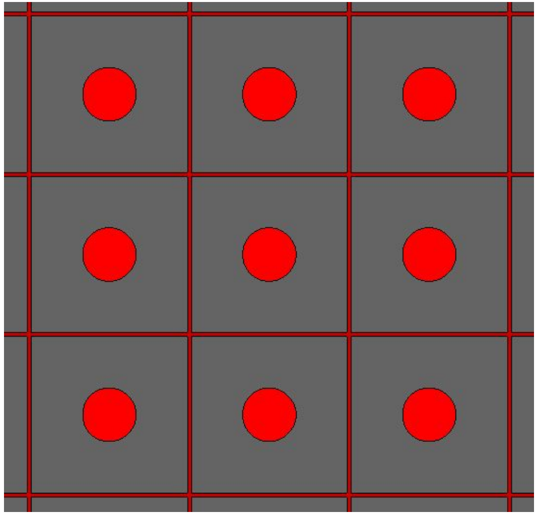

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Heat transfer in gap

Fuelsalt bulk temperature in gap:

$$T_{bulk}(z) = T_{in} + \frac{1}{\dot{m}c_p}\int_{z_{in}}^{z} q'(z)dz$$

Heat transfer coefficient:

$$Nu = 0.0243Re^{0.8}Pr^{0.4} \times \frac{1}{1+\frac{q'''_{gen}D}{q''_{wall}}\phi(Re,Pr)}$$

accounts for fission in fluid*

Gap wall temperature:

$$T_{wall}(z) = T_{bulk}(z) + \frac{q''_{wall}(z)}{h}, \; h = \frac{Nu\,k}{D}$$

* C. Fiorina et al., *Thermal-hydraulics of internally heated molten salts and application to the Molten Salt Fast Reactor*. Journal of Physics: Conference Series 501 (2014) 012030

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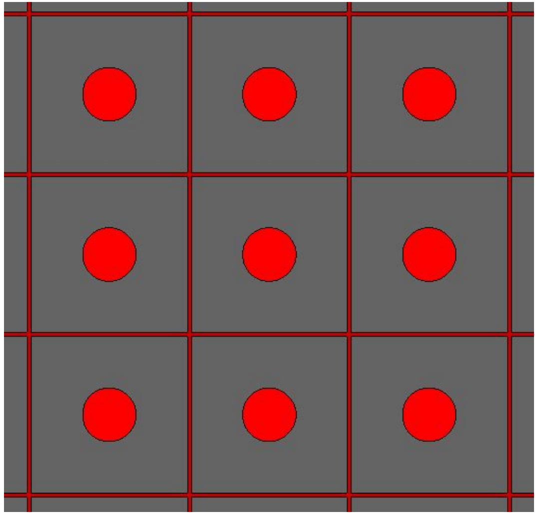
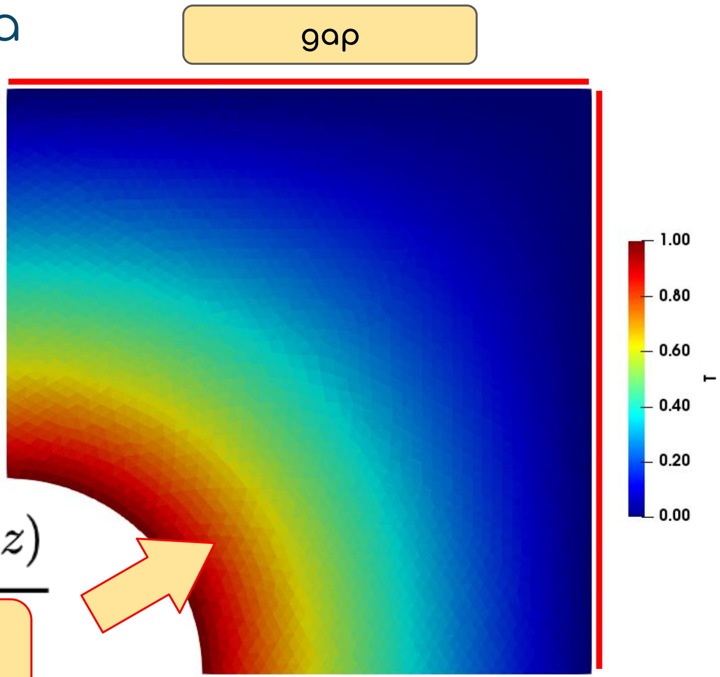


Conduction in graphite brick

Conduction in graphite can be solved with a 2D conduction heat transfer simulation, imposing a **1 °C temperature difference** between hole and gap, and **measuring the thermal power exchanged per unit length**.

Temperature increase is proportional to conducted thermal power:

$$T_{wall,hole}(z) = T_{wall,gap}(z) + \frac{q'_{salt,hole}(z)}{\frac{\partial q'_{cond}}{\partial \Delta T}}$$



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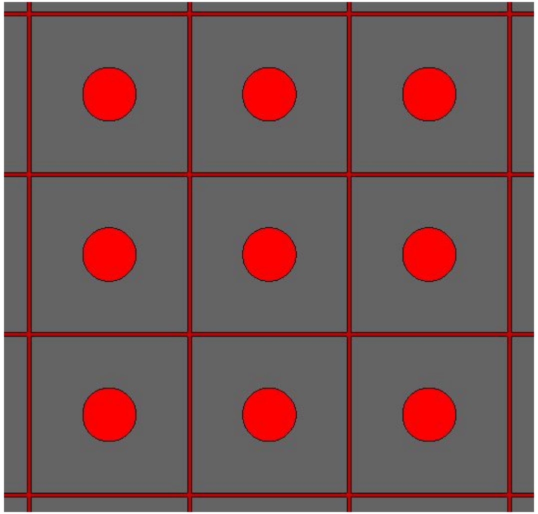

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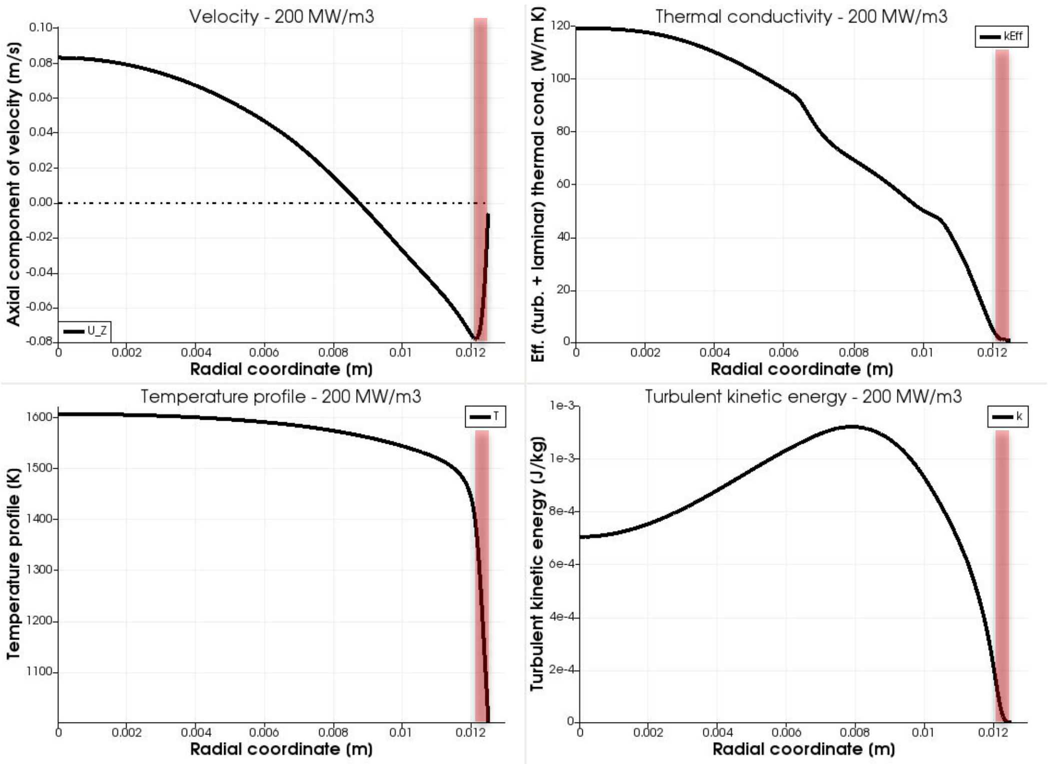
Free convection in blocked hole (1)

Inside the blocked hole all power is transferred to the graphite walls through free convection.

2D CFD analysis w/ Boussinesq approximation

Most of the temperature difference is in the sub-millimeter viscous sublayer close to the wall.



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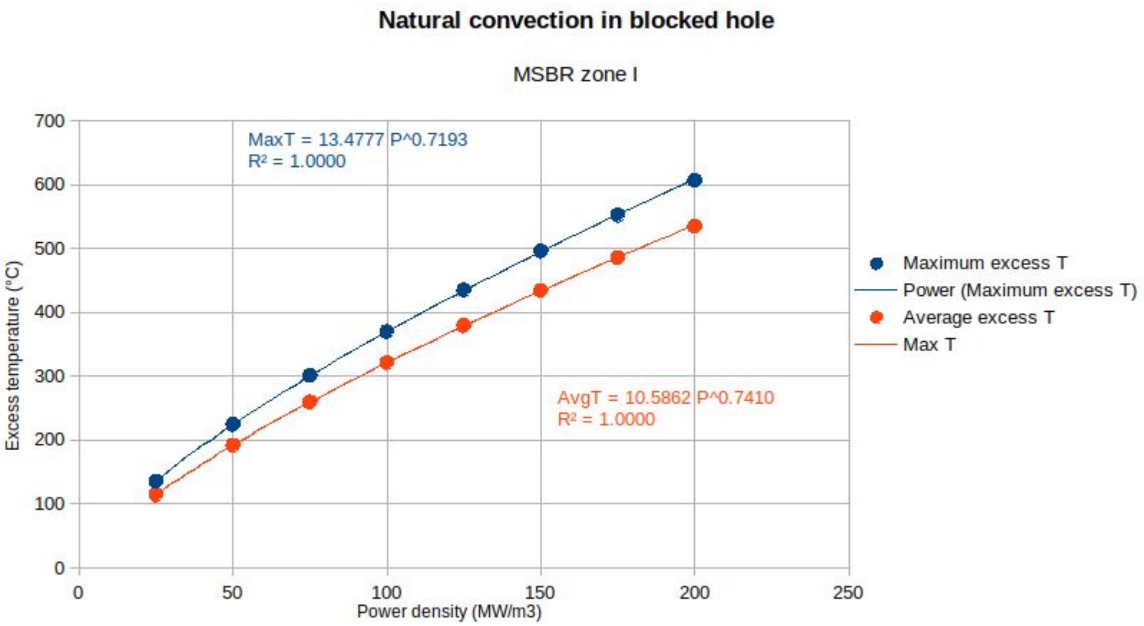
Free convection in blocked hole (2)

Inside the blocked hole all power is transferred through free convection.

A CFD-derived correlation was obtained by simulating different power levels and measuring the maximum excess temperature.



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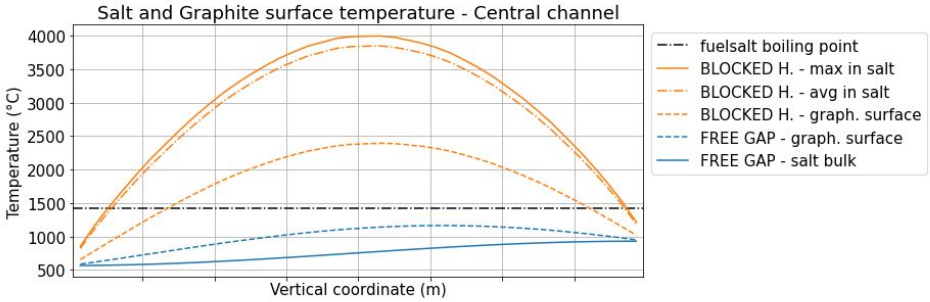
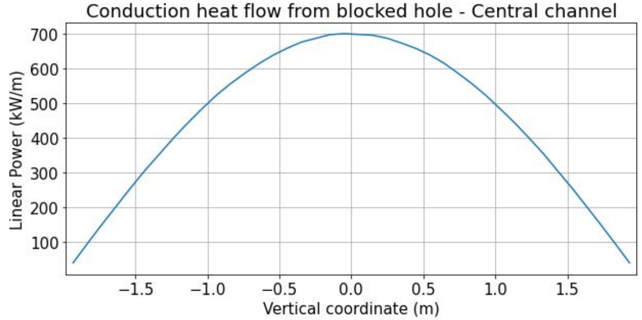
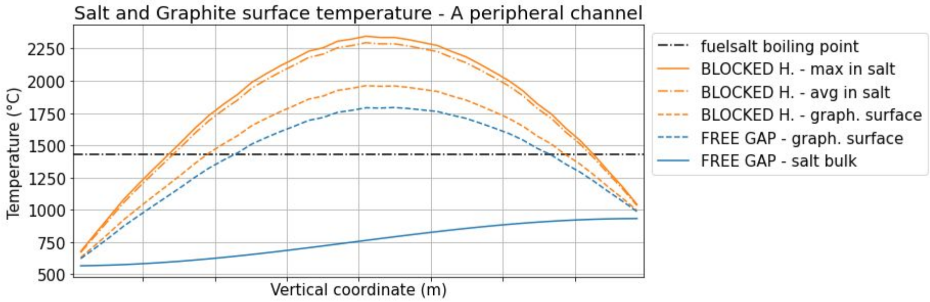
Blockage temperature profiles

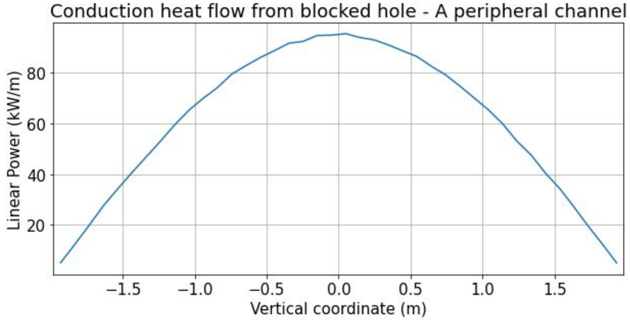
Central channel - 3.1 MW





A peripheral channel - 0.42 MW





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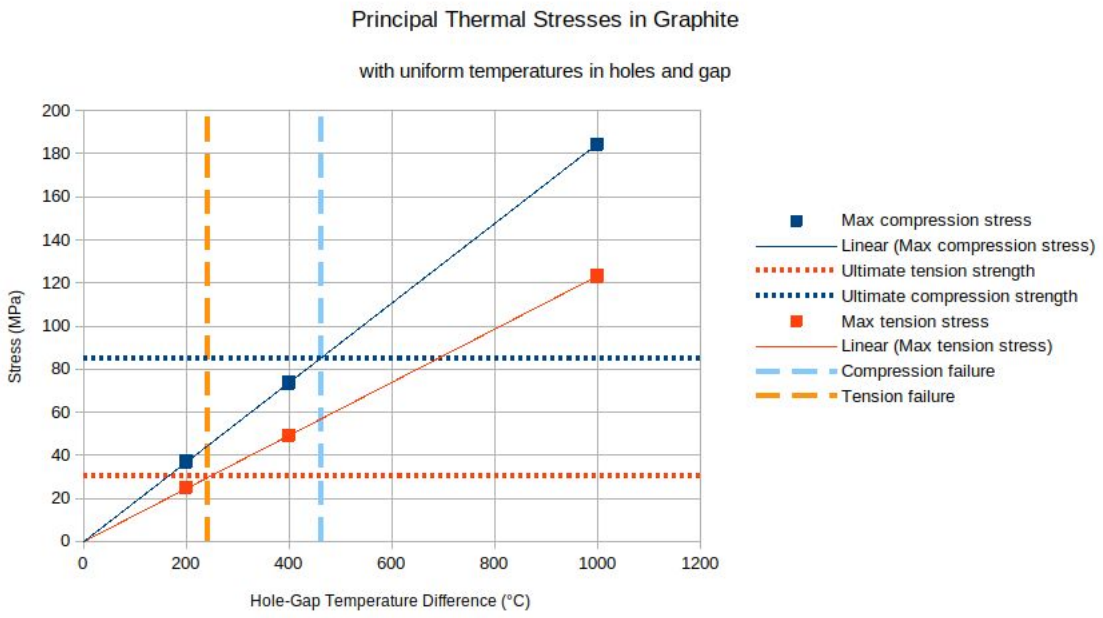
Graphite brick stress analysis (1)

The integrity of the graphite bricks is assessed by measuring the principal stresses. Multiple cases with various temperature differences between hole and gap were simulated.

For this geometry, failure occurs at:

- 244 °C for tension
- 462 °C for compression

using the **maximum principal stress (Rankine) criterion.**



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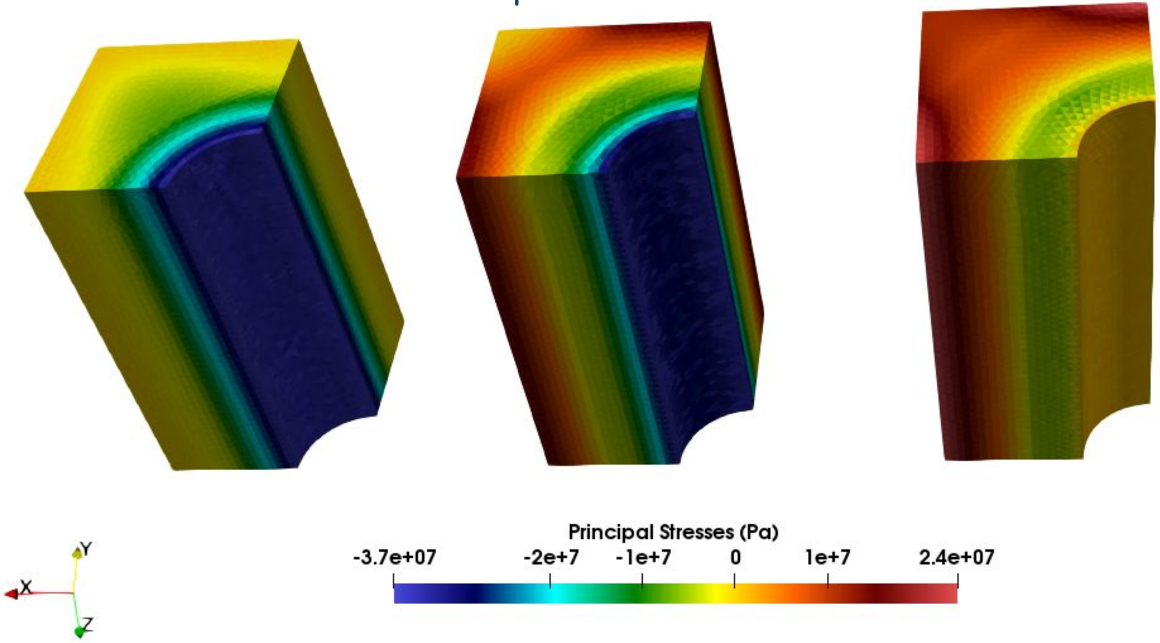
Graphite Brick Stress Analysis (2)

Principal thermal stresses at brick central horizontal plane
200 °C temperature difference



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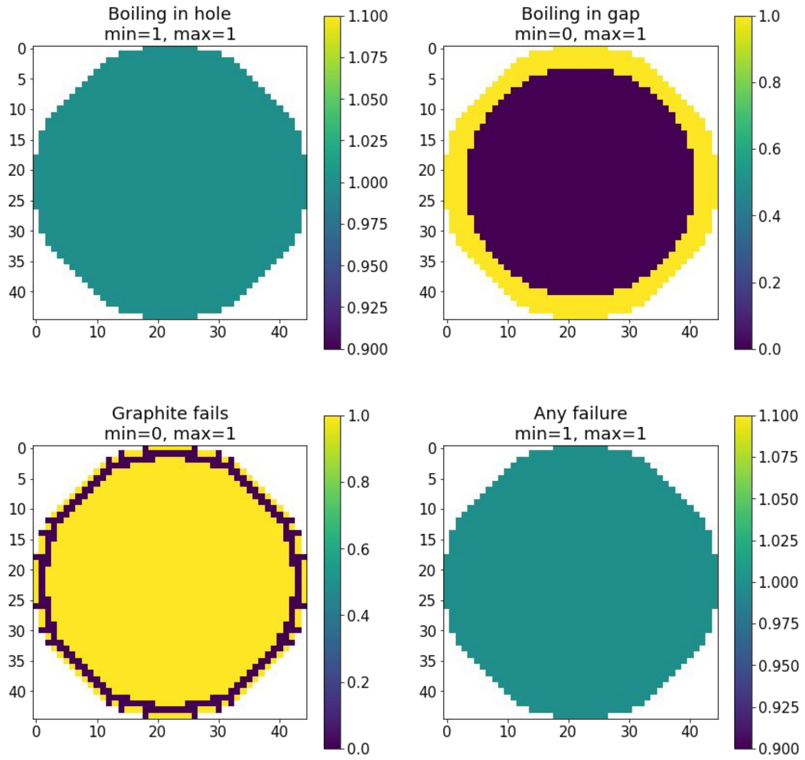
Channel failure map

We can build a map of all the channels that fail under blockage. A channel cannot withstand blockage if any of these occur:

- Fuelsalt boiling in gap
- Fuelsalt boiling in hole
- Graphite brick breaking



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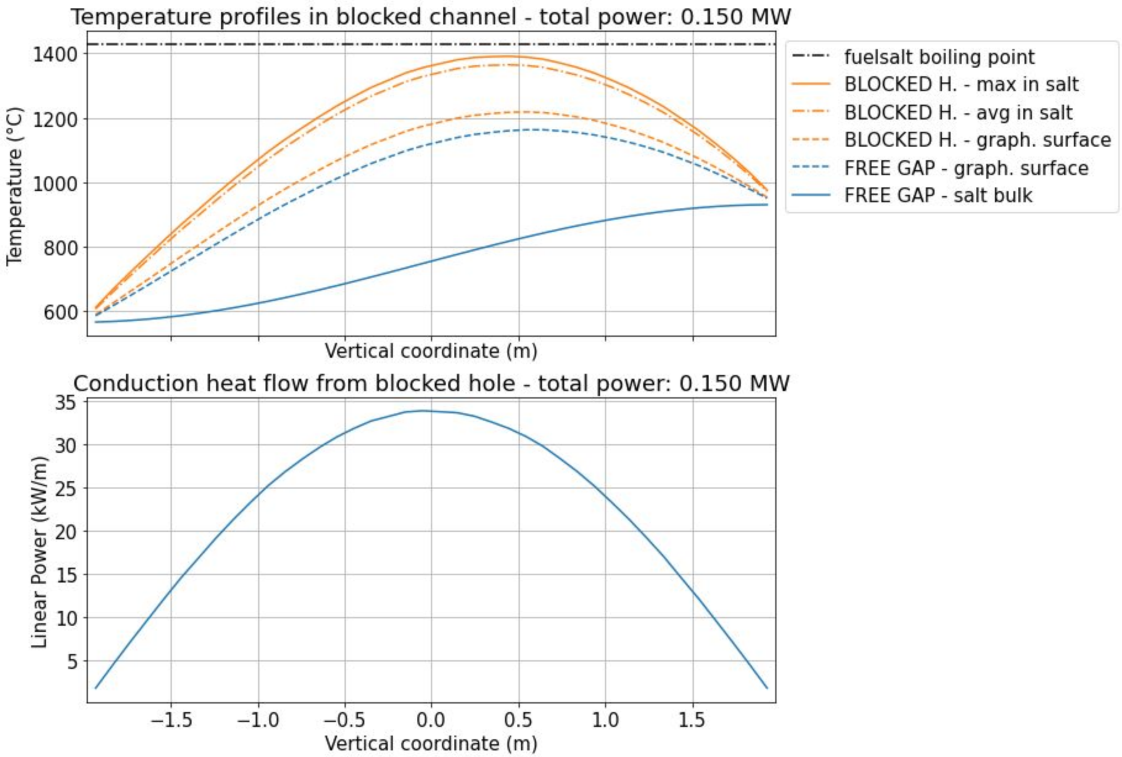
Allowable blockage temperature profiles

In this analysis, every channel of the MSBR core cannot withstand a blockage.

In this case, the maximum power generated in one channel is 0.15 MW.



Conclusions

- A **simple thermal-hydraulic model** was developed to analyze the hole blockage accident in MSRs
- First applied to the ThorCon MSR
- **Assessment of graphite rupture and fuelsalt boiling** in the blocked channel
- **Results were shown for the MSBR**, since we do not have permission to show ThorCon data here
- **In the MSBR model we considered, all channels fail**
- The **ThorCon design** instead is optimized so that **all channels that can be physically blocked do not suffer from fuelsalt boiling or graphite brick cracking**

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THANK YOU FOR YOUR ATTENTION!

References

1. ORNL-4541 - Conceptual Design Study of a Single-fluid Molten-salt Breeder Reactor
2. Leppänen, J., Pusa, M., Viitanen, T., Valtavirta, V. and Kaltiaisenaho, T. "The Serpent Monte Carlo code: Status, development and applications in 2013." Ann. Nucl. Energy, 82 (2015) 142-150.
3. C. Fiorina et al., Thermal-hydraulics of internally heated molten salts and application to the Molten Salt Fast Reactor. Journal of Physics: Conference Series 501 (2014) 012030
4. OpenFOAM: www.openfoam.com

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