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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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# MULTIPHYSICS STEADY-STATE SIMULATION OF THE HIGH TEMPERATURE TEST REACTOR WITH MAMMOTH, BISON AND RELAP-7

**Vincent Laboure[1], Javier Ortensi[1], Yaqi Wang[2], Sebastian Schunert[2], Frederick Gleicher[1], Mark DeHart[1] and Richard Martineau[3]**

[1]Reactor Physics and Analysis, Idaho National Laboratory, Idaho Falls, ID, USA
[2]Nuclear Engineering Method Development, Idaho National Laboratory, Idaho Falls, ID, USA
[3]Modeling and Simulation, Idaho National Laboratory, Idaho Falls, ID, USA

vincent.laboure@inl.gov

## ABSTRACT

In this work we present a new approach to solving a multiphysics steady-state simulation for the High Temperature Test Reactor (HTTR) using one Super Homogenization (SPH) corrected 3-D neutronics model in MAMMOTH, multiple heterogeneous 2-D axisymmetric fuel pin models in BISON and several 1-D annular flow thermal-fluids models in RELAP-7. The coupling of the different physics is complicated by the fundamentally disparate models, potentially affecting the stability of the global system. A pseudo-transient to converge the temperature fields is used to circumvent this difficulty. The benefit of doing so as opposed to having fully 3-D heterogenous models for all physics is that the computational burden for reactors as complex as HTTR may quickly become unbearable while coarse models may not capture all the essential phenomena of the problem. The driving purpose of this work is to establish a self-sustaining steady-state solution that can be used to start safety transients.

KEYWORDS: Multiphysics, HTTR, MAMMOTH, BISON, RELAP-7

## 1. INTRODUCTION

Most nuclear reactor physics applications are inherently multiphysics, in the sense that capturing the essential phenomena in the system requires to combine several fields of physics. For instance, the topic of this work focuses on the High Temperature Test Reactor (HTTR) [1] whose behavior is fundamentally governed by neutronics, heat transfer and thermal-fluids. Two main approaches are typically used to resolve the nonlinearities of such a problem: in a strongly or tightly coupled manner. For strong coupling, all the equations are combined into one system and all the unknowns are simultaneously solved for. Although this can be very efficient – in particular for highly nonlinear problems, it may be quite challenging or practically unfeasible if the various physics have intrinsically different features (such as space and time scales) or desired discretizations. Tight coupling consists of solving each physics in turn using Picard iterations, updating the coupling terms until global convergence is reached.

A difficulty of the multiphysics coupling then resides in transferring data from an application to another. This task can be fairly straightforward if the same mesh is used for each. In many instances, however, it is desired to adopt different meshes tailored to each physics so as to efficiently converge each one to a satisfying level of accuracy while keeping the computational resources to a minimum. In addition, each individual code may have fundamentally different requirements for optimal performance, such as the preferred coordinate system, problem dimensionality, ability to perform transient or steady-state solves etc.

This is particularly true for the High Temperature Test Reactor (HTTR), whose design has a high level of complexity for the analyst: strong axial temperature gradient, dozens of distinct fuel enrichment zones, different numbers of fuel pins depending on the fuel column, etc. A detailed full-core, 3-D heterogeneous mesh to solve for the neutron flux and the fuel, moderator, and coolant temperatures would necessitate massive computational resources. Rather, we opt to use distinct models for each physics: a 3-D homogenized core for neutronics and heat conduction/convection in the graphite moderator, representative 2-D axisymmetric models for heat transfer at the pin level and 1-D coolant channels for thermal-fluids. These are respectively simulated using the reactor physics code MAMMOTH [2,3] relying on the radiation transport code Rattlesnake [4,5], the fuel performance code BISON [6] and the nuclear reactor system safety analysis code RELAP-7 [7]. All of these applications are based on the Multiphysics Object Oriented Simulation Environment (MOOSE) framework [8] and developed at Idaho National Laboratory (INL), thereby facilitating their coupling – as well as the data transfer – owing to consistent data structures.

In this work, we focus on establishing a self-sustaining 30 MW steady-state – or *null-transient* – solution at 390 effective full power days (EFPD) to be used as the initial condition for transients such as Loss of Forced Cooling (LOFC) accidents. One challenge in the coupling is that the neutronics solve is an eigenvalue solve while we find that trying to couple the heat transfer and thermal-fluids in a steady-state fashion can lead to numerical instabilities. Therefore, we separate the neutronics from the other physics and run the latter with a pseudo-transient using Picard iterations to fully converge the problem.

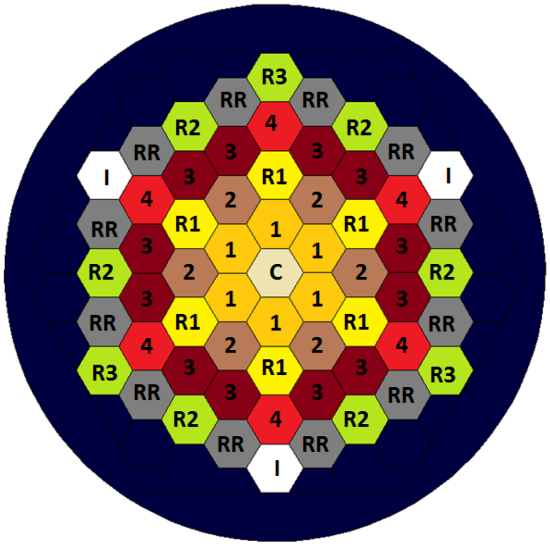
## 2. HIGH TEMPERATURE TEST REACTOR MODEL

### 2.1. Sub-models

Figure 1 gives a glimpse of the complexity of the HTTR design. In particular, the enrichment of both the fuel and the burnable poison varies significantly axially and radially. Fuel blocks contain either 31 or 33 fuel pins while control rod (CR) blocks have two control rod insertion holes and one reserved shutdown pellet insertion hole [10]. All these blocks are cooled by pressurized helium which is forced – in normal operation – to flow downwards with an inlet temperature of 395°C. More comprehensive details can be found in [1,10].

Our numerical model consists of the following sub-models coupled to each other through the MOOSE framework [8]. A schematic representation of their meshes and interrelation is given on Figure 2.

✓ One full-core, 3-D MAMMOTH input with homogenized blocks to solve the linearized Boltz-



| Stack 1 | Stack 2 | Stack 3 | Stack 4 |
|---|---|---|---|
| RR | RR | RR | RR |
| RR | RR | RR | RR |
| 6.7/2.0 | 7.9/2.0 | 9.4/2.0 | 9.9/2.0 |
| 5.2/2.5 | 6.3/2.5 | 7.2/2.5 | 7.9/2.5 |
| 4.3/2.5 | 5.2/2.5 | 5.9/2.5 | 6.3/2.5 |
| 3.4/2.0 | 3.9/2.0 | 4.3/2.0 | 4.8/2.0 |
| 3.4/2.0 | 3.9/2.0 | 4.3/2.0 | 4.8/2.0 |
| RR | RR | RR | RR |
| RR | RR | RR | RR |

**(a) HTTR core layout with fuel (columns 1-4), control rods (C, R1, R2, R3), replaceable reflectors (RR), and instrumentation (I).**

**(b) Description of the four different HTTR fuel columns/stacks ($UO_2$ wt.% fuel enrichment / burnable poison wt.% enrichment).**

**Figure 1: Overall depiction of the HTTR model. Pictures courtesy of [9].**

mann transport equation. The multigroup cross-sections are computed with a heterogeneous Serpent [11] model depleted to 390 EFPDs with 10 energy groups. A Super Homogenization (SPH) correction is applied to run transport-corrected diffusion, as described in [9,12]. The power is normalized to 30 MW. The main purpose of this input is to compute the power density to transfer to the other physics.

✓ One full-core, 3-D MOOSE modules * input with homogenized blocks to solve for the moderator temperature, modeling heat conduction in the core and convection at its boundaries. The mesh is the same as the one used for MAMMOTH with one more level of spatial refinement. The goal of this input is to evaluate the temperature of the graphite throughout the core, particularly capturing how the heat not removed from the cooling channels dissipates and leaks from the core boundaries. This phenomenon becomes especially important for transients such as LOFC, since the coolant mass flow rate quickly drops to zero (at least before any natural convection takes effect).

✓ 150 instantiations of a BISON input representing fuel pins with a heterogeneous 2-D axisymmetric geometry. To each of the 30 fuel columns correspond 5 BISON inputs stacked on top of each other between the upper and lower two layers of reflectors (see Figure 1b). The power density is deposited in the fuel (in gray on the BISON mesh shown on Figure 2). Radiation heat transfer is modeled in the gaps between (i) the fuel and the graphite sleeve (in red on that same mesh) and between (ii) the sleeve and the graphite on the other side of the cooling channel

*Fundamental physics such as heat conduction are available directly in so-called MOOSE modules and are available in any application based on MOOSE.

(in blue on that same mesh), where the temperature is set to the moderator temperature from the full-core MOOSE modules sub-model. The primary objective of this BISON sub-model is to compute the fuel temperature for cross-section interpolation and the inner wall temperature needed to simulate the thermal-fluids of the corresponding RELAP-7 channel.

✓ 46 one-dimensional RELAP-7 instantiations: 30 for the fuel column (1-4 on Figure 1a) and 16 for the CR columns (C, R1, R2 and R3 on Figure 1a). Each input models a single representative fuel/CR channel over the entire height of the core, though in reality fuel columns have either 31 or 33 fuel pins and CR columns have two control rod holes. However, fuel and CR channels are modeled differently, as shown on Figure 3: (I) For fuel channels, helium is assumed to go through a channel of diameter 41 mm inside the graphite moderator. It is only forced around the fuel sleeve of diameter 34 mm over the slices corresponding to actual fuel blocks (see Figure 1b), i.e. for $1.16 < z < 4.06$ m. This particular annular flow is the one shown as the RELAP-7 channel on Figure 2. (II) For CR channels, helium is assumed to flow through a channel of constant diameter 123 mm over the entire height of the core. This is an approximation because some control rods should be partially inserted during 30 MW steady-state operations.

In addition, the bypass flow – corresponding to the proportion of the total flow circulating in the CR channels is assumed constant and equal to 8%, similarly to what was done in [13]. The total mass flow rate $\dot{M}$ varies depending on the operation mode of the reactor, as described in Section 3.

This sub-model allows to compute the heat flux removed from the coolant as well as the fluid temperature.

### 2.2. Multiphysics Coupling

We find that trying to couple BISON and RELAP-7 directly in a steady-solve leads to numerical instabilities. This is because in steady-state, a small power density can induce very large temperatures. Inversely, very small power sinks (such as the energy removed by the coolant) can make the temperature negative, which is not only non-physical but also often leads to code failure. Thus, the path to convergence can be difficult. Rather, solving the temperature fields using a pseudo-transient with Picard iterations proved to behave in a much more stable manner. Figure 4 summarizes the workflow of the coupling between all the applications, while Algorithm 1 gives insight about the two-step Picard iteration algorithm that we use to achieve convergence. In practice, it is advantageous to loosen the tolerances of the inner Picard iterations until the power density is sufficiently converged.

The variable transfers between application needed for the problem are detailed on Table 1. The power density from MAMMOTH is deposited in both the fuel pins (by adjusting to the volume of the representative pin) and the moderator with the heat flux removed by the coolant being added as a power sink in the moderator. BISON and RELAP-7 exchange the wall and fluid temperatures while MAMMOTH receives the average fuel and moderator temperatures for cross-section tabulation.

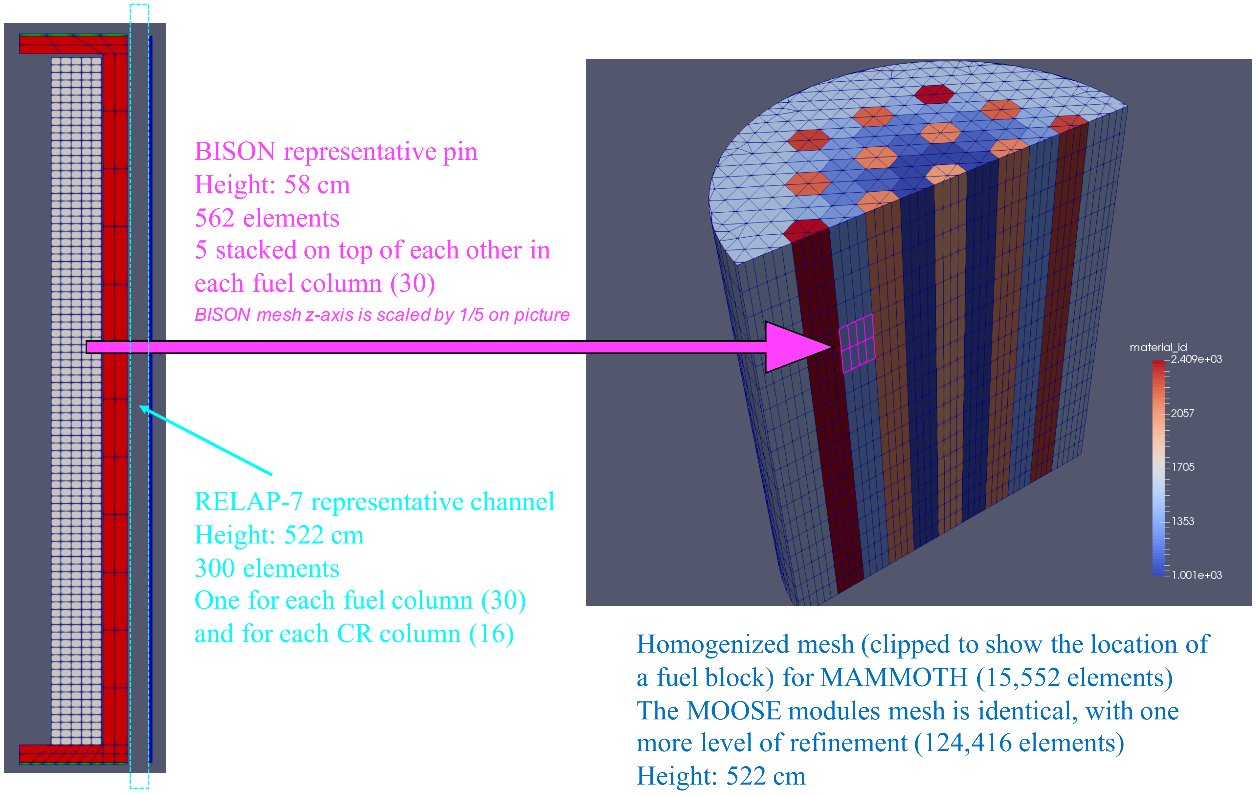



**Figure 2: Interrelation of the various sub-models and their meshes.**

## 3. RESULTS

Two 30 MW operation modes are described in [1]: high temperature test operation and rated operation with 950°C and 850°C outlet primary coolant temperature, respectively. We particularly wish to compare the numerical and measured values reported in Table 12.8 of [1].
Assuming that the helium heat capacity is independent of $T$, we compute the outlet coolant temperature using:

$$\overline{T}^{\text{out}}_{\text{fluid}} = \sum_{i=1}^{I} \frac{\dot{m}_i \, n_{\text{channels},i}}{\dot{M}} T^{\text{out}}_{\text{fluid},i} \tag{1}$$

where $I = 46$ is the total number of representative RELAP-7 channels. For each channel $i$, $\dot{m}_i$ is its helium mass flow rate, $n_{\text{channels},i}$ is the number of actual channels in that block (whether fuel or CR) and $T^{\text{out}}_{\text{fluid},i}$ is the outlet coolant temperature of that particular channel. Table 2 shows that – in both cases – the computed value is within the uncertainty of the measurement.

Let us now focus more specifically on the high temperature test operation. Figure 5 shows the steady-state temperature profiles obtained for the graphite and coolant temperatures along the straight line $(x, y)$ =(0, 0.36 m), which is in the middle of a column containing fuel. The coolant enters at the top of the core ($z = 5.22$ m) at 668.15 K and is in contact with fuel elements for 1.16 $< z <$ 4.06 m. Based on our model, it comes out at the bottom of the core from that particular

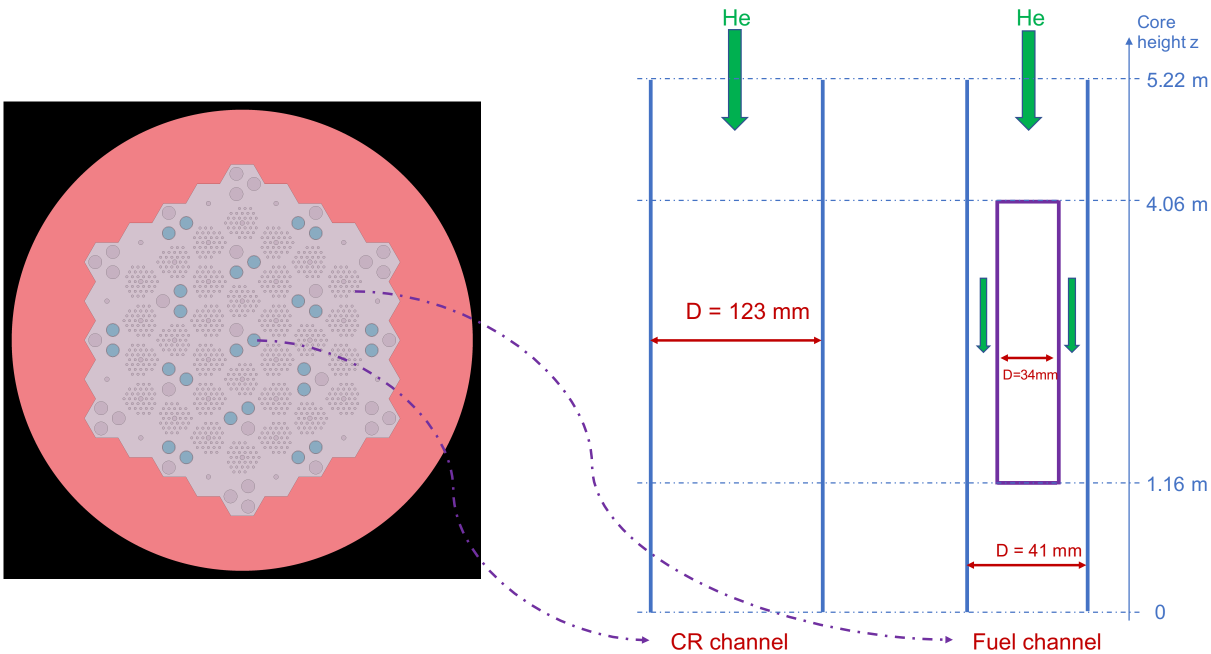



**Figure 3: Left: Cross section view of the Serpent model. Right: description of the RELAP-7 models for fuel and CR channels.**

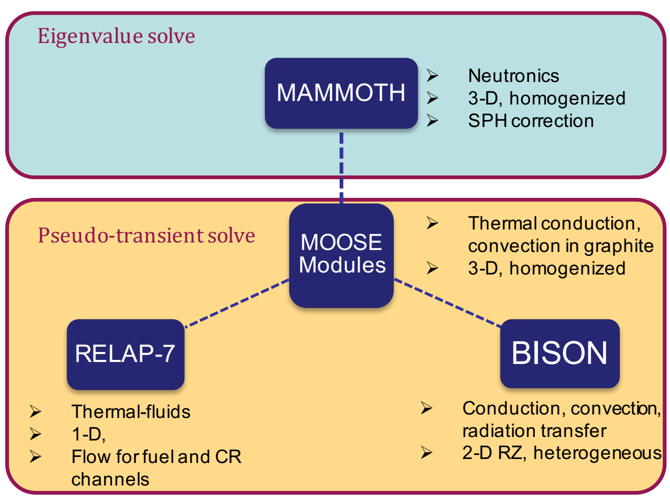



**Figure 4: Workflow of the coupling**

channel at 1247 K, which is a little higher than the average of 1228 K from Table 2 since that channel is near the center column of the core. It is noted that having a moderator temperature lower than the fluid temperature at the bottom of the core is not unphysical. It simply means that the fluid releases some of its energy into the bottom reflector regions, which is consistent with the very slight decrease in fluid temperature as $z$ goes from 1.16 m to 0. This is further emphasized

**Algorithm 1** Two-level Picard iteration algorithm for establishing a steady-state.

```
while Picard tolerances (1) not met do
    Run an eigenvalue calculation [MAMMOTH] with cross-sections interpolated using the fuel and graphite temperature.
    while steady-state not reached do
        Take a time-step
        while Picard tolerances (2) not met do
            Solve in turn for the full-core heat conduction [MOOSE modules], representative pin [BISON] and representative cooling channels [RELAP-7], updating required fields at the end of each solve.
        end while
    end while
    Update fuel and graphite temperatures in MAMMOTH.
end while
```

**Table 1: Transfers performed between applications**

| To \ From | MAMMOTH | MOOSE Modules | BISON | RELAP-7 |
|---|---|---|---|---|
| MAMMOTH | X | Moderator temperature (for cross-sections) | Fuel temperature (for cross-sections) | X |
| MOOSE Modules | Power density (homogenized) | X | X | Heat flux removed by coolant (homogenized) Fluid temperature at $z = 0$ (for BC) |
| BISON | Power density (scaled to fuel pin) | Moderator temperature (for BC) | X | Fluid temperature |
| RELAP-7 | X | Outer wall temperature | Inner wall temperature | X |

**Table 2: Measured and computed values of the outlet coolant temperature.**

| | High temperature test operation | Rated operation |
|---|---|---|
| $\dot{M}$ | 10.2 kg/s | 12.4 kg/s |
| $\overline{T}_{\text{fluid}}^{\text{out}}$ (reported in [1]) | 1223 $\pm$17 K | 1123 $\pm$19 K |
| $\overline{T}_{\text{fluid}}^{\text{out}}$ (computed) | 1228 K | 1138 K |
| Absolute error | 5 K | 15 K |

when we look at the homogenized fission power density and the coolant volumetric heat removal rate along that channel, also shown on Figure 5. The reason their difference is not zero is that some of the heat is removed/added by conduction in the surrounding graphite moderator. Nevertheless, their difference being relatively small emphasizes that – in steady-state – most of the heat is removed by the coolant. This could be the reason why the computed outlet coolant temperatures are so close to the reported values, despite the many approximations of this model. Figure 6 displays the moderator temperature throughout the homogenized core, with the fuel and CR columns clearly appearing at the bottom of the core.

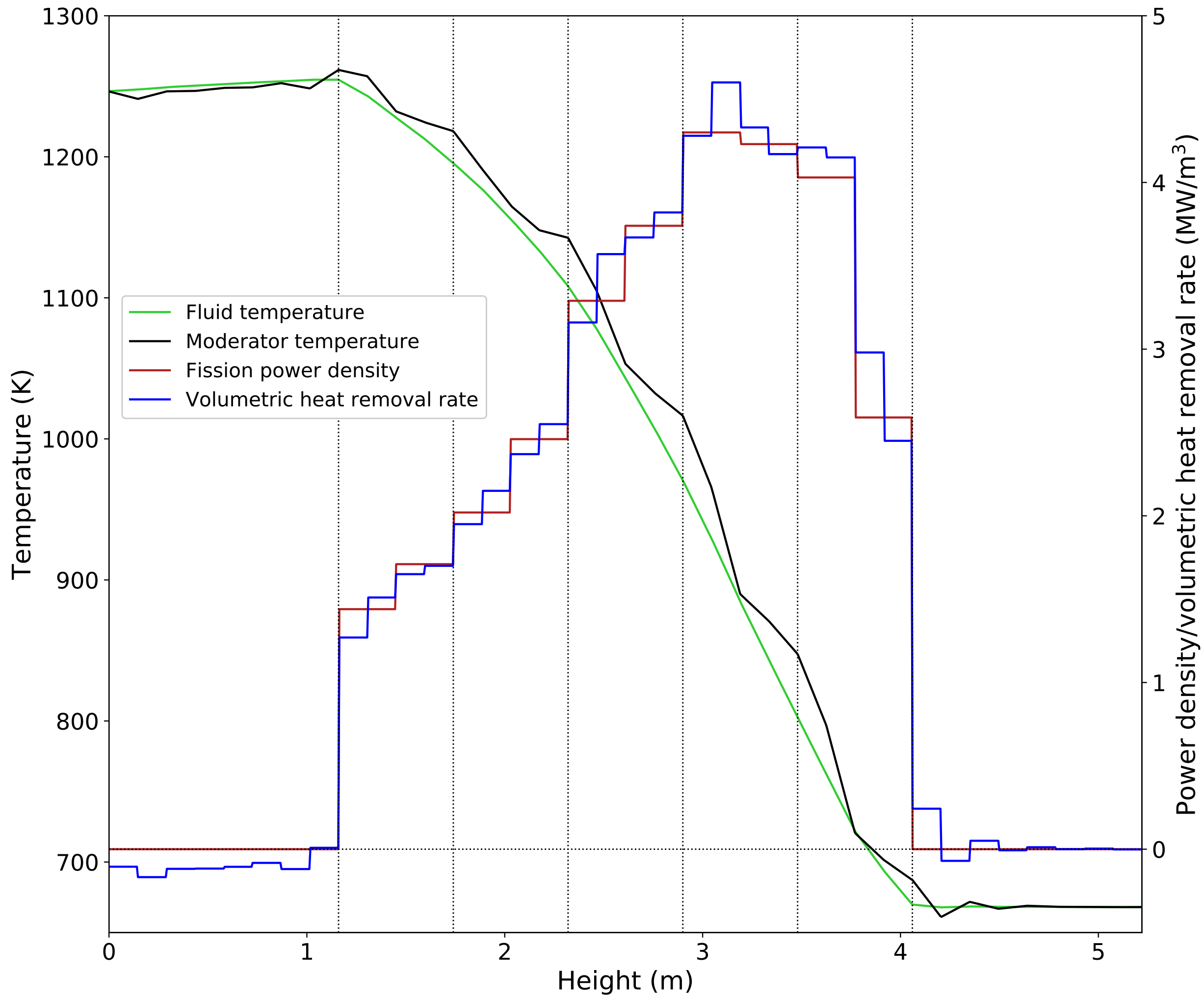



**Figure 5: Fluid and moderator temperature along $(x, y)$ = (0, 0.36 m), which is the center of a fuel column. The homogenized fission power density and the coolant volumetric heat removal rate in that channel are also shown. The vertical dotted lines outline the five slices corresponding to the fuel blocks. Note that the fluid enters from the top of the core ($z$ = 5.22 m).**

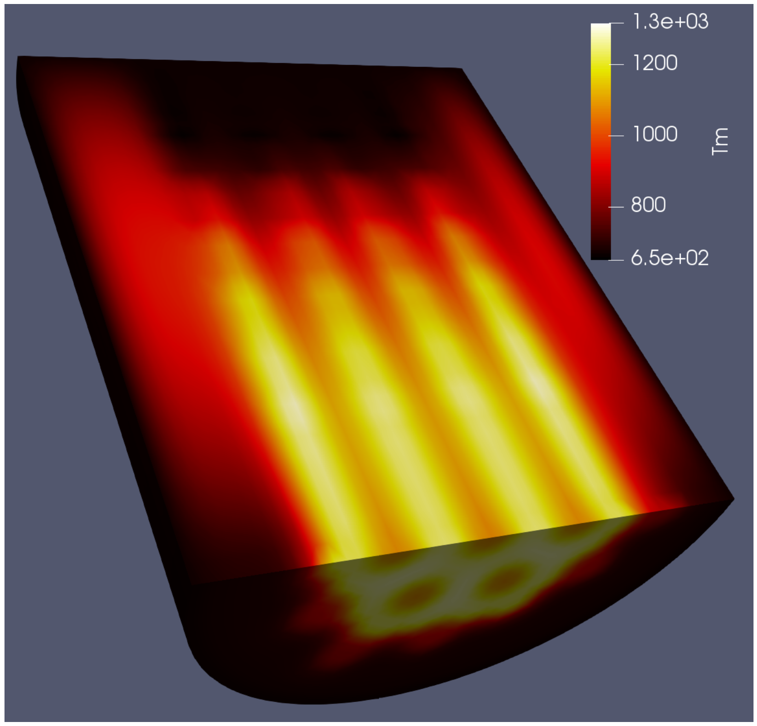



**Figure 6: Moderator temperature (in K) on the 3-D homogenized mesh.**

## 4. CONCLUSIONS

In summary, we have presented an approach to compute a steady-state solution using a HTTR model coupling neutronics, heat transfer and thermal-fluids with MAMMOTH, BISON and RELAP-7, respectively. The main challenge is to numerically converge the temperature fields in steady-state. The selected approach consists of using Picard iterations with a pseudo-transient to reach self-sustaining fields between the fuel, moderator and coolant temperatures for a given power density. The interest of the presented method also lies in its generality demonstrated by the fundamentally different meshes used for the various physics of the problem, therefore avoiding the large computational cost of full 3-D heterogeneous models. In particular, the results for the outlet coolant temperature are within the uncertainty for both 30 MW operation modes.

Future work will involve refining this model, particularly including radiation heat transfer between the blocks of the reactor. Then, LOFC transients will be performed and the results will be compared to experimental data.

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