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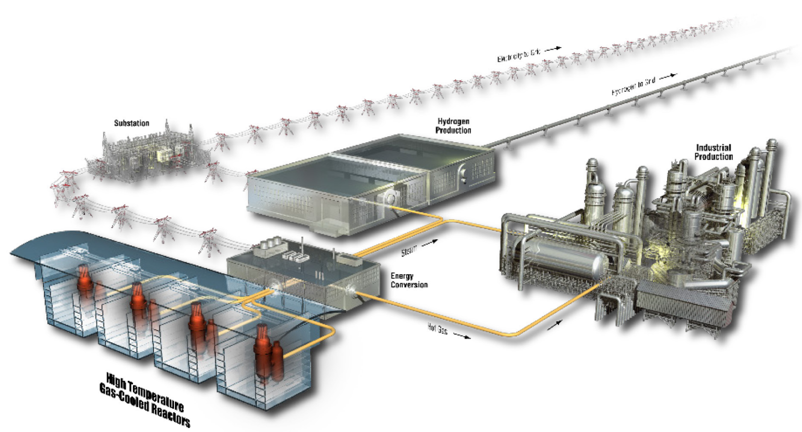

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
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FIGURES

Calculation of Helium Coolant Behavior in a Single Cooling Channel in MHTGR Reflector Region during Pressurized Conduction Cooldown Scenario Using the COMSOL Multiphysics Code

1. INTRODUCTION

The objective of the calculation performed and discussed in this report was to examine the behavior of the helium flow through a single cooling channel in the modular high-temperature gas-cooled reactor (MHTGR) core during a pressurized-conduction cooling scenario (PCC).[a] The region of interest for the single cooling channel flow calculation is in the upper reflector blocks. Flow from the upper reflector blocks moves upward and into the upper plenum during the PCC scenario.

The report is divided into four sections:

1. This introduction.
2. Background: a summary of the motivation for performing the calculation and a description of the scenario including calculational boundary conditions.
3. Description of the calculation and calculational results
4. A summary.

2. BACKGROUND

Following a loss-of-offsite power, the circulators in a very high temperature gas-cooled reactor (VHTR) quickly coast down in conjunction with insertion of the control rods. Thereafter, if the VHTR does not have a leak in the primary pressure boundary, the scenario is commonly known as a PCC. On the other hand, if boundary does have a leak in the primary pressure boundary, the scenario is commonly known as a depressurized conduction cooldown (DCC).

In either case, the core flow, normally downward-oriented under operational conditions, reverses and flows upward. The core flow rate is governed by the heat transferred to the gases in the core and is affected by the core geometry, frictional pressure-loss characteristics, and relevant material properties. The core flow in either situation is density-gradient dominated in the core coolant channels. Gases flow from the core region into the upper plenum. Depending upon the flow velocity, either the gas impinges on the upper vessel head as jets or it flows gently upward to merge with gases in the upper regions of the plenum. In some situations, the flow may emerge from the core coolant channels as a jet and then evolve to a plume prior to reaching the nearest structure, as it moves upward.

To investigate the behavior of the helium flow in the cooling channels during these scenarios, Reactor Excursion and Leak Analysis Program (RELAP)5-3D calculations were performed.[1] RELAP5-3D is a systems analysis tool and is generally used to calculate global behavior in large regions of a system. To study the flow in an MHTGR core, the core region was divided into three rings in a plane normal to the coolant channel flow. The inner ring is in the center. The middle ring is an annular region nested between the inner and outer rings while the outer ring is the peripheral region—represented as an annulus.

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[a] The focus of this effort was shifted to the PCC condition from the depressurized conduction cooling condition (DCC) when system calculations performed using RELAP5-3D showed helium flow rates following a leak in the primary pressure boundary resulting in the depressurization of the reactor pressure vessel were very low with Reynolds numbers less than 10. Such low Reynolds numbers for the DCC scenario are indicative of very low quantities of helium remaining in the core following reactor-vessel depressurization.

2.1 PCC Scenario

The average Reynolds number and average temperature of the gas flowing from the core into the upper plenum for the three rings are plotted in Figure 1 and Figure 2. Because the model was constructed to study the capability of the MHTGR to survive a PCC scenario without the availability of external heat sinks, e.g., a heat exchanger located in the balance of plant, natural circulation flow was restricted to the MHTGR vessel.

Figure 1, showing the average Reynolds-number behavior, indicates that throughout the PCC scenario the average exit Reynolds numbers of the gases moving from the core into the upper plenum never exceed 700. Therefore, they are for the most part laminar, with only a low probability of forming a jet capable of impinging on the upper surfaces of the upper plenum. The flow has the following characteristics:

- Flow from the rings with highest power (the inner and outer rings) is upward while flow in the peripheral ring is downward
- The Reynolds number in the inner and middle rings is less than 200 from 8 hours (28800 s) onward.

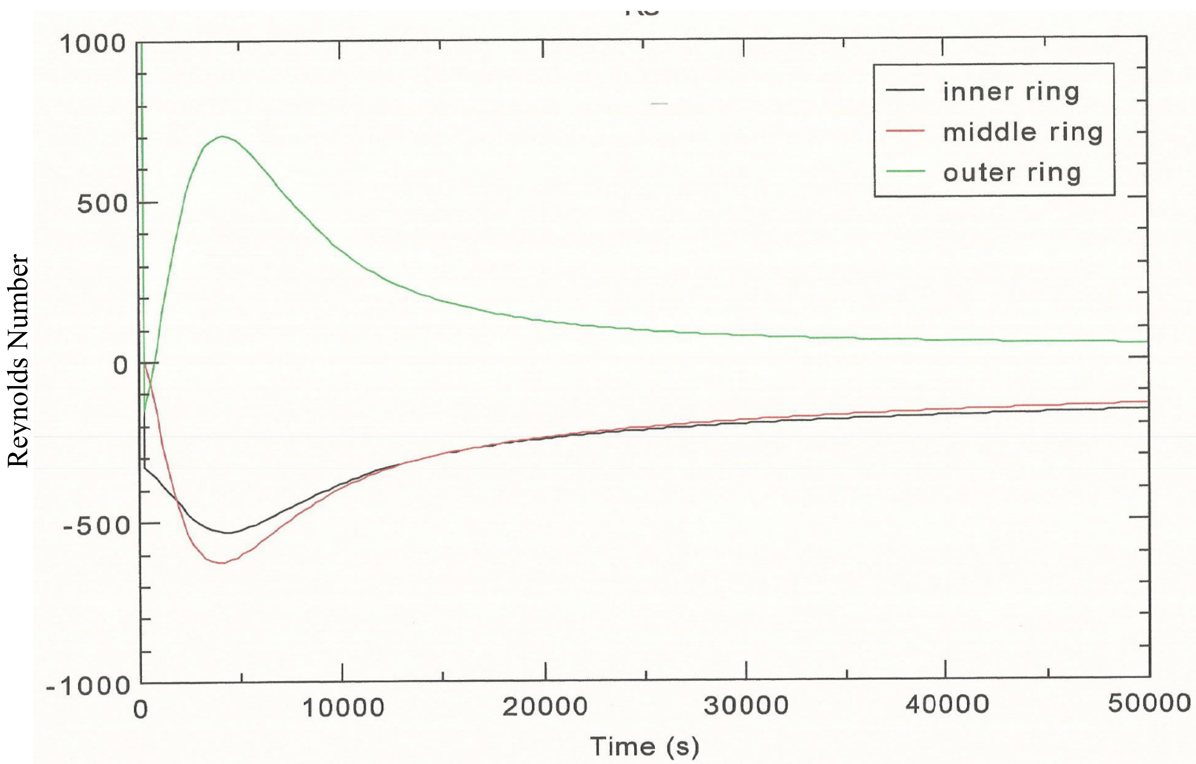

Figure 1. Average Reynolds number of gases moving from core into upper plenum of MHTGR during PCC scenario from the inner, middle and outer rings.

Figure 2 shows the average temperature for the gas moving from the three rings into the upper plenum. The average temperature reaches 900 K in about 3 hours (627°C), but does not reach peak temperature (950 K = 677°C) until 2.8 days (2.4×10^5 s). However, it is instructive to examine the changes in coolant temperature between the top of the active core region and the top of the reflector blocks. Keeping in mind that there are two reflector blocks above the top of the active fuel region and that there are no sources of heat in the reflector blocks, the flow moving from the active core region into the reflector blocks undergoes cooling. Figure 3 shows the average temperature of the coolant flow at the exit of the active core region for the inner and middle rings as the flow enters the reflector blocks. Also shown is the average coolant temperatures in the upper plenum.

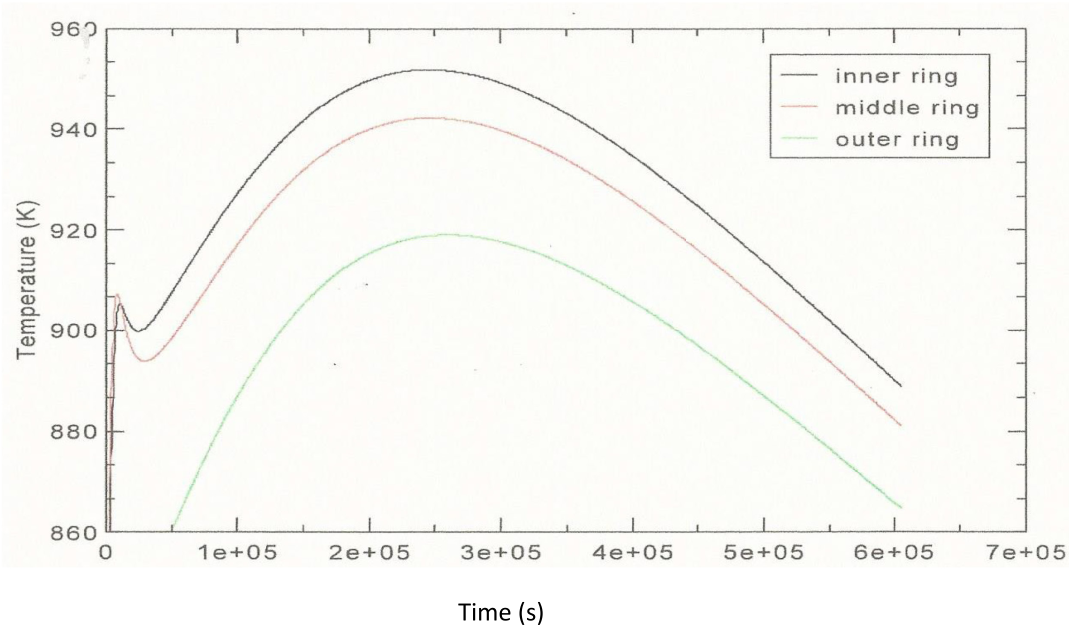

Figure 2. Average temperature as a function of time (s) of gases moving from core into upper plenum of MHTGR during PCC scenario from the inner, middle, and outer rings.

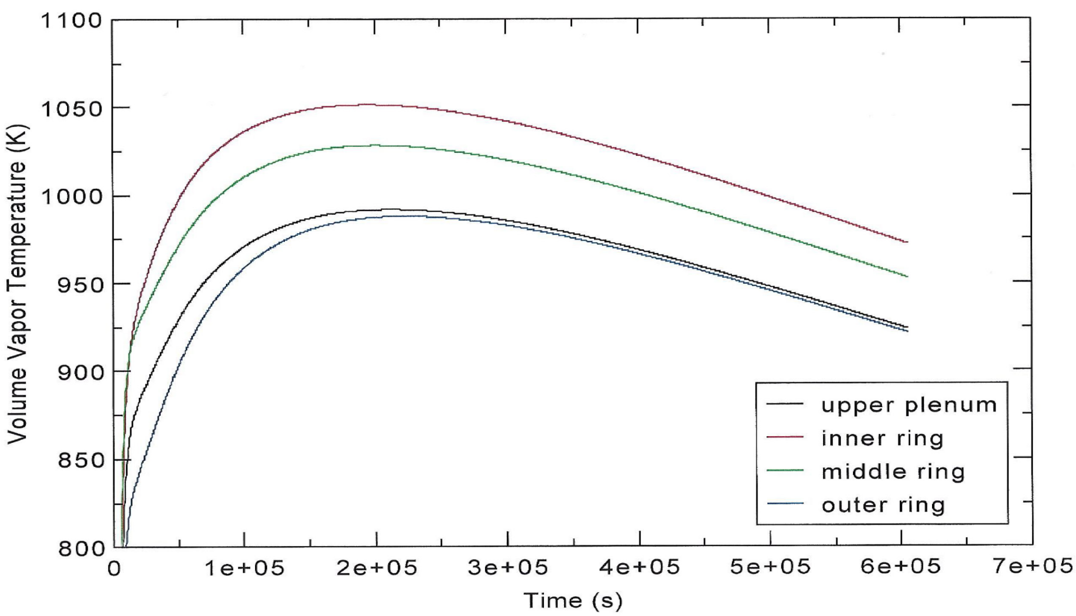

Figure 3. Average temperature of gases moving from active core region into upper reflector compared to average gas temperature in upper plenum.

The difference between the temperatures of the flow entering the reflector blocks and the helium entering the upper plenum is indicative of heat losses sustained by the coolant flow to the reflector blocks; the difference ranges between ~40 and ~70 K. The reflector blocks are initially cooler than the core and as such are a heat-storage repository by design for the MHTGR for the PCC scenario.

The above calculation suggests the following:

- The reflector blocks exert an important influence on the temperature and behavior of the helium coolant prior to moving into the upper plenum.
- Cooling sustained by the helium coolant in the region of the reflector blocks will act to increase the helium density adjacent to the wall in the reflector region and will reduce the gas velocity adjacent to the wall. This effect will show as a marked velocity gradient near the wall, which is more pronounced than would be obtained for isothermal flow.

2.2 DCC Scenario

The average Reynolds number and average temperature of the gas flowing from the core into the upper plenum are shown in Figure 4 and Figure 5. The calculation was performed using the same model for the reactor vessel as for the PCC calculation. The confinement air was allowed to flow into the lower plenum following the depressurization, and the natural circulation flow moving upward from the core into the upper plenum was allowed to flow down the riser and out the hot duct outer annulus into the confinement. Therefore, all three core rings had gas moving upward into the upper plenum. However, the gas in the core moved at very low Reynolds numbers for the DCC scenario, as indicated in Figure 4. Thus, even though the gas temperatures were much higher for the DCC scenario than for the PCC scenario, the gas clearly moved into the upper plenum via very slow moving plumes and created stratified gas layers that would result in uniform heat transfer to the upper plenum structures with a low probability of localized high thermal stresses.

3. DESCRIPTION OF COMSOL CALCULATION AND CALCULATIONAL RESULTS

To investigate the behavior of the helium coolant in the reflector region above the active core of the MHTGR during the PCC scenario, a single cooling channel was created using triangular two-dimensional meshes that were deemed coarse, nominal, and fine using the COMSOL computational fluid dynamics software.[2] The calculation was a steady state and had the following assumptions and boundary conditions:

1. The reflector blocks were assumed to be at a uniform temperature of 900 K.
2. The helium flow moving into the upper reflector region was assumed to be laminar, with a Reynolds number of 500 and a gas temperature of 1000 K.
3. The helium moving into the upper reflector region was assumed to enter the reflector cooling channels from a plenum.[3] This assumption is justified using data measured and recorded in Williams, et al, 2015.

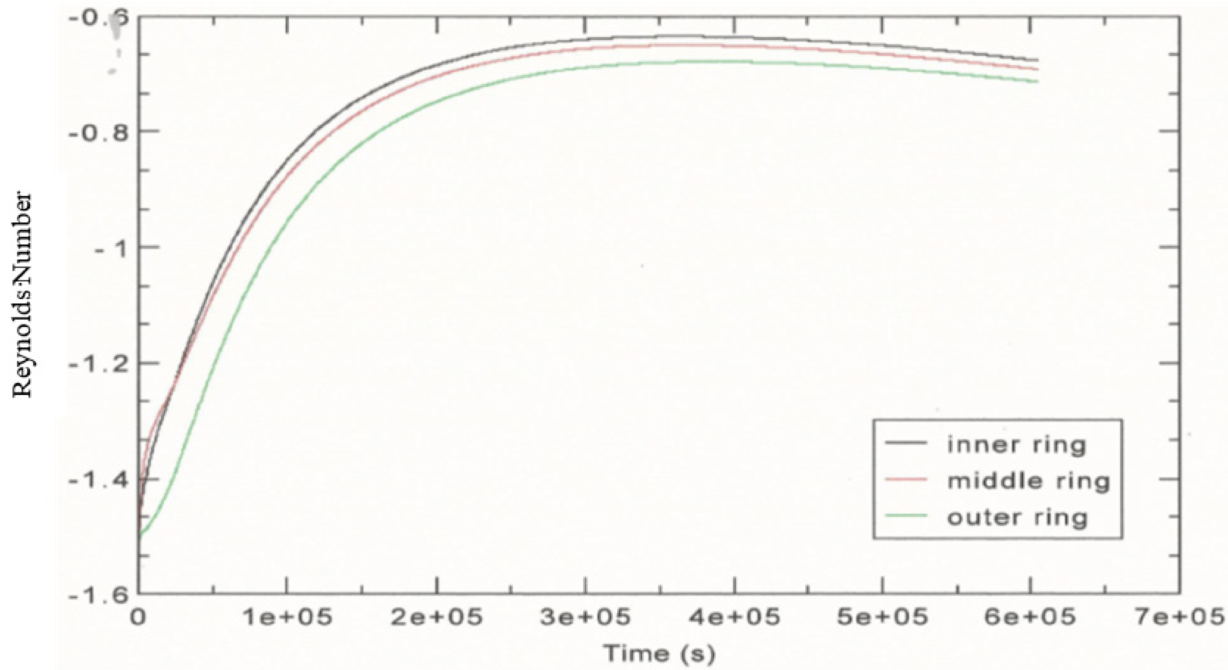

Figure 4. Average Reynolds number of gases moving from core into upper plenum of MHTGR during DCC scenario from the inner, middle, and outer rings.

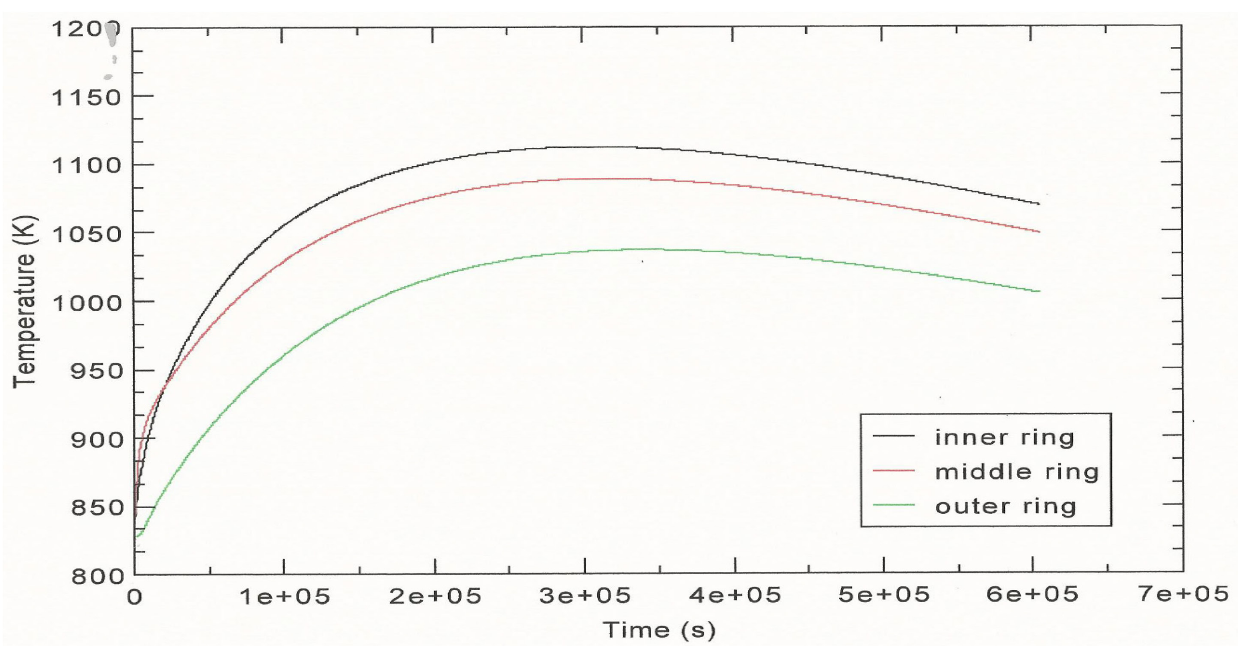

Figure 5. Average temperature of gases moving from core into upper plenum of MHTGR during DCC scenario from the inner, middle, and outer rings where (a) an irradiated active core region will likely have a geometrical mismatch with the upper reflector blocks and (b) the resulting plenum-like region between the active core and reflector blocks results in a flat entrance velocity profile in the reflector block cooling channels.

The calculations performed using the three coarse, nominal, and fine meshes indicated no significant change in going from the nominal to the fine mesh, indicating mesh convergence. The velocity distribution over the length of a typical MHTGR single cooling-channel in the reflector blocks above the active core is shown in Figure 6 using a fine mesh. The calculation is two-dimensional because the cooling channel is symmetrical about the channel centerline, and the surrounding reflector block is assumed to be at a uniform temperature of 900 K. Velocity profiles at distances from the reflector block inlet of 0.15 m, 0.30 m, 0.45 m, 0.60 m, 0.75 m, and 0.89 m are shown. The exit plane separating the reflector block from the upper plenum is at 0.89 m above the reflector inlet. The velocity profile across the cooling channel near the inlet to the reflector blocks shows the greatest variation stemming from a variation in helium density ranging from 3.38 kg/m^3 at the cooling channel to 0.33 kg/m^3 at the cooling channel centerline—a difference of ~0.05 kg/m^3 as shown in Figure 7. As the helium progresses up the channel, the helium temperature decreases. The density variation across the channel at the exit decreased to ~0.03 kg/m^3, causing the velocity profile to flatten.

The velocity profiles shown in Figure 8 are considerably different from those present in the active core region where the helium coolant is heated. The helium velocity profiles within the active core region will show higher velocities at the periphery of the cooling channel, depending on the wall heat flux. The peripheral velocities may exceed the centerline velocity during the early portion of the PCC scenario. Therefore, it is important to take the cooling effect of the reflector blocks into consideration when estimating the velocity profiles of jets and/or plumes entering the upper plenum.

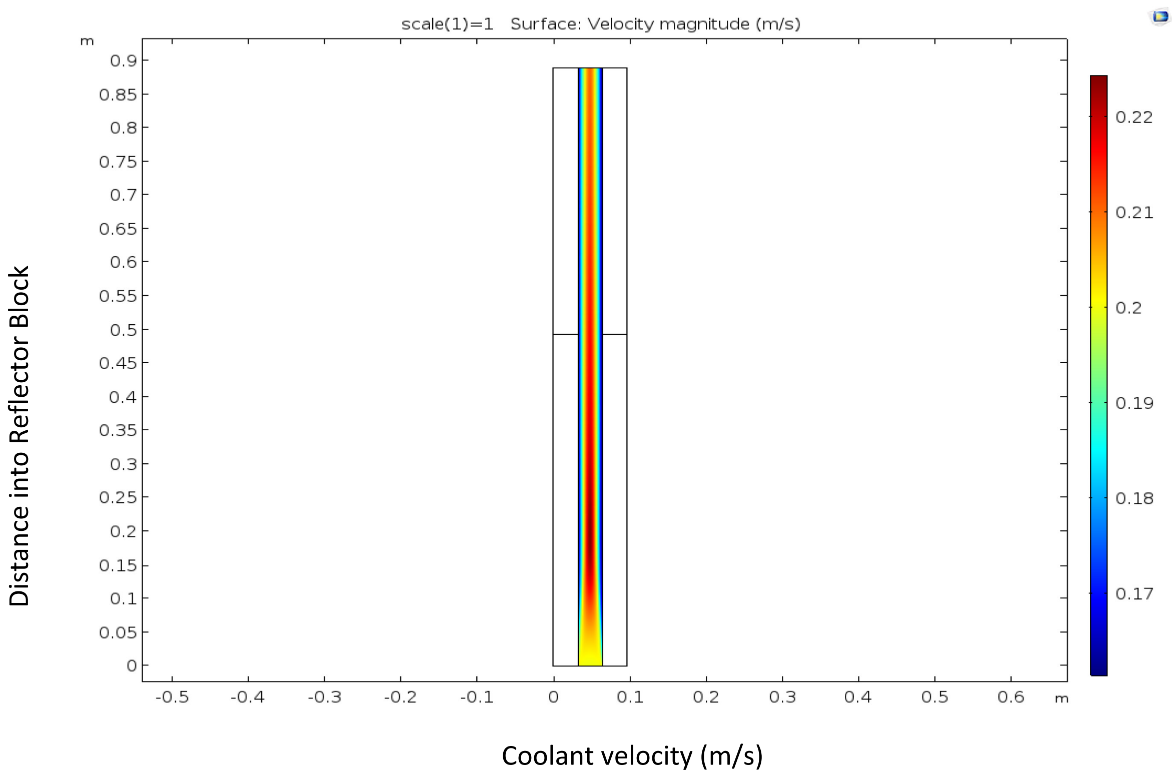

Figure 6. COMSOL calculation: velocity distribution in single-channel in MHTGR reflector blocks.

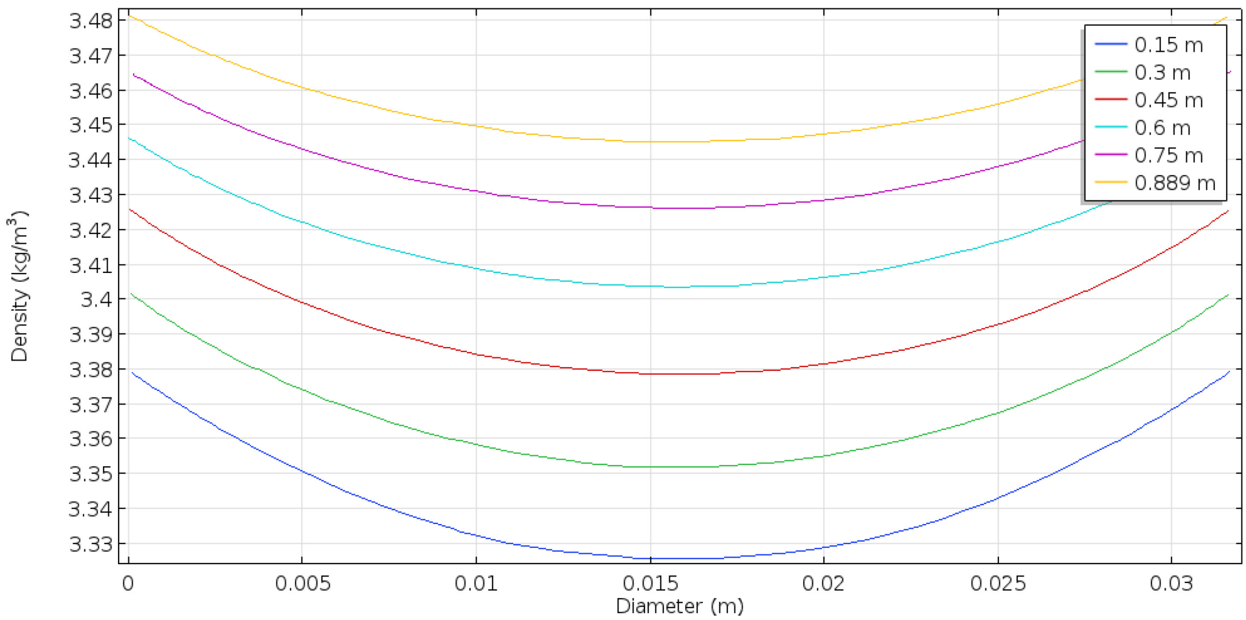

Figure 7. COMSOL calculation: density profiles as a function of diameter in a single-channel in MHTGR reflector blocks at 0.15 m, 0.30 m, 0.45 m, 0.60 m, 0.75 m, and 0.89 m above the reflector inlet.

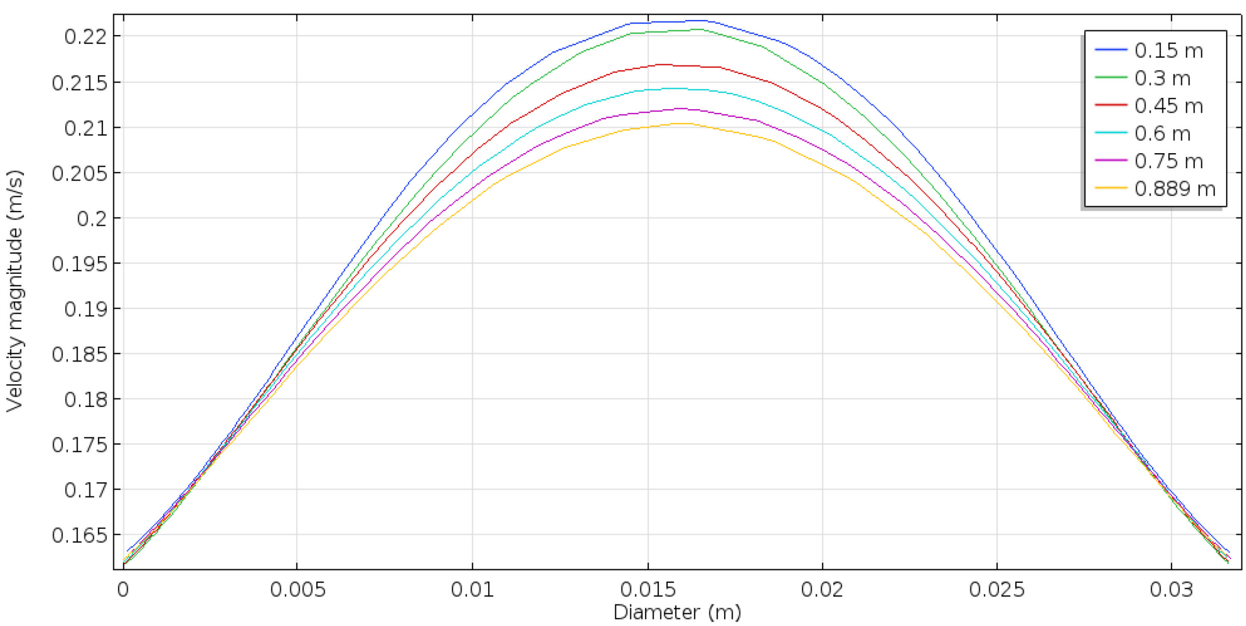

Figure 8. COMSOL calculation: velocity profiles as a function of diameter in a single-channel in MHTGR reflector blocks at 0.15 m, 0.30 m, 0.45 m, 0.60 m, 0.75 m, and 0.89 m above the reflector inlet.

4. SUMMARY

A COMSOL multiphysics code calculation of the helium coolant behavior in a single MHTGR cooling channel leading from the active core region to the upper plenum during a PCC scenario was completed. The boundary and initial conditions conform to conditions calculated to occur in the early portion of the PCC when the helium flow is at higher Reynolds numbers, on the order of 500. The coolant channel flow is laminar and, in the reflector region, energy is being transferred from the helium to the reflector block structure, resulting in helium velocity profiles, which are centered with large gradients adjacent to the wall.

The calculation shows the importance of considering the cooling effect resulting from the presence of the reflector blocks—which are a heat sink—in the consideration of the entrance-velocity profile to the upper plenum. The velocity profiles from the reflector blocks are boundary conditions for jets and plumes that will move upwards through the upper plenum with the potential to either impinge on the upper plenum structures or form stratified layers. These considerations are important in evaluating the magnitude and scope of thermal gradients that may be present in the upper plenum structures.

5. REFERENCES

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