Semi-Annual Report for Horizontal Compact High Temperature Gas Reactor (HC-HTGR) Development During Performance Period April 2023-September 2023

Nuclear Science and Engineering Division
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Semi-Annual Report for Horizontal Compact High Temperature Gas Reactor (HC-HTGR) Development During Performance Period April 2023 – September 2023

prepared by
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September 2023
ABSTRACT

Horizontal Compact High Temperature Gas Reactor (HC-HTGR) is being designed by a multi-disciplinary team of nuclear, mechanical, and structural engineers under the support of a DOE-NE Advanced Reactor Demonstration Program’s Advanced Reactor Concepts-20 (ARC-20) award. The objective of this ARC-20 project is to deliver a conceptual design for the proposed HC-HTGR in 3 years and support its commercialization as a safe, low-cost HTGR. Argonne National Laboratory (Argonne) is responsible for the design and analysis of the reactor cavity cooling system (RCCS) as a safety system for passive decay heat removal of the reactor concept. Additionally, Argonne is providing analysis of the primary coolant system to ensure temperatures within the core remain below safety margins during steady-state and potential accident scenarios.

This fourth semi-annual report summarized the progress made at Argonne on the two tasks during the second half of FY23. As a part of the RCCS design task, recent efforts have been made to complete a conceptual design of the RCCS for the HC-HTGR, including the design update of the water panel and system configuration favorable in point of view of fabrication and system operation. Design calculations were conducted under various heat load conditions to validate the system design. Transient simulations using RELAP5-3D were conducted to investigate system dynamics under transients of interest and to evaluate the system performance in the design condition. The results demonstrated the overall system feasibility that the RCCS design maintains structures temperatures lower than maximum allowable temperature with sufficient system inventory without any active heat sink.

In the primary system thermal hydraulics task, the preliminary analysis was performed for a long term pressurized conduction cooldown (PCC) transient. This analysis used a combination of a fully resolved and coarse homogenized mesh to predict the temperature distribution for the steady-state initial condition and the PCC transient. The steady-state initial condition was determined using a fully resolved full core model with 3D solid to 1D fluid coupling. The fully resolved mesh was also used to model the first 20 seconds of the PCC. The temperature difference between fuel pins and the graphite matrix becomes minimal and the dominant heat transfer shifts to a larger scale radially towards the RCCS. After 20 seconds, a homogenized coarse mesh is used, greatly reducing the computational costs of the model. These results demonstrate that the core is designed to passively remove enough decay heat in a protected loss of primary coolant flow to prevent an unsafe rise of core temperatures.
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1 Introduction

The Horizontal Compact High Temperature Gas Reactor (HC-HTGR) is being designed by a multi-disciplinary team of nuclear, mechanical, and structural engineers led by MIT under the support of a DOE-NE Advanced Reactor Demonstration Program’s Advanced Reactor Concepts-20 (ARC-20) award. The objective of this ARC-20 project is to deliver a conceptual design for the proposed HC-HTGR in 3 years and support its commercialization as a safe and low-cost HTGR with a focus on minimizing the overnight capital cost of the power-generation system and explicit considerations of functionality, constructability, transportability, modularity, safety, and future licensing.

Argonne National Laboratory (“Argonne”) is responsible for the design and analysis of the reactor cavity cooling system (RCCS) as a safety system for passive decay heat removal of the reactor concept. Work performed by Argonne also includes the thermal hydraulics analysis of the primary heat transport system including reactor pressure vessel (RPV) internals for normal operation, shutdown, and accident conditions.

For the RCCS design task, efforts made in the first half of FY23 focused on parametric analyses for design updates on the water panel and the major system figurations to improve system thermal performance of the RCCS for the HC-HTGR. Design studies on the updated water panel geometry and natural circulation loop configurations were conducted to investigate impacts of design parameters to the natural circulation and heat transfer behavior of the RCCS. The recent updates to the RCCS have enabled two independently operating loops in the system configuration. In the primary system thermal hydraulics task, a reduced order fuel assembly model and preliminary analysis of a pressurized conduction cooldown (PCC) transient was presented. A single assembly model of the PCC was used to identify early trends in the transient. It was shown that fuel and matrix temperatures quickly homogenize, allowing the use of a homogenized mesh in a long term transient analysis. A method for determining the material properties in a homogenized mesh was also presented. Finally, a coupling methodology between the 3D core model and 1D RCCS coolant model was shown.

This fourth semi-annual report summarizes the progress made at Argonne on the two tasks during the second half of FY23. Chapter 2 highlights the conceptual design of the RCCS for the HC-HTGR and design calculations using RELAP5-3D by operating mode and under various transient heat load conditions. From the results, the RCCS design achieves the design target of the RCCS for the HC-HTGR in the design condition. Chapter 3 documents a continued analysis of the PCC transient. A full core steady-state model was developed to determine the initial condition of the transient. Then, the first 20 seconds of the PCC transient was modeled on a fully resolved, full core mesh to allow the homogenization of fuel and matrix temperatures as shown in the previous single assembly model. Then, the homogenized temperature distribution was transferred to a coarse, homogenized core mesh where the long term PCC was modeled.
2 Task 1 Update: RCCS Design

For the RCCS design task, efforts made in the first half of FY23 focused on parametric analyses for design updates on the water panel and the major system configurations to improve system thermal performance of the RCCS for the HC-HTGR. Design studies on the updated water panel geometry and natural circulation loop configurations were conducted to investigate impacts of design parameters to the natural circulation and heat transfer behavior of the RCCS.

The RCCS design for the HC-HTGR has been iterated to improve thermal performance to achieve the target heat removal rate of ~1 MW, in the design condition and to have more favorable features in terms of fabrication and operation. From the efforts from past FYs [1,2], the water panel now has a long-width of up to 9 m without breaks from structural interface, and the system consists of two independently operating loops, where each loop has a single water panel surrounding the RPV and two water panels are located at each RPV side. As the system design becomes mature, dimensions of the riser tubes have been updated to have more favorable features in fabrication and system operation point of view, which leads to a complete system design of the RCCS for the HC-HTGR. For the design of the RCCS, design calculations have been conducted to investigate system dynamics under transients of interest and to evaluate the system performance in the design condition.

This section summarizes the efforts made in the second half of FY23 focused on finalizing the design of the RCCS for the HC-HTGR. The conceptual RCCS design was derived reflecting recent updates on the water panel dimensions and the system configurations based on past design parametric study. Design calculations were performed to evaluate the system performance in various operating mode and heat load conditions.

2.1 Descriptions of the conceptual RCCS design

A total of 66 1-inch Sch. 160 riser tubes with a P/D of 4.0 are arranged in a single water panel. The top tank configuration might be updated by the project team to enhance the natural circulation performance of the system and to minimize reactor building radiation level from potential water activation. Still, the reference location of the top tank remains above the RPV in the current design stage [3]. The RCCS consists of two redundant loops. Water coolant in each loop is heated by direct radiation heat transfer from the RPV to the water panel, which drives circulation from the water panel to the tank through upper collector and hot leg. During normal operation, water in the tank is cooled by an immersed air or water-cooled heat exchanger, which would be determined in the future. Then, the water returns to the water panel through downcomer and cold leg. The current RCCS design has been characterized to have 11 segments of upper and lower collectors, where each segment holds six riser tubes per segment. Two downcomers are connected per tank, where piping details would be updated by the number of top tank segments and reactor internal structures design. Figure 1 shows the loop configuration of the HC-HTGR RCCS, and Table 1 summarize of the RCCS configuration parameters.
To maximize the RPV coverage area, the water panel has 115-degree angled surfaces at the top and bottom, and the middle part is vertical with a height of 3 m. The center of the water panel is 0.1 m apart from the RPV. In a full system configuration, 66 of Sch. 160 1-inch carbon steel riser tubes are arranged with a pitch-to-diameter (P/D) ratio of 4.0 and connected with the 10-mm thick carbon steel panel. The reference emissivity for the water panel is 0.8 which can be achieved through surface treatment of the base material. Specifications of the water panel dimensions for the HC-HTGR RCCS are summarized in Table 1. The riser tubes from each loop have been alternately positioned one after another to maintain a cooling capability on both sides of the RPV when one of loops fails. Figure 2 shows a potential configuration of connection details between the riser tubes and the upper collectors, which enables the loops to isolate from each other but are still thermally connected by the panels.

Table 1 Updated dimensions of the water panel of the HC-HTGR RCCS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of water panel</td>
<td>1 at each RPV side (total 2)</td>
</tr>
<tr>
<td>Width of water panel</td>
<td>9.0 m</td>
</tr>
<tr>
<td>Number of riser tubes</td>
<td>66 per water panel</td>
</tr>
<tr>
<td>Riser tube grade</td>
<td>Sch. 160</td>
</tr>
<tr>
<td>Riser tube size</td>
<td>1 inch (ID 0.815”, OD 1.315”)</td>
</tr>
<tr>
<td>Pitch-to-diameter ratio (calculated by OD)</td>
<td>4.0</td>
</tr>
<tr>
<td>Panel thickness</td>
<td>10 mm</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.8</td>
</tr>
</tbody>
</table>
2.2 RCCS Design Calculations

Performance characteristics of the RCCS design would be addressed with considering a range of operation conditions such as two loop and single loop operation and different system heat loads. As the development of the HC-HTGR is currently in the early conceptual design phase, the reactor design sharing interfaces with RCCS will evolve over time through refinement and optimization by a series of trade studies. For that reason, detailed analyses on RCCS performance would be pursued during later stages of the design process with final selections made regarding dimensions, materials, and more detailed elements of the reactor. Nevertheless, the design calculations performed in the conceptual design phase will confirm the RCCS performance being consistent with the passive safety approach under the selected power level of the HC-HTGR and provide confidence in reducing risk of significant changes in the reactor design which would bring subsequent conceptual design studies in reactor designs sharing interfaces with the RCCS.

Based on the preliminary simulations conducted in past FYs on the RCCS design for the HC-HTGR, it has shown that evenly distributed flow rate for each riser tube during single-phase natural circulation could be achieved [1]. Furthermore, with the updated water panel design that now covers the RPV surface as a single piece at each side, any distortion in the heat transport performance of riser tubes located at the ends of the water panel, as previously observed in the past design, would be minimized. This leads to the strategy of modeling one segment of the upper and lower collectors and a part of the water panel, in line with scaling a series of connecting pipes and a water tank to investigate the performance characteristics of the RCCS under various conditions of interest. Therefore, for the purpose of the design calculations, a segment of the water panel embedding 6 riser tubes has been considered to represent two identical water panels located on each RPV side. The RELAP5-3D reactor transient analysis code [4] is being used to investigate the performance characteristics of the HC-HTGR RCCS by design calculations described in this work.

Figure 3 shows the nodalization diagram of the current RELAP5-3D model of the HC-HTGR RCCS. 6 riser tubes are modeled with vertical pipes, 1 inch Sch. 160 pipes (P301 to P306). The pipes feature bends of 25-degrees at the two initial and two final axial nodes as determined by their
shapes. The top and the bottom collectors of the riser tubes are modeled as a series of branches, namely B201-B206 and B401-B406, respectively. The top water tank is modeled with three components, namely P550, P560, and B555, to represent the water tank volume below and above injection port and thermal mixing region, respectively. A series of connecting pipes is modeled with P600 to P620 from the top tank to the bottom collector and P510 from the top collector to the top tank. Each piping except the upper and lower collectors and the water tank are set to have a cross-sectional area scaled by 1/11 of actual dimensions as 6 are modeled among total of 66 riser tubes of each water panel, while setting actual diameters as hydraulic diameters for the scaled components.

The water panel is modeled with heat structures of 6 carbon steel cylindrical pipes and carbon steel flat plate panels. The pipes have convective boundary conditions for inner surfaces with water. The panels have adiabatic boundary conditions on right surfaces (opposite side facing the reactor building), which would be replaced with corresponding convective boundary conditions once reactor building configuration is available to reflect the actual condition. A half of the RPV was modeled as a carbon steel vertical flat plate with 7 axial nodes, where the inner RPV surface is set with the heat flux boundary condition. Conduction and radiation enclosures are employed to thermally connect all structures. Since any surfaces of RELAP5 heat structures cannot be set in both conduction enclosure and radiation enclosure at the same time, modeling approach of the water panel has been proposed to incorporate major heat transfer mechanisms of the RCCS from past effort, where the details of the model approach of the water panel are available in [1]. With that, inner surfaces of the pipes and right surfaces (outer surfaces) of the panels are set by a conduction enclosure to take account for the conduction heat transfer through the water panel. The outer surface of the RPV, outer surfaces of the pipes, and the left surfaces (inner surfaces facing the RPV) of the panels are set by a radiation enclosure with an emissivity value of 0.8 for all participating surfaces and a series of view factors in actual configurations obtained from the STAR-CCM+ view factor calculation solver [5]. To model active cooling in the water tank and control the exit temperature of the water from the top tank, heat structure is connected to the three components for the top tank set with the tables of temperature and convective heat transfer coefficient specified at the outer surface of it.
2.2.1 System performance by operation mode

The configuration of the HC-HTGR RCCS allows for the cooling of both sides of the RPV, even when only a single loop is in operation. A single loop operation of the system would affect both panel conduction performance and natural circulation performance throughout the system. Compared to two-loops operation, the distance between working riser tubes will increase, therefore, the panel temperature and the heat load on individual riser tube will change significantly.

Figure 3 Nodalization diagram of the RELAP5-3D model used in design calculations
Per current configuration of each loop, it is reasonable to assume that every alternate riser tube within the panel is included while the non-operational riser tubes in between remain empty during single loop operation of the RCCS. In the RELAP5 model, every other three riser tubes were connected to the loop (P301, P303, P305) and others (P302, P304, P306) were disconnected, while maintaining heat structures of the pipes and the interconnecting panels which allow conduction heat transfer between working riser tubes. Under the same design condition of two loop operation, a single loop operation was simulated with the RPV temperature of 420 °C and the controlled water exit temperature of 25 °C from the tank.

Figure 4 and Figure 5 show the water panel temperature distribution at the design condition by operation mode – two loops and single loop operation. For two loops operation, temperature differences between all 6 tubes and adjacent panels were fairly small of ~1.6 °C, with the maximum riser tube and panel temperatures being 69.98 °C and 71.61 °C, respectively. For single loop operation, 3 working riser tubes (tube 1, tube 3, tube 5) had lower temperatures than 3 non-operating riser tubes (tube 2, tube 4, tube 6) as removing radiation heat from the RPV and conduction heat from adjacent panels by natural convection. Tube 6 and tube 5 had the maximum temperature of 92.23 °C and 85.46 °C respectively among all the non-operating and operating riser tubes. The maximum panel temperature was 91.66 °C at the panel 6. Mass flow rates in the operating riser tubes were 8.95E-02 kg/s, 9.23E-02 kg/s, and 9.50E-02 kg/s for tube 1, tube 3, and tube 5, respectively. The rightmost of the water panel had higher temperature from the flow direction of the lower and the upper collectors, where flow directions of both collectors in dividing and combining flow headers are modeled the same. The type of header is referred as a Z-manifold, where the channel flow rate generally increases in the direction of the intake stream [6]. Even if the water panel temperature shows asymmetric distribution, temperature gradient between non-operating rise tube and adjacent panel is up to ~4.8 K, which is insignificant to structural integrity.
a) Two loops operation

b) Single loop operation (Only tube 1, 3, 5 are connected to the loop)

Figure 4 Comparison of the water panel temperature at the design condition by operation mode
Figure 5 Temperature distribution of the water panel at the design condition by operation mode

Table 2 summarizes the comparison of RCCS performance of two loops operation and single loop operation at the design condition. The maximum water panel temperature increases by ~20 K when only a single loop operates. Riser tube and panel temperatures rise, and total system mass flow rate decreases accordingly. However, the mass flow rate of each individual operating riser tube is higher, and it has a heat load on each individual riser tube doubled as half of the riser tubes are not working. Overall, even if only a single loop is operating, similar level of thermal performance can be achieved.

<table>
<thead>
<tr>
<th></th>
<th>Two loops</th>
<th>Single loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>System ΔT [°C]</td>
<td>26.54</td>
<td>38.52</td>
</tr>
<tr>
<td>Maximum tube temperature [°C]</td>
<td>69.98</td>
<td>92.23 (Non-operating) 85.46 (Operating)</td>
</tr>
<tr>
<td>Maximum panel temperature [°C]</td>
<td>71.61</td>
<td>91.66</td>
</tr>
<tr>
<td>Average flow rate of individual riser tube [kg/s]</td>
<td>6.76E-02</td>
<td>9.23E-02</td>
</tr>
<tr>
<td>Average heat load on individual riser tube [kW]</td>
<td>7.50</td>
<td>14.86</td>
</tr>
<tr>
<td>System mass flow rate [kg/s]*</td>
<td>8.93</td>
<td>6.09</td>
</tr>
<tr>
<td>Total heat removal rate [MW]*</td>
<td>0.99</td>
<td>0.98</td>
</tr>
</tbody>
</table>

* Scaled by factor of 22 to represent the entire system
2.2.2 System performance under various system heat load conditions

System dynamics during transients is also important to consider during the design process as various RCCS operating regimes can be encountered. To cover expected RCCS operation conditions – beginning with single-phase natural circulation, progressing to two-phase natural circulation, and gradual boil-off of the coolant inventory of the system, heat sink to cool the water tank of the RCCS was assumed immediately unavailable under various heat load conditions. In this work, two heat load conditions have been considered for transient simulations for the design purpose ensuring that the system operation maintains structural temperatures below the maximum allowable temperature while maintaining sufficient system inventory for it.

The most challenging heat removal event for a typical HTGR is a depressurized conduction cooldown (DCC), which is generally considered to be the defining accident for determining the reference case accident peak fuel temperature [7], therefore, it has been key consideration in design calculations in guiding future design activities for design optimization of the RCCS. For the water-based the Natural Shutdown Test Facility (NSTF) program, the prototype decay heat load to RCCS based on Framatome’s 625 MWt SC-HTGR was provided to the Argonne team [8,9]. Conditions and assumptions made for DCC calculations for the SC-HTGR were unknown. Taking the most conservative case (V.2) among available data, a specific power-time curve was created by post-processing. This involved normalizing the data using the heat load at time=0 s, which represents the parasitic heat loss during normal reactor operation and multiplying it by the parasitic heat loss of the current design of RCCS for the HC-HTGR under conditions of a constant RPV temperature of 220 °C (0.22 MW), which is expected during normal operation of the HC-HTGR. Figure 6 shows the power-time curve considered for the HC-HTGR design calculation scaled from the estimated heat load during DCC by Framatome. The heat load to the RCCS initially decreased to 80 % of the parasitic heat loss within the first 7 hours, after which it began to rise to reach a peak heat load of 153 % of the parasitic heat loss and then reduced until 500 hours. The DCC heat load profile was imported to a heat flux-time table after converted for each axial node of the RPV and set for the left surface (inner surface) of the RPV. Initial conditions were obtained by running the RELAP model for 1E+5 sec with conditions of constant RPV temperature of 220 °C and the tank exit water temperature of 25 °C to ensure fully developed steady state. Then, the transient calculation was conducted for the heat load condition of hypothetical DCC event without heat sink for the water tank starting at 0 sec. The case was run using a restart model where one of the trips triggering the accident scenarios was set to true so convective heat transfer of the heat structure at the top tank was set to zero and the heat flux profile changed by the table provided.
Figure 6 Heat load to RCCS during DCC (Scaled from Framatome's input) [9]

Figure 7 shows the transient behavior of the system during hypothetical DCC heat load condition. Starting with the single-phase natural circulation, the first jump of the mass flow rate occurred ~40 hours as flashing initiated at the horizontal returning pipe to water tank at the first node of the P510, and significant increase of the mass flow rate was followed. The coolant in the system kept heating up and quickly reached saturation temperatures corresponding to the tank inlet and outlet elevation. The tank inlet and outlet temperatures started to decrease after ~100 hours as the system inventory started to decrease while the tank inlet and outlet pressure have local peaks due to flashing. Total coolant mass did not start to drop until 100 hours as steam coming from the riser tubes was initially condensed in the tank until the entire tank is saturated. It resulted in gradual decrease of system pressure accordingly. After ~250 hours, both tank inlet and outlet pressures were stabilized to the atmospheric pressure, as the top part of the tank (P560) was depleted and their temperatures had saturation temperatures correspondingly. Overall, 67 % of the total water inventory was lost for 500 hours, and it took 370 hours to lose half of the system coolant under the hypothetical DCC heat load.
a) System mass flow rate (Scaled per loop)

b) Void fraction at tank inlet (P510(9))

c) Tank inlet and outlet temperatures

d) Tank inlet and outlet pressures

e) Void fraction of the tank (P560)

f) System coolant inventory

Figure 7 Transient behavior of RCCS for the HC-HTGR under the hypothetical DCC heat load
Figure 8 shows the changes of the RPV temperature and the radiative heat transfer over time under the hypothetical DCC heat load. The maximum RPV temperature was 269.6 °C at the center of the RPV in the axial direction after ~122 hours. Axial distribution of the RPV temperature was fairly even within ~ 2.0 °C. The RPV temperature overall followed the heat load exerted on the RPV, and it had its peak at the same time as that of peak RPV temperature, which was 12 hours later than the time of the maximum heat input at ~110 hours. The ratio of the radiative heat from the RPV to the panels and the riser tube outer surfaces maintains around 25 % and 75 % respectively for 500 hours, which aligns with the surface area ratio between the two. This confirms that the major affecting factor of the thermal performance is still the water panel area at the design condition, which have been updated accordingly.

Subsequently, Boston Atomics provided the RPV heat flux profile to the Argonne team created as part of an in-core study of fuel performance and graphite properties estimated with the initial geometry of the HC-HTGR [10]. The conditions and assumptions made for creating the RPV heat flux profile are business sensitive. It should be noted that as the core performance carries many uncertainties and imperfections to evaluate RCCS performance until the design is finalized, this would be only used as a trial case for the RCCS analysis to avoid extrapolating analysis. Figure 9 shows the potential heat load to the RCCS of interests. The data only goes out to 100 hours, but they are sufficient to estimate a peak temperature when the vessel surface heat flux becomes steady and it also aligns with that the maximum RPV temperature during DCC of the SC-HTGR occurs at around 100 hours [9]. The new heat load profile was imported to a heat flux-time table and set for the left surface (inner surface) of the RPV. With the same initial conditions used for the hypothetical DCC simulations, the transient calculation was conducted under the new heat load without any heat sink available for the water tank. The calculation was run using a restart model where one of the trips triggering the accident scenarios was set to true so that convective heat transfer of the heat structure at the top tank was set to zero and the heat flux profile changed by the table provided.
Figure 9 Heat load to RCCS provided by Boston Atomics – vessel average heat flux

Figure 10 shows the transient behavior of the system under the heat load Boston Atomics provided. Starting with the single-phase natural circulation, the first jump of the mass flow rate occurred ~17 hours as flashing initiated at the inlet of the horizontal returning pipe to water tank (P510) and significant increase followed. As the heat load increased continuously, the coolant in the system kept heating up and quickly reached saturation state. The second jump of the mass flow rate variation following significant reduction of the system pressure was occurred at ~45 hours, causing a sudden decrease of the top tank pressure and a quick depletion of coolant inventory of the top region of the tank (P560). This might be caused by an artificial effect due to modeling, which requires additional investigation, and it might be enhanced by turning on the level tracking option for the tank domain. Overall, 26 % of the total water inventory was lost for 100 hours under the heat load Boston Atomics provided for design calculations.

Figure 11 shows the changes of the RPV temperature and the heat flow over time under the heat load Boston Atomics provided. The maximum RPV temperature was 440.5 °C at the center of the RPV in the axial direction after 100 hours. Axial distribution of the RPV temperature was fairly even within ~3.3 °C. The RPV temperature also followed the radiation heat transfer from the RPV, and it had its peak same with the time of peak RPV temperature with ~10 hours delay. Similar to the hypothetical DCC event results, the ratio of the radiative heat from the RPV to the panel and the riser tube outer surface maintains around 25 % and 75 % respectively.
Figure 10 Transient behavior of RCCS for the HC-HTGR under heat load provided by Boston Atomics.
Figure 11 RCCS performance under heat load provided by Boston Atomics

Figure 12 shows the comparisons of the various heat load conditions used in this study along with a typical decay heat curve. The decay heat by time was approximated by using the Wigner-Way formula assuming thermal power of 160 MW ($P_0$) with half year as the time elapsed before the shutdown in seconds ($t_0$), Equation (1). Heat load during hypothetical DCC approximated by Framatome’s SC-HTGR is lower than decay heat curve for the first 7 days (~6.0E+5 s) but becomes close to the decay heat in long term. On the other hand, the heat load Boston Atomics provided is lower for the first 11-14 hours (4.0E+5 – 5.0E+5 s) but becomes higher than the decay heat after then. It should be noted that the transient calculations with approximated heat load profiles would not be the actual conditions, which probably appears close to the heat load Boston Atomic provided for the first dozen hours, followed by a transition to a decay heat curve in the long term. The purpose of the transient calculations is to confirm that the system design satisfies its design target. It was shown that the total system inventory would be sufficient to remove decay heat from the RPV for ~21 days (500 hours) without any active heat sink available for the RCCS, while maintaining low RPV temperatures based on the results of the hypothetical DCC simulation. The results under the Boston Atomics provided heat load condition also demonstrated that the maximum RPV temperature would be maintained below the maximum allowable temperature by the RCCS operation. The current calculations are expected to demonstrate the overall system feasibility in the design process with certain transients addressed.

$$P_d = 0.0622P_0 [t^{-0.2} - (t_0 + t)^{-0.2}]$$  \hspace{1cm} (1)
Transient simulations for the HT-HTGR RCCS were conducted in order to investigate the system behavior under various transients of interest in this work. As mentioned above, the heat load on RCCS would be predicted by the RCCS integrated primary system analysis using SAM to simulate selective accident scenarios of interest. It will also continue interacting with other efforts made in the project such as shielding structural/seismic, and primary system thermal hydraulics, which would have system interfaces with the RCCS.
3 Task 2 Update: Primary System Heat Removal Analysis

In the first half of FY23 efforts began on the analysis of a pressurized conduction cooldown (PCC) transient. This transient is characterized by an interruption of primary system coolant flow and subsequent reactor scram, necessitating the passive removal of decay heat to prevent core damage. Using a single fuel assembly model, it was demonstrated that shortly after the reactor is scrammed the temperature difference between fuel pins and the surrounding graphite matrix becomes negligible, indicating it is not necessary to resolve each fuel pin in the reactor to capture the peak temperature in the core during a PCC transient. In the second half of FY23, analysis of the PCC transient expanded beyond a single assembly model to the full reactor core. This section details these efforts including; steady-state initialization of the full reactor core, homogenization of the core and parameter transfer, and long-term PCC analysis.

3.1 Steady-state initial condition

The first step in the analysis of the PCC transient is determining the initial condition of the temperature distribution in the core. It is assumed that the PCC transient will begin with the reactor operating at a full power steady-state condition. To determine the temperature profile of this state SAM and the MOOSE heat conduction module are used to create a coupled 1D fluid domain to 3D solid domain model. This approach was described in a previous report as applied to a single fuel assembly model [1]. Figure 13 shows a representation of the solid domain from the core mid-plane. The bottom right quadrant is also included in the solid domain model to account for the asymmetries in the y dimension. This mesh is considered fully resolved because it directly represents every fuel pin and coolant channel. Note that at present control drums in the outer reflector are neglected for simplicity.
In the active region of the core thermal and irradiation effects in the core will cause distortions of fuel assembly geometries resulting in bypass gaps in the vertical boundaries between assemblies and in the horizontal gap between the top row assemblies and the outer reflector. External calculations performed by MIT predict that these gaps will be 3-5mm and 15-20mm for vertical and horizontal gaps respectively [11]. To account for the thermal resistance of these gaps in the thermal conduction model the MOOSE InterfaceKernel approach was used. This approach models gap heat transfer using user provided inputs for gap length and gap thermal conductivity rather than directly representing the gap in the mesh allowing an undistorted mesh to be used. Surface emissivity values can also be supplied to model radiation heat transfer across the gap. A gap conductivity of 0.3 W/m-K based on helium properties, vertical and horizontal gap lengths of 3 mm and 15mm respectively, and a surface emissivity of 0.8 was implemented into the model. Horizontal interfaces between assemblies are also modeled using the InterfaceKernel approach. Because these assemblies are in full contact, the gap length and thermal conductivity were specified so that the effective gap heat transfer coefficient is $1e5$ W/m$^2$K.

Outside of the core, a larger 20 cm gap is present between the core barrel and reactor pressure vessel. This gap is shown in teal in Figure 13. To utilize the simplicity of the InterfaceKernel method for conduction and radiation modeling the physical representation of this gap was modeled with a very high thermal conductivity while a gap length of 10 cm, thermal conductivity of 0.3 W/m-K and surface emissivities of 0.8 were implemented in the interface kernel. This avoids any contributions of the physical representation of the gap to the heat conduction solution.

A radiation boundary condition was applied to the outer surface of the reactor pressure vessel wall to approximate heat transfer with the reactor cavity cooling system. A surface emissivity of 0.8 and an ambient temperature of 100°C were applied. In the future, the coupling scheme between the 3D solid model and the RCCS discussed in the last semi-annual report will be applied.

In the coolant domain, 1D fluid components are used to model each coolant channel in the core. Coolant channels are grouped on an assembly-wise basis, with all channels in an assembly sharing a common inlet and outlet channel. This allows the solver to predict the flow rate distribution between coolant channels in the assembly. In the current model, the total flow rate through the core is split uniformly across each assembly. A model with all assemblies sharing a common inlet and outlet was attempted, however computational issues due to the large domain size led to an impractical solve time. Future efforts may be made to ensure the pressure drop in each assembly is uniform across the core. During steady state operation, coolant will flow in the bypass gaps between fuel assemblies, reducing the cooling power of the core channels and increasing heat transfer between assemblies. The flow in these gaps was omitted from the current model for simplicity but can be added in future iterations of the model.

Figure 14 shows the steady-state temperature distribution in the core. The peak fuel temperature is found in the pins nearest to the inner reflector as a consequence of the high power density in this region. The peak fuel temperature of 1259°C is slightly above the design safety limit of 1250°C. This indicates the need for a core design adjustment to reduce the power density near the inner reflector. This model uses a conservative assumption for graphite thermal conductivity that can be revisited to assess the impact on peak fuel temperatures.
At the onset of the PCC transient, it is assumed that the coolant flow rate immediately drops to zero. Because of the horizontal orientation of the core, it is assumed that there is little potential for natural circulation flow patterns to develop within the core. With these assumptions, 3D heat conduction during the PCC transient can be modeled without coupling 1D fluid components, greatly simplifying and reducing the computational costs of the model.

### 3.2 Temperature Homogenization

After finding the steady-state temperature distribution on the fully resolved mesh, the next step in the modeling methodology for the PCC transient is to model the homogenization of fuel and graphite matrix temperatures. To model this, the Wigner-Way formula, Equation 1, was used to determine the power density in the fuel pins. Figure 15 shows that after 20 seconds fuel power densities drop to 3% of the steady-state, full power value. With this significant drop in power, heat stored in the fuel pins will be transferred to the surrounding graphite matrix until there is only a slight temperature difference between the two. As shown by the single assembly model analysis performed in the previous semi-annual report, this is expected to take around 20 seconds. After this, the dominant heat transfer phenomena shift to a larger assembly scale. Figure 16 shows the temperature distribution in the core 20 seconds after the PCC transient began.
Figure 15 Plot of the Wigner-Way formula for the first 20 seconds after reactor shutdown.

Figure 16 Temperature distribution at t = 20s at z = 8m

After 20 seconds the temperature difference between the fuel pins and surrounding matrix reaches a quasi-equilibrium based on the decay power level. At this stage, temperatures have homogenized enough to utilize a homogenized fuel assembly representation. Figure 17 shows a comparison of the fully resolved and homogenized assembly mesh. The fully resolved mesh uses 2,489,670 nodes while the homogenized mesh uses only 269,433 nodes, leading to a significant reduction in computational costs with the homogenized mesh. The material properties used in the homogenized mesh were discussed in the previous semi-annual report [2]. The SolutionUserObject
functionality in MOOSE was used to translate the temperature distribution from the fully resolved mesh to the homogenized mesh. Figure 18 shows the temperature distribution in the model before and after the transfer.

Figure 17 Fully resolved assembly mesh (left) and homogenized assembly mesh (right). The green ring in the homogenized mesh is modeled with graphite properties while the blue middle area uses homogenized properties. All other areas of the core use the same mesh in the fully resolved and homogenized model.

Figure 18 Temperature distribution at $t = 20s$ at $z = 8m$ in peak fuel assembly shown in fully resolved mesh (left) and transferred to homogenized mesh (right).
3.3 Long term PCC model

With the homogenized mesh initialized using the $t = 20s$ temperature distribution, it can now be used to model core temperatures during a long-term PCC transient. This model uses the same boundary and interface conditions described in section 3.1. To model decay heat power generation a volumetric heat generation found with the total assembly power and assembly volume was used with the same fully resolved model used in the fully resolved model.

A key motivation of this study is to predict whether or not the reactor is designed such that it can passively remove enough decay heat to prevent core damage during a PCC event. As such, the peak temperature in the core is one of the primary parameters of concern. A time step sensitivity study on this parameter was performed using 25, 50, and 100 time steps with time steps increasing with time as shown in Figure 19.

![Figure 19 Time steps marked on the Wigner-Way formula.](image)

The results of the timestep sensitivity study, shown in Figure 20, demonstrate that with shorter times steps a lower peak temperature is predicted. This can be explained by the constantly decaying nature of the Wigner-Way formula, meaning each timestep refinement leads to less total energy being added to the core resulting in a lower peak temperature.
Figure 20 Timestep sensitivity study of the peak core temperature during the PCC transient.

Figure 20 shows the peak temperature reaching a local minimum 3 hours after the transient began, followed by a local peak at hour 20, then a steady decrease for the remainder of the modeled time. The local minimum is explained by the peak temperature shifting away from the core outlet where the steady-state max was located towards the core center where the highest power density is located. After this, the peak temperature is correlated to the relationship between power generated in the core and the power at the RPV boundary. Figure 21 shows the peak core temperature, the heat removed at the RPV, and the decay heat generated. Note that power values calculated by the MOOSE model are multiplied by a factor of 2 to represent the full core. At 29 hours into the transient the heat removed at the RPV surpasses the decay heat generated. The 9 hour span between this point the peak core temperature can be explained by the thermal capacity of the outer ring of core assemblies and reflectors. At 40 hours, a peak heat removal of 0.75 MW is predicted. Importantly, this value is below the 1 MW design target of the RCCS described in Section 2. Figure 22 shows the location of the peak core temperature at t = 0, 3, 20, and 240 hours. Note the continuous shift of the peak temperature towards the center of the core. Figure 23 shows the temperature distribution between the core and the outer RPV wall at t = 0, 40, and 240 hours. The peak RPV wall temperature at hour 40 is predicted to be 375°C.
Figure 21 Peak core temperature, power removed at RPV wall, and decay heat generated during PCC transient.
Figure 22 Location of peak core temperature at t=0, 3, 20, and 240 hours
Figure 23 Temperature distribution in outer reflector, core barrel, and reactor pressure vessel wall at t = 0, 40, and 240 hours
3.4 Conclusions and Future work

To perform the PCC analysis, the steady-state initial condition was determined using a fully resolved full core model with 3D solid to 1D fluid coupling. After the initial condition was found, the fully resolved mesh was used to model the first 20 seconds of the PCC. During this period fuel pins are rapidly transferring heat to the surrounding graphite matrix because of the sudden decrease in power density after reactor shutdown. After 20 seconds the temperature difference between fuel pins and the graphite matrix becomes minimal and the dominant heat transfer shifts to a larger scale: axially towards the core center and radially towards the RCCS. With heat transfer occurring on a larger scale it is no longer necessary to model small scale features in the core, i.e. fuel pins and coolant channels. Instead, a homogenized coarse mesh is used, greatly reducing the computational costs of the model. Results from the homogenized model show that the peak temperature in the core drops during the first 3 hours of the PCC as the heat is diffused from the steady-state temperature distribution towards cooler regions of the core. After three hours decay heat addition becomes dominant over this diffusion and temperatures in the core begin to rise. At 20 hours a peak temperature of 1100°C is reached. After 20 hours decay heat levels have fallen enough that the core begins to cool. Peak heat transfer to the RCCS occurs at hour 40. At this point, total heat removed by the RCCS is 0.75 MW, below the design limit shown in the RCCS design task. These results demonstrate that the core is designed to passively remove enough decay heat in a protected loss of primary coolant flow to prevent an unsafe rise of core temperatures.

The next iteration of the PCC transient model will include a more detailed RCCS model with 1D fluid components used to determine the RCCS wall temperature instead of the 100°C uniform boundary used with the current radiation heat transfer method. This coupling will provide more confidence that the RCCS is designed to handle the requirements of a PCC transient.
References


11. B. Borman, private communication, April 2022.

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