Semi-Annual Report for Modular Integrated Gas High Temperature Reactor Development during Performance Period October 2021- March 2022

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ABSTRACT

Modular Integrated Gas High Temperature Reactor (MIGHTR) 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 MIGHTR in 3 years and support its commercialization as a safe and low-cost HTGR. Argonne National Laboratory 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.

This first semi-annual report summarizes the progress made at Argonne on the two tasks since the start of the project. For the RCCS design task, high-level design work was performed including identification of design requirements for the conceptual MIGHTR RCCS and initial design calculations. The baseline dimensions of the MIGHTR RCCS were derived from scoping analysis results and preliminary steady state performance was estimated. At the initial stage of the primary system analysis task, the primary system thermal fluids model for the MIGHTR core was outlined to use a simplified two-dimensional model to predict the temperature distribution and coolant pressure losses in the fuel assembly blocks.
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1 Introduction

Modular Integrated Gas High Temperature Reactor (MIGHTR) is being designed by a multidisciplinary 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 MIGHTR 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.

This first semi-annual report summarizes the progress made at Argonne on the two tasks since the start of the project. Chapter 2 documents the identification of design requirements and the high-level design work for the initial concept of the MIGHTR RCCS. A design parametric study was performed incorporating the unique features of the MIGHTR. The baseline dimensions of MIGHTR RCCS were derived and preliminary steady state performance was estimated. Chapter 3 outlines the primary system thermal fluids model for the reactor core. A simplified two-dimensional model will be used to predict the temperature distribution and coolant pressure losses in the fuel assembly blocks. Additional coolant paths will be modeled to predict bypass coolant flow rates. Where possible, predictions made using the simplified two-dimensional model will be verified against a coupled 1D fluid-to-3D solid model of a fuel assembly.

2 Task 1 Update: RCCS Design

The Reactor Cavity Cooling System (RCCS) is a safety-related system that provides a passive means of removing decay heat in the core when the power conversion system, the primary and secondary heat transport systems, and the normal shutdown cooling system are unavailable to remove decay heat. As ex-vessel cooling means the RCCS achieves heat removal by radiation and convection cooling from the reactor pressure vessel walls to a network of cooling channels. There are design variations that have been chosen to feature specific reactor types and design choices such as primary coolant, geometry, and dimensions of individual cooling channels.

The MIGHTR concept is a prismatic high-temperature gas-cooled reactor (HTGR) in a horizontal layout with a total power of 160-230 MWt. The MIGHTR integrates the reactor pressure vessel (RPV) and steam generator into a single vessel. It has a horizontal orientation to achieve its construction cheaper and faster instead of a vertical alignment of traditional HTGR and steam generator (SG) housed in the tall reactor building [1], but it poses additional challenges for passive decay heat removal using the RCCS concepts. The MIGHTR’s ex-vessel natural circulation utilizing RCCS targets a high performance with relative simplicity and inherent safety characteristics maintaining its compactness.
2.1 Design Requirements of MIGHTR RCCS

2.1.1 Initial Concept of MIGHTR RCCS

The initial concept of the RCCS design proposed by Boston Atomics is described in [1]. It uses water as a primary coolant and consists of two tanks one above the RPV and one below and interconnecting pipes surrounding RPV as shown in Figure 1. The ultimate heat sink is not described at its present state, but this could be an active non-safety system during normal operation and rely on the thermal inertia of the water inventory in accident conditions such as a station blackout with a conduction cooldown situation. Initial assessment of this concept showed that it can potentially provide sufficient cooling for 5 to 10 days without replenishment [1].

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Figure 1 Schematics of the conceptual RCCS of MIGHTR (Boston Atomics) [1]

2.1.2 Functional Requirements

The RCCS is designed to use natural forces and be relatively simple and potential for high levels of performance for the passive safety of HTGR to remove core decay heat during both normal operation and off-normal conditions [2]. Differences between various RCCS designs are mainly in their working fluid and passive mode of operation for the range of the reactor design, for instance, General Atomics (GA) modular high temperature gas-cooled reactor (MHTGR) [3], Next Generation Nuclear Plant (NGNP) [4], and Framatome Steam Cycle – High Temperature Gas Cooled Reactor (SG-HTGR) [5]. GA’s MHTGR and NGNP are good references on the basis of system design requirements, where both have experienced the license application process in the past. Since they adopted the air-cooled natural convection open loop type system, those requirements could be modified to be applicable to other concepts, such as the water-based design or the design having different operating strategies.

The key functions of the RCCS are defined with acceptable RPV wall temperature and reactor cavity concrete temperature during power operation, startup, shutdown, anticipated operational occurrences (AOOs), and various Design Basis Events (DBEs). Working with the project team, design requirements applicable to the MIGHTR RCCS were derived in Table 1, where its design-specific values and features are represented in bold. It could be updated as the core, nuclear system design, and plant configurations of the MIGHTR evolve. Other categories in design requirements such as codes and standards, physical protection, material control, and safeguards, quality assurance, construction, or decommissioning have been considered, but not listed in the table.

A potential strategy for cooling the reactor cavity could be supported by a heating, ventilation, and air-conditioning (HVAC) system along with the RCCS performance, which capability might
be adjustable to satisfy the design limits of the reactor building concrete and the RPV. Nevertheless, the design of the MIGHTR RCCS shall target potential licensing basis events to remove most of the decay heat from the core to protect the RPV and the reactor cavity concrete from overheating together with the conduction through the reactor cavity concrete wall without HVAC when the reactor is shutdown.

Table 1 Requirements applicable to the MIGHTR RCCS (selected)

<table>
<thead>
<tr>
<th>Category</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System configuration and essential features</td>
<td>1.1) The RCCS shall remove heat from the reactor cavity by passive means.</td>
</tr>
<tr>
<td>requirements</td>
<td>1.2) The RCCS heat transfer surfaces shall remove heat from the full length and circumference of the reactor vessel.</td>
</tr>
<tr>
<td></td>
<td>1.3) The RCCS shall accommodate reactor vessel vertical supports, axial supports, and perhaps shutdown circulator openings and lateral restraint structure</td>
</tr>
<tr>
<td>2. Operational requirements</td>
<td>2.1) If required based on containment design and function, the RCCS shall maintain reactor cavity concrete temperatures less than $65 , ^\circ\text{C}$ during normal operation and less than $177 , ^\circ\text{C}$ for off-normal events.</td>
</tr>
<tr>
<td></td>
<td>2.2) The heat loss through the RCCS will be as low as reasonably achievable while the reactor is operating between 0 % and 100 % power. A target maximum heat loss is $\sim1 , \text{MWt}$.</td>
</tr>
<tr>
<td></td>
<td>2.3) The RCCS shall limit the maximum reactor vessel temperature below $427 , ^\circ\text{C}$ for a pressurized conduction cooldown and below $482 , ^\circ\text{C}$ for a depressurized conduction cooldown</td>
</tr>
<tr>
<td></td>
<td>2.4) As designed for continuous operation, the RCCS heat load during normal plant operation will be based on the module operating conditions.</td>
</tr>
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<td></td>
<td>2.5) The RCCS will be designed for an operating life of 40 years.</td>
</tr>
<tr>
<td>3. Structural requirements</td>
<td>3.1) All components and piping of the RCCS shall be designed against seismic loads and tornado.</td>
</tr>
</tbody>
</table>

2.2 High-level Design of MIGHTR RCCS

The initial MIGHTR RCCS design targets the reactor with a total power of 160 MWt at first, such that it could be utilized for assessing the feasibility of the concept. Design work for the MIGHTR RCCS design was performed in the first principle including an estimation of the total water inventory and a standalone RCCS analysis. Total water inventory was estimated by calculating the time elapsed until all amounts of water in the system are boiled off using the existing decay heat curve. Standalone RCCS analysis was performed to set design boundaries including system dimensions and operating conditions in de-coupled conditions. Then, the baseline dimensions of the MIGHTR RCCS design were derived based on the results.
2.2.1 Estimation of system inventory

According to the design objectives, the total water inventory in the system should be sufficient to secure at least 7 days until the boil-off of all coolant inventory in the system. To estimate the total water inventory required, two reference decay heat data were considered; ANS standard [7] and calculation results from a reference HTGR [8], shown as the ratio of decay power (P) to the nominal power (P₀) in Figure 2. As the ANS standard is specific to light water reactors, particularly for the UO₂ fuel decay power curve. Afterheat power was calculated for GA’s MHTGR modeled as a semi-homogeneous graphite-moderated core using thorium-uranium cycle, where results predicted a bit higher than that from ANS standard as a larger amount of thorium and ²³⁵U enrichment of the HTGR fuel considered in calculations [8].

![Reference decay power rates](image)

Assuming the RCCS is an open system operating in the system pressure of 1 atm and all decay heat is transferred to the RCCS coolant without any cooling that would otherwise be available during normal operation, the estimated amount of water required for securing 7 days of operation were approximately 170 tons and 220 tons for MIGHTR RCCS having a total power of 160 MWt based on the ANS standard and GA’s decay heat curve, respectively. This result is consistent with Boston Atomics’ preliminary calculation of ~200 tons of water inventory. It could be updated to accomplish design objectives in desired operation conditions according to the system design of MIGHTR RCCS.

2.2.2 Standalone RCCS analysis

Design analyses were performed to determine the design and operational conditions boundaries of the MIGHTR RCCS. As the MIGHTR primary system design is in the early stage, the RPV temperature could be set as the boundary condition independent of the decay heat level after shutdown in a standalone RCCS analysis. It consists of a coupled thermal resistance network analysis and a simplified natural circulation loop analysis. Thermal resistance network analysis estimates the amount of heat transfer from the RPV in desirable RCCS operation conditions. The simplified natural circulation loop analysis predicts a natural circulation flow rate according to the system dimensions. Two steps are then combined by exchanging the amount of coolant temperature increase across the riser tube (ΔT) and the natural convective heat transfer coefficient.
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(htc) of the riser tube while iterating until achieving heat balance. It estimates steady state RCCS performance in desirable RCCS operation conditions to derive the baseline design of the system. The flowchart of the analysis is summarized in Figure 3. Each analysis model is briefly described in the following subsections.

**Figure 3 Schematics of standalone RCCS analysis**

*Thermal resistance network model*

The domain of the thermal resistance network consists of the RPV, the panel, and the coolant in the riser tubes. Heat transfer in the gap from the uninsulated RPV outer wall to the RCCS riser tubes/panels consists of natural convection and thermal radiation. The convective and radiative components are assumed to be independent processes in the model. Heat transfer from the panel to the coolant in the riser tube consists of natural convection. From the initial concept of MIGHTR RCCS, the panel plays the role of heat transfer fin. By assuming a sufficiently high efficiency of heat transfer between the panel and the riser tube, conductive heat transfer between the panel and the riser tube wall is ignored. A schematic of the representative thermal resistance network is shown in Figure 4.

*Figure 4 Thermal resistance network of the MIGHTR RCCS*

*Natural circulation loop analysis model*

The domain of the natural circulation loop analysis consists of the top/bottom tanks, the collectors, pipes connecting the tank and collector, riser tubes, and downcomers representing half of the MIGHTR RCCS configuration, as shown in Figure 5. For modeling simplicity, it was assumed that a single-phase fluid flow in a steady state and negligible heat conduction from the panel to the fluid and inside the fluid. A minimum number of elbows were considered in the form loss pressure drop calculation. Calculations were iterated until a set of system dimensions and operation conditions which satisfy design requirements is sufficient to form a natural circulation flow, then the flow rate is calculated and the temperature difference between the hot and cold regions. Governing equation is from total pressure drop ($\Delta P_{\text{total}}$) across the loop expressed in Equation (1), which consists of the sum of pressure drop from friction ($\Delta P_f$), form loss ($\Delta P_{\text{form}}$),...
acceleration \( (\Delta P_{ac}) \), and head loss \( (\Delta P_g) \) between two nodes divided into the inlet and outlet of each component.

\[
\Delta P_{\text{total}} = \sum (\Delta P_{f,i} + \Delta P_{ac,i} + \Delta P_{g,i} + \Delta P_{\text{form},i}) = 0
\]

where \( \Delta P_f = f \frac{\sum L \rho v^2}{D_h} \), \( \Delta P_g = \rho g \Delta H \), \( \Delta P_{ac} = \dot{m}^2 \left( \frac{1}{\rho_i} - \frac{1}{\rho_o} \right) \), \( \Delta P_{\text{form}} \)

\[
= \sum K_j \rho v^2
\]

Figure 5 A schematic of a natural circulation loop representing the conceptual MIGHTR RCCS

2.2.3 Baseline Design of MIGHTR RCCS

The design space of system parameters was prepared based on the Boston Atomics inputs and major design requirements, where the selected design criteria are listed below. For the scoping study of the RCCS performance, some flexibilities in the design of the piping system could be allowed.

- The total water inventory of the system should be larger than \( \sim \) 200 tons as estimated for securing 7 days until boiled off.
- The MIGHTR has 9 vertical load supports on each side of the RPV equally spaced, 1.25 m in the axial direction. The RCCS panel and the riser tubes will be located between the structural supports and should have compatible dimensions with those.
- The top and bottom water tanks are assumed to be inside the reactor building. As the reactor building configuration is compact, the top and bottom tank dimensions are strictly restricted by height and width.
- The gap between the RPV side wall and the panels is assumed to be 10-20 cm.

Design parametric study

Standalone RCCS analysis was performed with the boundary conditions of the RPV surface temperature of 220 °C, and coolant bulk temperature of 60 °C assuming them during normal operational conditions of RPV and desirable RCCS operating conditions. A total \( \sim \)262,000 (4 points per 9 design parameters) sets of dimensions were compared to narrow down the design
space range to have better performance in terms of the heat removal rate of RCCS as shown in Figure 6. Baseline dimensions of the MIGHTR RCCS were derived based on the results to have the best performance within design ranges. Some of the design parameters were adjusted from engineering judgment by consulting the project team. For instance, the elevation change of the inlet and outlet ports of the bottom tanks is set as 0.65 m to secure marginal space for engineering purposes, while a smaller value is preferable from the parametric analysis showing the minimal influence on the RCCS performance.

![Table of Design Parameters]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dh1</td>
<td>2 – 10 inch</td>
</tr>
<tr>
<td>Dr</td>
<td>1/8 – 1/2 inch</td>
</tr>
<tr>
<td>Ddc</td>
<td>4 – 12 inch</td>
</tr>
<tr>
<td>L2</td>
<td>0.1 – 2.1 m</td>
</tr>
<tr>
<td>Lr</td>
<td>1.5 – 4.0 m</td>
</tr>
<tr>
<td>L6</td>
<td>0.1 – 2.5 m</td>
</tr>
<tr>
<td>Lbt</td>
<td>0.1 – 0.7 m</td>
</tr>
<tr>
<td>Ltt</td>
<td>1.1 – 3.1 m</td>
</tr>
<tr>
<td>PD</td>
<td>2.5 – 4.5</td>
</tr>
</tbody>
</table>

![Figure 6 Example Snapshots of Standalone RCCS Analysis Results]
In the next half of the year, we will proceed with in-detail components design work based on the derived RCCS baseline dimensions. It will include exploring configurations of top/bottom collector, heat sink options, and sectorizing top/bottom tank and relevant pipelines for system redundancy. Since standalone RCCS analysis was performed based on the lumped parameters, we have started system modeling using RELAP5-3D to incorporate the dimensional effect of the system configurations and details of system components. Then, coupled RCCS analysis for comprehensive system analysis will be performed coupling with primary system thermal-hydraulic modeling.

3 Task 2 Update: Primary System Thermal Fluids Analysis

Preliminary work has begun on the primary system thermal fluid analysis. A system-level approach with the System Analysis Module (SAM) [9,10] is being used to construct a thermal-hydraulic model of the core region. In this model, shown in Figure 8, the average flow within assembly coolant channels is modeled in one axial dimensional. These coolant channels are coupled via heat convection to a two-dimensional representation of solid fuel assembly blocks to create a simplified prediction for the temperature distribution within the core. To verify the predictions made by this simplified model, a coupled 1D fluid-to-3D solid model [11] of the fuel
assemblies will be used to create a more detailed and accurate prediction of the temperature distribution.

![Fuel assembly cross section with coolant-fuel unit cell outlined. Right: Representative 2D SAM model with $\delta_1$ and $\delta_2$ representing fuel radius and effective matrix thickness respectively.](image)

Figure 8

It is anticipated the bypass coolant flowing through gaps between assemblies will have a significant impact on the primary system thermal fluid model. As shown in Figure 9, predictions for assembly gap sizes have been made by collaborators at MIT based on thermal expansion and graphite irradiation calculations. Using these geometries, SAM will be used to predict the coolant flow distribution within the core based on calculations for the pressure losses in each assembly and bypass channel. Figure 10 shows a schematic of the flow paths in the SAM model with each channel connected to a common inlet and outlet branch. In addition to frictional losses in the channels, the impacts of form loss factors in the inlet and outlet plena will also be considered. Flow redistribution via cross-flow in axial assembly gaps may also play a significant role and can be included in future SAM models.

While the amount of heat removed by the bypass is expected to have a minimal impact on fuel temperatures (aside from the impacts of reduced assembly coolant channel flow rates), the increase in bypass flow temperature may have a significant impact on bypass coolant velocities and thus pressure losses, making it an important calculation. Work is ongoing to determine how to accurately implement thermal coupling between the coolant in bypass channels and the simplified two-dimensional assembly model.
Figure 9 Azimuthal assembly gap sizes as predicted by thermal expansion and graphite irradiation calculations.

Figure 10 Schematic of assembly and bypass flow paths in the SAM model.

Acknowledgement

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References
