Conceptual Design and Similarity Analysis of a Critical Assembly for HTGRs

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1. Introduction

The high-temperature gas-cooled reactor (HTGR) is one of the most promising Generation IV nuclear reactor concepts, owing to its inherent safety characteristics and high coolant outlet temperature. This high operating temperature enables diverse applications beyond electricity generation, such as hydrogen production and industrial process heat supply. HTGRs are generally categorized into pebble-bed and prismatic block types. Focusing on the latter, the Korea Atomic Energy Research Institute (KAERI) recently launched a public-private partnership project to develop a prismatic HTGR for process heat supply.

For the licensing and development of advanced reactors, experimental validation of nuclear design codes is an indispensable prerequisite. While extensive benchmark databases are available for light water reactors (LWRs), HTGRs exhibit unique physics phenomena—such as the double heterogeneity of TRISO fuel and graphite moderation effects—that necessitate specialized experimental validation. Currently, such HTGR experimental datasets are extremely limited worldwide. Relying on foreign facilities poses significant challenges, as overseas experiments cannot easily accommodate domestic design specifics and remain vulnerable to geopolitical uncertainties and budget overruns. Given that a dedicated research site is already secured in Gampo, South Korea, establishing a domestic HTGR critical assembly is both timely and essential.

Therefore, this study proposes a conceptual design of a prismatic block-type HTGR critical assembly (HTGR-CA) modeled using McCARD[1], a Monte Carlo code developed at Seoul National University (SNU). In nuclear data validation and criticality safety, sensitivity and uncertainty (S/U)-based similarity coefficients (c_k) have been widely used to quantify the representativeness of benchmark experiments[2,3]. Following this methodology, the neutronic similarity of the proposed HTGR-CA relative to the candidate core of the HElium-Cooled Thermal Application Reactor (HECTAR) was quantitatively evaluated in this work.

2. Design description

The HTGR-CA is a zero-power reactor employing a horizontal core configuration to facilitate component handling, as shown in Fig. 1. In particular, the bottom reflector features a separable structure, allowing convenient access for loading fuel compacts and experimental components into the core.

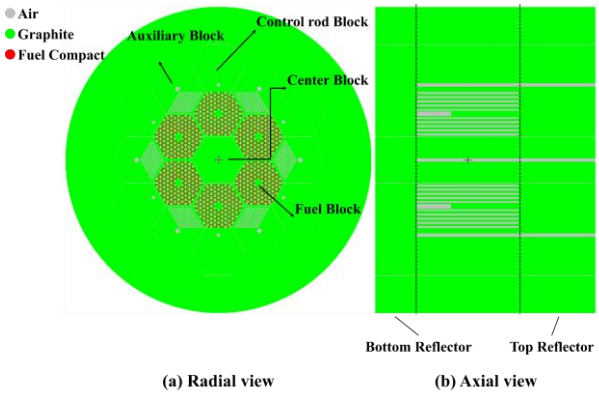


Fig. 1. Cross-sectional views of the HTGR-CA McCARD model: (a) radial view and (b) axial view.

2.1. Core configuration and design parameters

A primary design requirement of the HTGR-CA is to maintain the excess reactivity within 250 pcm under the cold all-rods-out (ARO) condition, thereby ensuring operational safety. The core features a cylindrical, air-cooled prismatic structure composed of various hexagonal graphite blocks. In addition, electric heaters are employed to raise the core temperature for high-temperature critical experiments. The top reflector accommodates penetrations for control rods and interfaces with upper core internals, while the bottom reflector has a cylindrical geometry that allows fine reactivity adjustment through the insertion or removal of graphite plates. As illustrated in Fig. 2, the core consists of four distinct types of hexagonal blocks: fuel blocks, auxiliary blocks, control rod blocks, and a center block. The fuel blocks are loaded with 15.5 wt.% ^{235}U-enriched fuel compacts and feature six compact-sized channels at their vertices to accommodate burnable poisons (BPs). These dedicated channels are intended for evaluation of BP reactivity worth rather than for excess reactivity control. The auxiliary blocks accommodate channels for graphite rods dedicated to reactivity compensation, as well as a 3-cm-diameter channel for various experimental purposes. The center block and control rod blocks each contain a single control rod channel. The detailed design parameters of the core are summarized in Table 1.

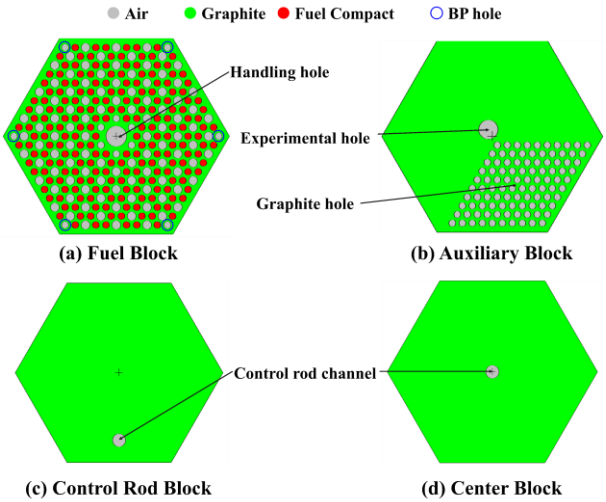


Fig. 2. Configuration of hexagonal graphite blocks: (a) fuel block, (b) auxiliary block, (c) control rod block, (d) center block.

Table 1. Core design parameters.

Core parameters	Value	Unit
Power	10	W
Core height	172.5	cm
Top reflector thickness	60.0	cm
Bottom reflector thickness	32.5	cm
Fuel block height	80.0	cm
Core diameter	2.4	m
Block pitch (Flat-to-Flat)	36.0	cm
Fuel enrichment	15.5	wt.%
Fuel material	UCO	-
^{235}U inventory	7.05	kg
TRISO packing fraction	35.0	%
TRISO fuel kernel radius	212.5	μm
TRISO buffer thickness	100.0	μm
TRISO inner PyC thickness	40.0	μm
TRISO SiC thickness	35.0	μm
TRISO outer PyC thickness	40.0	μm
Compact diameter	1.24	cm
Coolant channel diameter	1.588	cm
Fuel channel diameter	1.27	cm
Control rod channel diameter	2.0	cm

2.2. Neutronic modeling and criticality calculations

Although the core is designed to achieve elevated temperatures using electric heaters for high-temperature experiments, these auxiliary heating components were omitted in the present neutronic model. In addition, the bottom reflector was modeled as a single solid cylinder. Monte Carlo (MC) calculations were performed using the McCARD code with the ENDF/B-VII.1 cross-section library. The calculations employed 200,000 particles per cycle with 30 inactive and 480 active cycles. The double heterogeneity of the TRISO fuel was accounted for using the treatment implemented in McCARD.

The effective multiplication factor (k_{eff}) in the cold ARO condition was 1.00206 ± 0.00009 (corresponding to an excess reactivity of ~206 pcm), which satisfies the design requirement of an excess reactivity below 250 pcm, and the effective delayed neutron fraction (β_{eff}) was evaluated to be 705 pcm.

3. Similarity evaluation of the HTGR-CA

3.1. Definition of similarity coefficient (c_k)

To serve as an effective experimental benchmark, a critical assembly must demonstrate high neutronic similarity to the target HTGR under design. In this study, the neutronic representativeness of the proposed HTGR-CA is evaluated using the similarity coefficient (c_k), based on the sensitivity and uncertainty (S/U) method. As defined in Eq. (1), c_k is the Pearson correlation coefficient[4] that quantifies the correlation between the effective multiplication factors of the HTGR-CA and the target HTGR arising from shared cross-section uncertainties:

$$c_k = \frac{cov[k_{eff}^{CA}, k_{eff}^{target}]}{\sigma(k_{eff}^{CA}) \cdot \sigma(k_{eff}^{target})} \quad (1)$$

where $cov[k_{eff}^{CA}, k_{eff}^{target}]$ represents the covariance between k_{eff} of the two systems induced by nuclear data uncertainties, and $\sigma(k_{eff})$ denotes the corresponding standard deviation for each system. The superscripts 'CA' and 'target' denote the proposed HTGR-CA and the target HTGR system, respectively. The value of c_k ranges from −1.0 to 1.0, where a value close to 1.0 signifies a strong correlation between the two systems.

By applying the sandwich equation[5], the covariance and variance terms in Eq. (1) can be expressed using the sensitivity coefficient vector (S_i) and the cross-section covariance matrix (C). The sensitivity coefficient of k_{eff} with respect to a multigroup cross section is defined as:

$$S_i = \frac{x_{\alpha,g}^j}{k_{eff}} \frac{\partial k_{eff}}{\partial x_{\alpha,g}^j} \quad (2)$$

where $x_{\alpha,g}^j$ denotes the microscopic cross section for reaction type α of isotope j in energy group g, and the subscript i indicates the system under consideration. Consequently, c_k can be expressed in matrix notation as given in Eq. (3).

$$c_k = \frac{S_{CA}^T C S_{target}}{\sqrt{S_{CA}^T C S_{CA}} \cdot \sqrt{S_{target}^T C S_{target}}} \quad (3)$$

3.2. Neutronic conditions and evaluation setup

In this study, a candidate core design of HECTAR, currently under development at KAERI, is selected as the target system. Fig. 3 illustrates the overall radial core layout of the target HECTAR core. The target core is modeled with material compositions identical to those of the proposed HTGR-CA. Fig. 4 compares the normalized neutron energy spectra of the two systems at room temperature (300 K). Although discrepancies are observed in the spectral magnitude, the peak positions are in close agreement.

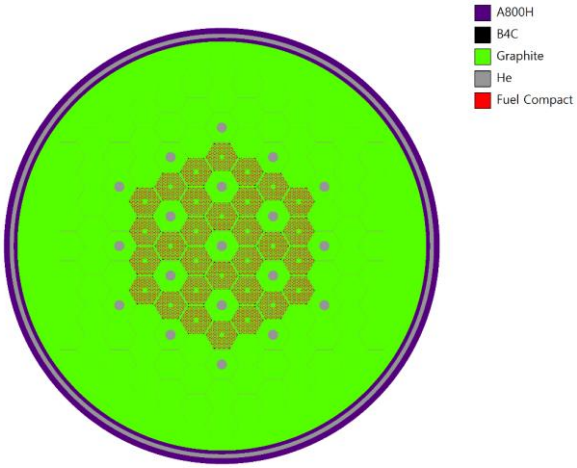


Fig. 3. Radial core layout of the target HECTAR core.

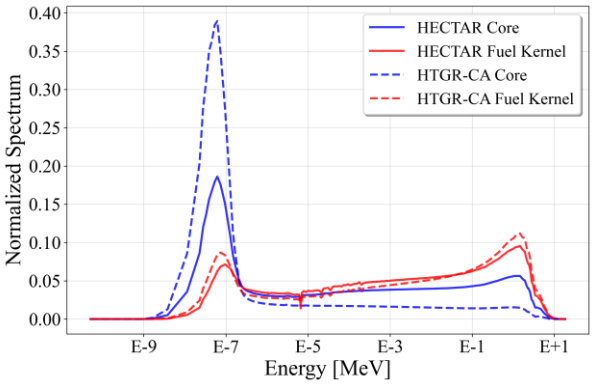


Fig. 4. Comparison of normalized neutron spectra between the target HECTAR core and the HTGR-CA.

The U.S. Nuclear Regulatory Commission (NRC) recommends utilizing multiple critical experiments with c_k values of at least 0.90 for criticality safety analysis[6]. Furthermore, studies suggest that when c_k exceeds 0.80, a suite of at least 20 benchmark experiments is required to ensure adequate validation for a target application[2]. To assess the neutronic representativeness of the HTGR-CA and examine the contributions of individual isotopes, three isotopes common to both systems were selected. The 44-group covariance data from the ENDF/B-VII.1 library were employed for the major reaction cross sections of the selected isotopes (^{10}B, ^{235}U, and ^{238}U) to evaluate c_k. Table 2 summarizes the selected isotopes and their corresponding reaction types.

Table 2. Key isotopes and cross sections for similarity evaluation.

Isotope	Key cross sections	Component
^{10}B	(n,n), (n,γ), (n,α)	BP compacts
^{235}U	(n,n), (n,n'), (n,f) (n,γ), $\bar{\nu}$	TRISO fuel kernels
^{238}U	(n,n), (n,n'), (n,f) (n,γ), $\bar{\nu}$	TRISO fuel kernels

3.3. Results

Table 3 summarizes the isotope-specific and overall similarity coefficients, together with the nuclear-data-induced uncertainties and covariances for the two systems. The overall similarity coefficient is 0.996, indicating a strong correlation between the nuclear-data-induced uncertainties in k_{eff}. The relative uncertainties are 0.72% for HTGR-CA and 0.71% for HECTAR, with ^{235}U providing the dominant contribution in both systems. These comparable uncertainty levels and the dominant role of ^{235}U are consistent with the use of the same fuel blocks. Taken together, these results support the representativeness of HTGR-CA for HECTAR with respect to the effects of nuclear data uncertainties on k_{eff}.

Table 3. Isotopic and overall similarity coefficients (c_k), relative uncertainties, and covariances between the two systems.

Isotope	Uncertainty ($\Delta k/k$ (%))		Cov.	c_k
	HTGR-CA	HECTAR		
Total	7.2E-1	7.1E-1	5.1E-5	0.996
^{10}B	1.4E-3	8.7E-3	1.2E-9	0.999
^{235}U	7.1E-1	6.9E-1	4.9E-5	0.998
^{238}U	1.2E-1	1.5E-1	1.7E-6	0.996

4. Conclusion

In this study, a conceptual nuclear design of the HTGR-CA was developed using the continuous-energy Monte Carlo code McCARD, and its neutronic similarity was evaluated against a candidate core design of HECTAR. The proposed core design satisfies the design requirement by maintaining the core excess reactivity below 250 pcm. Furthermore, the representativeness of the HTGR-CA relative to the target HECTAR core was quantitatively verified using the sensitivity and uncertainty (S/U)-based similarity coefficient (c_k). The evaluated overall c_k value reached 0.996, well exceeding established regulatory criteria and benchmark guidelines. The high overall similarity reflects both the dominant contribution of ^{235}U to the nuclear-data-induced uncertainties in the two systems and its high isotope-

specific similarity coefficient of 0.998. Consequently, these findings support the use of the proposed HTGR-CA as a representative experimental benchmark for nuclear design code validation for the target HECTAR system.

Future work will focus on completing the detailed engineering design of major core structures, including the control rods. While the present study excluded auxiliary components—such as electric heaters and instrumentation—to focus on fundamental reactor physics, subsequent investigations will conduct thermal analyses to verify that the heating system can reliably establish the required high-temperature isothermal conditions. Additionally, the radial extent of the core and surrounding shielding will be refined through radiation leakage and shielding analyses. Various critical experiments will also be evaluated computationally.

Acknowledgements

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