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# Analysis of Temperature Distribution of Graphite in HTGR Due to Radiation-Induced Variation of Thermal Conductivity

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## 1. Introduction

The High-Temperature Gas-cooled Reactor (HTGR) is a next-generation nuclear reactor characterized by high efficiency and safety, extensively utilizing graphite as both a moderator and a structural material. Graphite exhibits excellent thermal conductivity and neutron moderation properties; however, its physical properties tend to change under prolonged neutron irradiation. In particular, neutron irradiation alters the microstructure of graphite, leading to a decrease in its thermal conductivity, which consequently affects the temperature distribution inside the reactor.

Such changes in temperature distribution can induce thermal stresses in reactor structures, potentially causing structural degradation over long-term operation. Additionally, these variations can influence the thermal-fluid characteristics of helium, the reactor coolant, thereby impacting the thermal stability and overall safety of the reactor. Therefore, it is essential to quantitatively analyze the changes in the thermal conductivity of graphite due to radiation exposure and evaluate their effects on the internal temperature distribution of the HTGR to ensure its stable operation and long-term performance.

This study aims to quantitatively analyze the impact of radiation-induced changes in graphite thermal conductivity on the temperature distribution within the HTGR. To achieve this, a numerical simulation will be conducted incorporating the thermal conductivity variations of three representative nuclear-grade graphite materials: IG-110, H-451 [1], and G-347 [2], under different neutron dose conditions. By comparing the effects of neutron irradiation on different graphite types, this study seeks to explain the relationship between neutron irradiation levels and the resulting changes in temperature distribution.

The findings of this study will contribute to a deeper understanding of the thermal behavior of graphite structures in HTGRs under neutron irradiation, providing fundamental insights for the long-term operation and thermal management of these reactors. Furthermore, the results are expected to aid in the development of more sophisticated modeling and analysis techniques that account for radiation-induced changes in graphite properties, ultimately enhancing the design and safety evaluation of future HTGR systems.

## 2. Methods and Results

### *2.1 Numerical Model*

To model the internal structure of the High-Temperature Gas-cooled Reactor (HTGR), a three-dimensional computational fluid dynamics (CFD) analysis was conducted. A single graphite block within the reactor was modeled using ANSYS SpaceClaim (v24.1), following the MHTGR-350 design [3], describing in Figure 1. The generated mesh consisted of 16,774,240 elements.

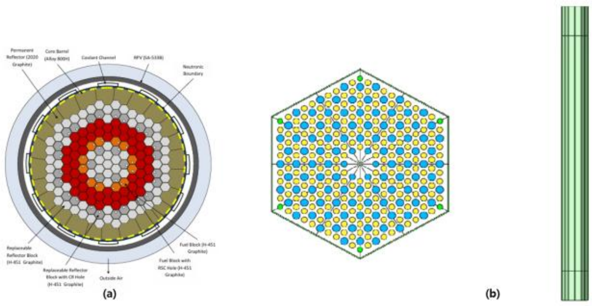


Fig. 1. (a) Schematic of MHTGR design. Adopted from [3]
(b) Geometry of graphite block model

The CFD analysis was performed using ANSYS Fluent (v24.1). The boundary conditions, including mass flow rate and outlet pressure, were set based on MHTGR-350 documentation. Additionally, the heat generation rate of the graphite block was also obtained from the same reference. The simulation was iteratively performed by adjusting the material properties to represent three types of graphite and various neutron irradiation levels.

### *2.2 Material Selection and Irradiation Conditions*

In this study, three types of nuclear-grade graphite—IG-110, H-451, and G-347—were used. These graphite materials are widely utilized in nuclear reactors and have been extensively studied.

Graphite undergoes microstructural changes under neutron irradiation, leading to a decrease in thermal conductivity. In general, even a small amount of neutron irradiation can significantly reduce thermal conductivity, but as the irradiation dose increases, it tends to stabilize at a certain level [2]. The thermal conductivity variations for each graphite type are described in Figure 2, 3, 4 and 5. CFD calculations were performed using a thermal conductivity function derived from these graphs, which was fitted using third-order polynomial equations for each irradiation condition.

While irradiation level of IG-110 is in term of displacements per atom (dpa), HTGR design data commonly use neutron fluence (n/m²). To ensure consistency, a conversion relationship was referenced from the ORNL report [4], where 1.0 dpa corresponds approximately to a fluence of $0.78 \times 10^{25}$ n/m² under representative HTGR irradiation conditions.

The expected neutron irradiation level in HTGR operation is below $6 \times 10^{25}$ neutron/m² [5]. Therefore, in this study, the neutron irradiation levels were set to unirradiated, 0.2, 1, 3, and $6 \times 10^{25}$ neutron/m² as analysis conditions, and simulations were conducted accordingly.

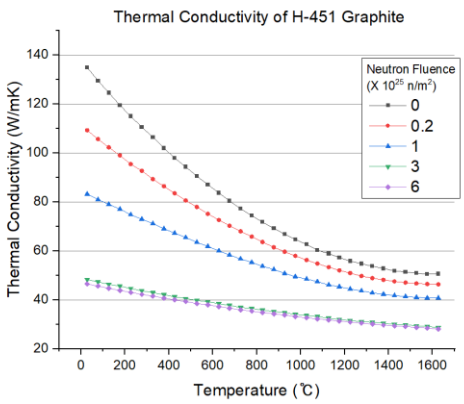


Fig. 2. Temperature dependence of thermal conductivity for H-451 graphite. Adapted from [3]

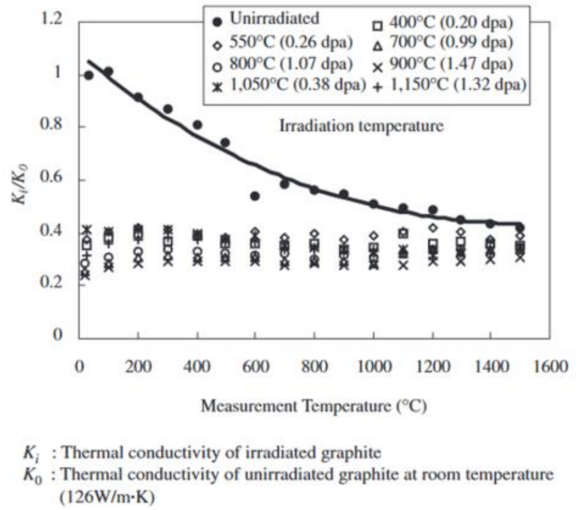


Fig. 3. Temperature dependence of thermal conductivity for IG-110 graphite (Fluence < 1.47 DPA). Adopted from [6]

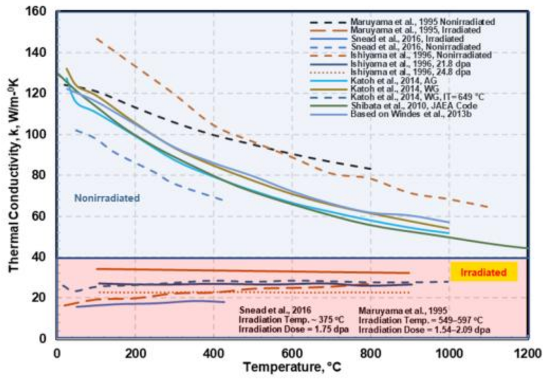


Fig. 4. Temperature dependence of thermal conductivity for IG-110 graphite. Adopted from [7]

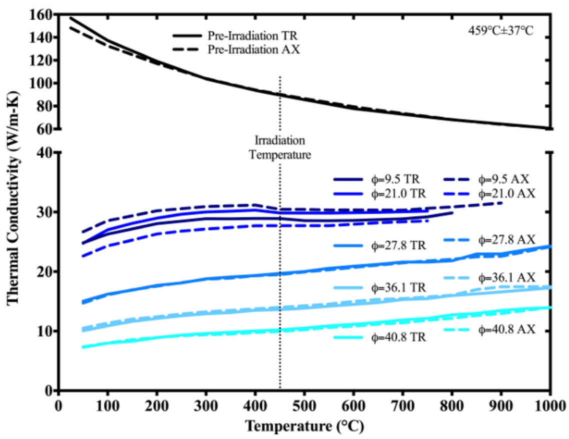


Fig. 5. Temperature dependence of thermal conductivity for G-347 graphite. Adopted from [2]
The labels indicate the specimen orientation and total neutron fluence ($x10^{25}$ n/m$^2$ [E>0.1MeV]).

*2.3 Results*

Neutron irradiation causes changes in the thermal conductivity of graphite, which in turn alters the overall temperature distribution within the graphite block. To quantitatively assess these variations, this study analyzes both the maximum and average temperatures of the graphite block. The maximum temperature is a critical parameter for calculating the margin to the melting point of graphite, providing insights into its thermal safety. Meanwhile, the average temperature helps in understanding the overall temperature distribution within the graphite block. Through this analysis, the study aims to gain a clearer understanding of the thermal behavior of graphite under neutron irradiation, contributing to the optimization of HTGR safety and operating conditions.

### *2.3.1 Maximum Temperature*

The maximum temperature of the graphite block was determined by performing calculations while varying the thermal conductivity to reflect neutron irradiation effects on the graphite.

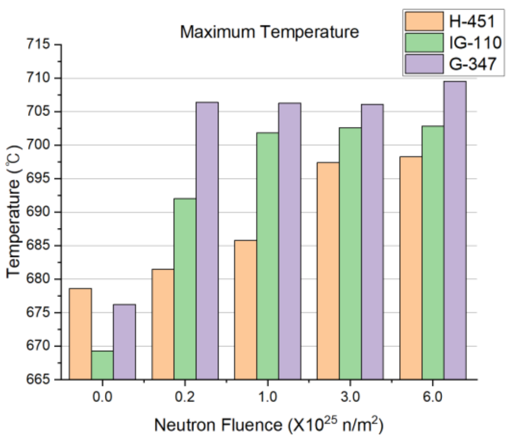


Fig. 6. Graphite maximum temperature

The results are presented in Figure 6, showing the maximum temperature variations for each graphite type under different neutron dose levels. The temperature distributions differ by graphite type, reflecting variations in thermal conductivity degradation behavior. Nevertheless, a common trend of temperature increase with neutron fluence is observed across all cases.

Figure 7 shows the cross-section of the IG-110 graphite block under $6\times10^{25}$n/m$^2$ fluence at a point near the outlet, where the maximum temperature point occurs. The figure illustrates that the maximum temperature region appears in a circular shape centered around a point that is not the exact geometric center of the graphite block cross-section.

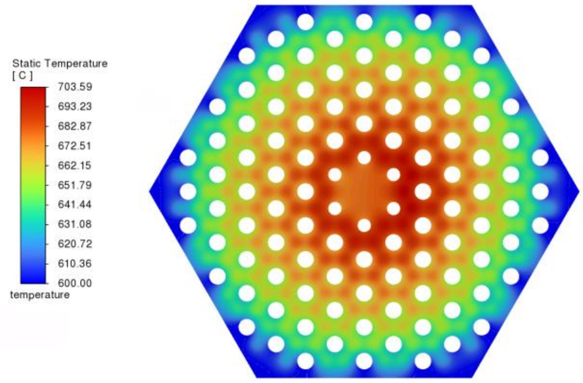


Fig. 7. The cross-section of IG-110 graphite at the point where the maximum temperature occurs. (5 cm away from outlet)

Table I: Graphite Maximum Temperature (℃)

| | Unirradiated | $6\times10^{25}$ n/m$^2$ | Difference |
|---|---|---|---|
| H-451 | 678.63 | 698.25 | 19.62 |
| IG-110 | 669.31 | 702.84 | 33.53 |
| G-347 | 676.24 | 709.49 | 33.26 |

The maximum temperature increased by ~30℃ under the neutron fluence condition. Moreover, while the maximum temperature increased, a sufficient margin remained compared to the melting point of graphite, indicating that structural stability would not be significantly affected.

### *2.3.2 Average Temperature*

The average temperature of the graphite block was determined. The results are presented in Figure 8, showing the average temperature variations for each graphite type under different neutron dose levels.

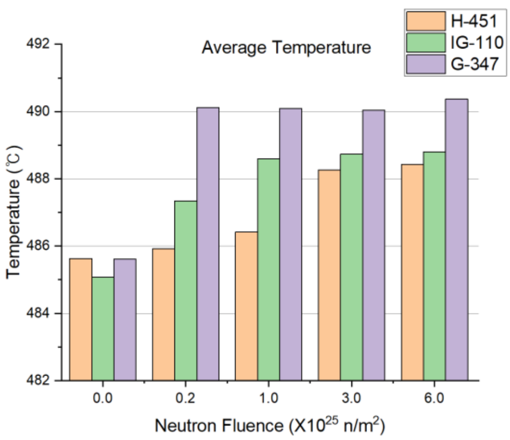


Fig. 8. Graphite average temperature

The average temperature shows a similar trend to the maximum temperature.

## 3. Conclusions

This study analyzed the thermal behavior of graphite blocks under neutron irradiation, revealing that both the maximum and average temperatures increased as neutron irradiation progressed.

Additionally, as the neutron irradiation dose increased, the temperature gradually rose, but the increase was minimal, suggesting that no sharp thermal changes would occur. This implies that once the thermal conductivity degradation of graphite due to neutron irradiation reaches a certain level, further significant variations are unlikely. This appears to be because the thermal conductivity decreases due to neutron irradiation, but further changes become limited as radiation damage saturates.

Furthermore, under the expected neutron irradiation conditions for HTGR operation ($6\times10^{25}$ neutron/m$^2$), the temperature distribution of the graphite block is predicted to remain stable. Even at the highest neutron fluence considered, the maximum temperature remains below approximately 710°C. Given that the typical melting point of nuclear-grade graphite is around 3,650°C [8].

The findings of this study contribute to quantitatively evaluating the thermal behavior of graphite structures within HTGRs and can serve as a fundamental reference for optimizing thermal management and improving reactor design in future research.

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