Assessment of TRISO Behavior in HTGR Coolant Temperature Conditions Using the COPA Code

Jae Joon Kim [a*], Young Min Kim [a], Eung-Seon Kim [a]
[a]*Advanced Nuclear Fuel Technology Development Division, KAERI, 34057, Yuseong-gu, Daejeon,*
[*]*Corresponding author: jaejoon@kaeri.re.kr*

Keywords : TRISO, Fuel analysis, HTGR

1. Introduction

This study aims to evaluate the fuel behavior in a block-type high-temperature gas-cooled reactor (HTGR) with a thermal power of 90 MW. To achieve this, the performance of TRISO-coated particle fuel was analyzed under various normal operating conditions, with a particular focus on the internal temperature distribution, gas accumulation in the void space, thermo-mechanical interactions, and failure probability. Because HTGR fuel performance is highly influenced by coolant temperature, this study considers four different coolant temperature conditions to analyze the thermal and mechanical behavior of the fuel during normal operation. Additionally, a probabilistic approach was applied to assess the structural integrity of TRISO-coated fuel particles. The objective was to determine whether long-term operational stability could be ensured under diverse thermal environments and to identify optimal operating conditions. For this evaluation, the COPA code, developed by the Korea Atomic Energy Research Institute (KAERI), was employed. [1] COPA is a computational code designed to analyze the thermal and mechanical behavior of HTGR fuel, providing functions such as predicting the internal temperature distribution, gas accumulation within the void space, mechanical and chemical failure probability, and fission product transport analysis. In this study, COPA was used to quantitatively assess the impact of fuel's physical and chemical properties, as well as external environmental conditions, on fuel performance. Furthermore, to evaluate the failure probability of TRISO-coated particles, a probabilistic approach was implemented by assuming a normal distribution (standard deviation of 5%) for the thickness of each TRISO layer. The effect of coolant temperature variations on fuel behavior was also investigated. Through this comprehensive assessment of the thermal and mechanical performance of HTGR fuel, this study aims to provide fundamental insights for ensuring the reliability of long-term reactor operation.

2. Methods

The average thickness and density of each TRISO layer are presented in Table 1, which served as the basis for evaluating the thermal and mechanical properties of the fuel. Additionally, for the probabilistic failure analysis, the thickness of each layer was assumed to follow a normal distribution with a standard deviation of 5%, allowing an assessment of how statistical variations affect the behavior of the fuel particles. Based on this analysis, this study comprehensively examines the structural integrity of TRISO particles to evaluate the feasibility of long-term operation in HTGRs. Table 2 presents the key design specifications of the graphite blocks and fuel compacts used in block-type HTGRs, which served as the basis for the quantitative evaluation of fuel performance.

Table 1. TRISO specifications for COPA calculations.

Layer	Thickness [μm]	Density [g/cm^3]
Kernel	*425 ± 21.5	10.4
Buffer	100 ± 5	1.05
IPyC	40 ± 2	1.9
SiC	35 ± 1.75.	3.19
OPyC	40 ± 2	1.9

Table 2. Graphite block specifications for COPA calculations.

Fuel block material	IG-110
Fuel block density (g/cm^3)	1.7
Fuel compact matrix material	A3-27 Graphite matrix
Matrix density (g/cm^3)	1.65
Packing fraction of CFPs in a compact (%)	35
Fuel compact diameter (cm)	1.24

Fuel compact length (cm)	2.5
Fuel hole diameter (cm)	1.270
Large coolant hole diameter (cm)	1.588
Pitch (cm)	1.8796

The fuel performance evaluation of block-type HTGRs was conducted based on the unit cell of the fuel block, as shown in Figure 1. The unit cell represents the smallest repeating structure within the fuel block, comprising a fuel compact and the surrounding structural graphite matrix. In this study, various fuel performance factors were analyzed at the unit cell level, including fuel burnup assessment, thermal analysis of the unit cell and individual TRISO particles, gas pressure accumulation within the TRISO kernel and buffer layer, and failure fraction evaluation of TRISO fuel assemblies. To simplify fuel performance calculations, the unit cell of the block-type HTGR fuel block was transformed into an equivalent cylindrical model for analysis. As depicted in Figure 2, this cylindrical model was designed such that the fuel compact region represents two original fuel compacts, while the structural graphite region was adjusted to maintain the same size as the unit cell.

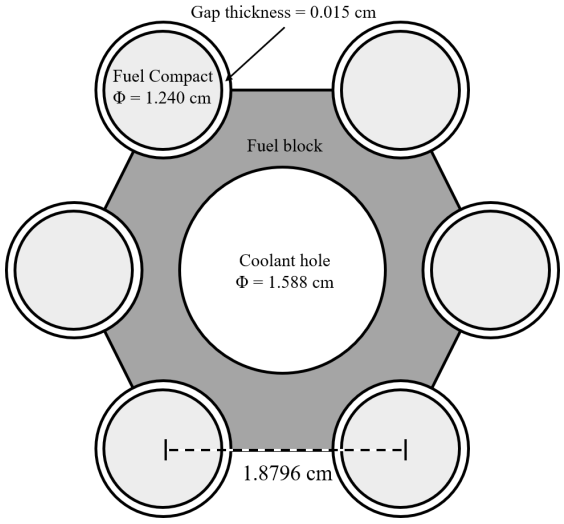

Figure 1. Unit cell of graphite block.

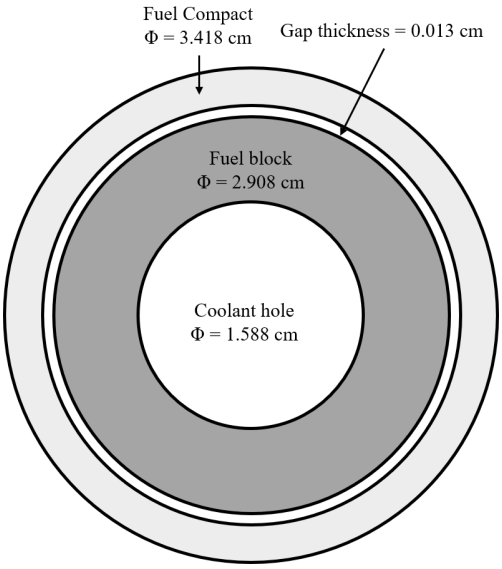

Figure 2. Transformation of the unit cell into an equivalent cylindrical model

3. Results

In this study, the burnup progression of the fuel compact was analyzed using McCARD, and the changes in burnup and the accumulated fast neutron fluence history were derived. [2] Figures 3 and 4 illustrate the burnup progression and the accumulated fast neutron fluence over 4,000 effective full power days (EFPD). The burnup analysis results indicate that the final burnup reached 167 GWd/tHM.

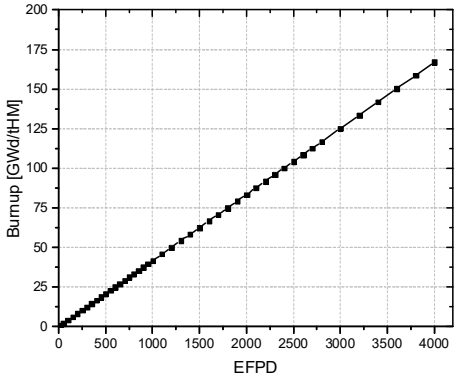

Figure 3. Burnup variation with EFPD.

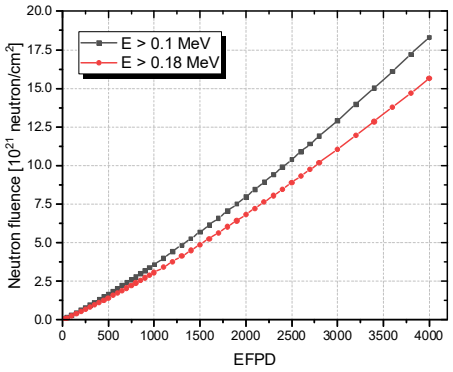

Figure 4. Fast neutron fluence variation with EFPD.

Figure 5 illustrates the temperature distribution within the equivalent cylindrical model for coolant temperatures set at 600, 750, 900, and 1200°C. The analysis results indicate a distinct temperature drop at the interface between the fuel compact and the structural graphite, which is attributed to the relatively low thermal conductivity of He within the gap. As the coolant temperature increases, the maximum temperature within the fuel compact also exhibits a rising trend. Figures 6, 7, 8, and 9 show the internal temperature distribution of TRISO-coated fuel particles located at the center of the fuel compact for each coolant temperature. The results reveal that the temperature of the TRISO-coated fuel particles generally increases with higher coolant temperatures. The most significant temperature gradient occurs in the buffer layer due to its considerably lower thermal conductivity compared to other layers. In contrast, the SiC and PyC layers exhibit relatively high thermal conductivity, resulting in minimal temperature differences between their inner and outer surfaces.

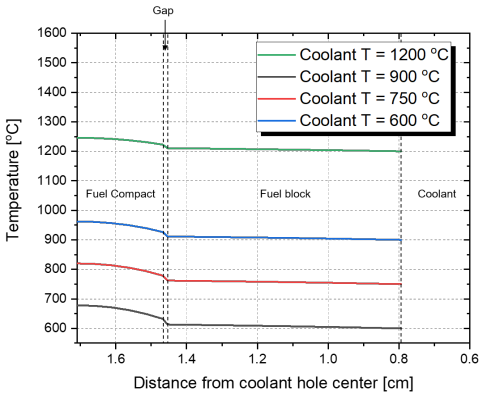

Figure 5. Temperature distribution variation with coolant temperature.

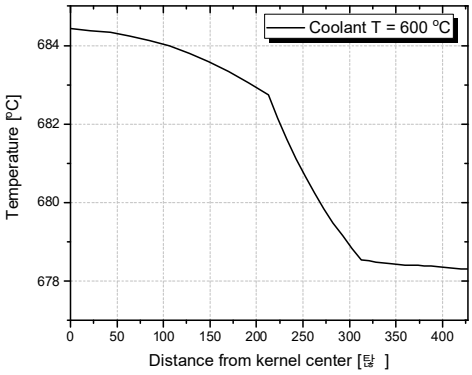

Figure 6. Temperature gradient of TRISO-coated fuel particles at the center of the fuel compact at a coolant temperature of 600°C.

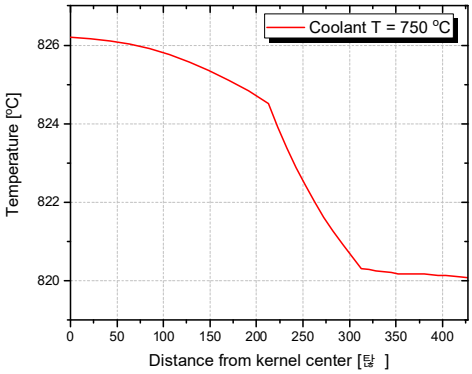

Figure 7. Temperature gradient of TRISO-coated fuel particles at the center of the fuel compact at a coolant temperature of 750°C.

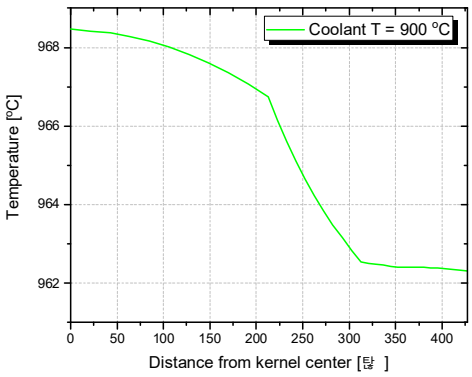

Figure 8. Temperature gradient of TRISO-coated fuel particles at the center of the fuel compact at a coolant temperature of 900°C.

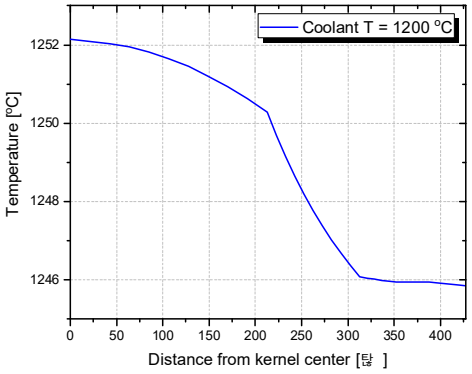

Figure 9. Temperature gradient of TRISO-coated fuel particles at the center of the fuel compact at a coolant temperature of 1200°C.

The gaseous species generated inside the TRISO-coated fuel kernel were calculated using the HSC software and the McCARD code. Various gaseous species are produced through fission reactions and subsequently released into the buffer layer. The release of gases from the kernel was approximated using the Booth model, which served as the basis for quantitatively analyzing the behavior of gases migrating from the kernel to the buffer layer. [3,4] Figure 10 illustrates the variation in total gas pressure inside the TRISO particle as a function of coolant temperature, showing that the final pressure reaches approximately 20 MPa at a coolant temperature of 1200°C.

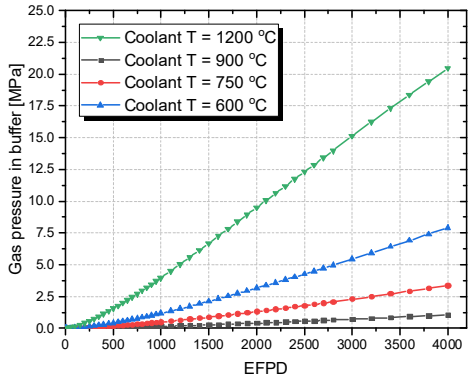

Figure 10. Total gas pressure variation inside TRISO-coated fuel particles.

When calculating the failure probability of TRISO-coated fuel particles used in HTGRs, the primary failure mechanisms considered are mechanical failure and SiC layer corrosion. Montgomery developed a model describing the SiC corrosion rate as a function of temperature, which was used to assess the potential degradation of the SiC layer. [5] The failure probability of TRISO-coated fuel particles was calculated using the COPA code, employing a Monte Carlo method for probabilistic sampling. The tensile strength of PyC and SiC layers was assumed to follow a Weibull distribution, while the coating layer thicknesses were assumed to follow a normal distribution. Figure 11 presents the corrosion damage fraction of. the SiC layer at a coolant temperature of 1200°C. The analysis results indicate that corrosion damage begins to increase at approximately 1250 EFPD, and by 1500 EFPD, all SiC layers were calculated to have experienced corrosion damage. In contrast, no significant SiC corrosion damage was observed at other coolant temperature conditions (600°C, 750°C, and 900°C). Figure 12 illustrates the analysis results for mechanical failure. No mechanical damage to the SiC layer was observed under any coolant temperature condition. However, at a coolant temperature of 1200°C, localized damage to the PyC layer was identified in some TRISO particles. The fraction of TRISO particles with only the IPyC layer damaged was calculated to be approximately 6.0×10^{-5}, while the fraction with only the OPyC layer damaged was approximately 9.0×10^{-7}. These failure probabilities remain below the allowable defect limits in the TRISO fuel manufacturing process, indicating that the structural integrity of the fuel is maintained.

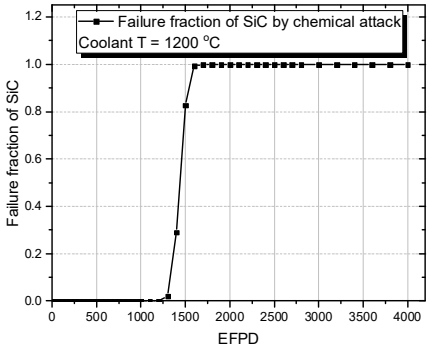

Figure 11. Failure fraction of SiC due to chemical attack under a coolant temperature of 1200 °C.

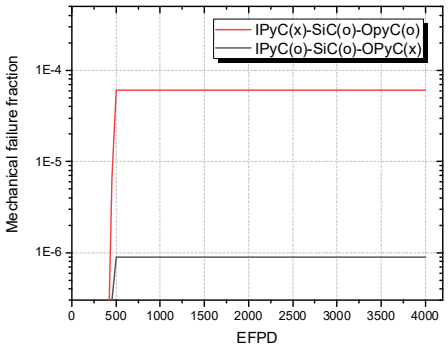

Figure 12. Mechanical failure fraction under a coolant temperature of 1200 °C.

4. Conclusions

In this study, the safety analysis of TRISO-coated fuel particles was conducted using the COPA code, McCARD, and HSC Chemistry programs over 4,000 EFPD at four different coolant temperatures, with a final burnup of 167 GWd/tHM. Through this analysis, the thermal, mechanical, and chemical behavior of the fuel was quantitatively evaluated, and its reliability under long-term operation was assessed. Based on the comprehensive evaluation of the safety analysis results, it was found that TRISO-coated fuel maintained its integrity even at a coolant temperature of 900°C. However, at 1200°C, TRISO failure occurred due to chemical corrosion of the SiC layer.

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