Study on the Effects of Enrichment and Fraction of Coated Fuel Particles on Fissile Utilization of 100 MWt Prismatic-type of High Temperature Gas Reactor

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Abstract. High Temperature Gas-cooled Reactor (HTGR) is one of Generation-IV reactor technology that has graphite moderate, Helium gas-cooled, and Coated Fuel Particle (CFP) layered by Tristructural-Isotropic (TRISO). The HTGR has an outlet temperature of around 1000°C that can be utilized for many co-generation processes other than to generate electricity. Due to characteristics of the CFP and TRISO, utilization of fissile material during reactor operation becomes important. This study aims to analyze the effects of enrichment and fraction of CFP on the fissile utilization of 100 MWt HTGR for two different fuels; UO₂ and (Th-U)O₂. Fissile enrichment is analyzed from 1-20% while the fraction of CFP from 10-60%. Using SRAC2006 code and JENDL-4.0 as nuclear data library, calculation and analysis are performed to find the optimal values of several important neutronic parameters.

1. Introduction

The Generation IV International Forum (GIF) determined the High Temperature Gas Reactor (HTGR) as one of the advanced reactors due to its safety features, proliferation resistance, efficient fuel utilization, and economics. HTGR with high outlet temperature of about 1000°C can be utilized for electricity production, hydrogen production, coal gasification, oil recovery, and seawater desalination [1]. The HTGR has graphite moderate, Helium gas cooled, and Coated Fuel Particle (CFP) layered by Tristructural-Isotropic (TRISO).

There are two different fuel forms of HTGR based on Coated Fuel Particle (CFP); prismatic design and pebble bed design, as shown in Figure 1. The CFP design supports the safety features of HTGR because it surrounded by coated layers; a buffer pyrolytic carbon layer (buffer PyC), an inner low-density pyrolytic carbon layer (IPyC), a silicon carbide layer (SiC), and an outer high-density pyrolytic carbon layer (OPyC) to obstruct the released fission products [2].
This study aims to analyze the effects of enrichment and fraction of CFP on the fissile utilization of 100 MWt prismatic-type HTGR for two different fuels; UO$_2$ and (Th-U)O$_2$; while some previous studies focused on pebble bed-type HTGR [3] [4]. The optimization of fissile utilization is very important in HTGR design due to the use of CFP, which is very small and multilayered that make it difficult to reprocess.

![Figure 1](image.png)

*Figure 1. Two different fuel forms of HTGR; (a) Pebble bed design [2], (b) Prismatic design [5].*

### 2. Design Parameters and Method

The primary specification of the HTGR, as well as fuel specification, are adopted from High Temperature Test Engineering Reactor (HTTR) [6] Japan with modified power of 100 MWt and operation period target for two years as shown in Table 1 and 2. In this study, two different nuclear fuels are calculated and analyzed; UO$_2$ and (Th-U)O$_2$.

The SRAC2006 code system [7] developed by Japan Atomic Energy Agency (JAEA) with JENDL4.0 [8] as nuclear data library was used in this study to calculate and analyze the value of several important neutronic parameters. Figure 2 shows the neutronic calculation in assembly level using SRAC2006.

| Table 1. Major specification of the HTGR |
|----------------------------------------|
| Design parameter | Unit | Value |
|------------------|------|-------|
| Thermal power    | MWt  | 100   |
| Coolant outlet temperature | °C  | 950   |
| Coolant inlet temperature | °C  | 395   |
| Core structure   | -    | Graphite |
| Equivalent core diameter | m  | 2.3   |
| Effective core height | m  | 2.9   |
| Fuel enrichment  | %    | 1-20  |
| Fuel coating     | -    | TRISO |
| Fuel element type | -  | Pin-in-block |
| Coolant material | -    | Helium gas |
| Burn-up period   | years | 2     |
Table 2. Fuel specifications

| Fuel parameter       | Specification |
|----------------------|---------------|
| Kernel diameter      | 0.5 cm        |
| CFP diameter         | 0.091 cm      |
| Compact inner diameter | 1 cm        |
| Compact outer diameter | 2.6 cm    |

3. Result and Discussion

3.1 Effect of fissile enrichment

Parametric surveys were performed to analyze the effect of enrichment in the 100 MWt prismatic-type HTGR. The fissile enrichment is varying from 1% to 20% with the operation period target of two years.
Figure 3. k-inf profiles for 1% to 20% fissile enrichment of UO$_2$ fuel in 100 MWt prismatic-type HTGR design

Figure 4. k-inf profiles for 1% to 20% fissile enrichment of (Th-U)O$_2$ fuel in 100 MWt prismatic-type HTGR design

Figure 3 and 4 depict the infinite multiplication factor (k-inf) profile with various enrichment in fuel blocks for UO$_2$ and (Th-U)O$_2$ fuels, respectively. The k-inf result as a function of fuel burn-up in Figure 3 and 4 indicate that the enrichment value which could achieve operation period target of two years are 15% for UO$_2$ and (Th-U)O$_2$. 
3.2 Effect of CFP fraction
The various fraction of CFP is another main concern in this study. Using fissile enrichment value that obtained from previous analysis, the calculation for different fractions of CFP is performed to get the optimal fraction of CFP that could achieve operation target of two years and gives the highest fissile utilization. The various fractions of CFP used in this study are shown in table 3.

| Number of CFP | Kernel’s fraction | CFP’s fraction |
|---------------|-------------------|----------------|
| 4500          | 1.67%             | 10%            |
| 8950          | 3.32%             | 20%            |
| 11200         | 4.15%             | 25%            |
| 11500         | 4.26%             | 26%            |
| 13000         | 4.42%             | 30%            |
| 17900         | 6.64%             | 40%            |
| 22380         | 8.30%             | 50%            |
| 26850         | 9.96%             | 60%            |

Table 3. Variations of CFP fraction

Figure 5. k-inf profiles for different CFP fraction of 15% enrichment for 100 MWt prismatic-type HTGR using UO$_2$
Figure 5 and 6 show the calculation result of k-inf with various CFP fraction for UO$_2$ and (Th-U)O$_2$ fuels, respectively. From the results in Figure 5 and 6, the optimal fraction of CFP that could achieve the operation target is 13000 for both UO$_2$ and (Th-U)O$_2$ fuels.

**Figure 6.** k-inf profiles for different CFP fraction of 15% enrichment for 100 MWt prismatic-type HTGR using (Th-U)O$_2$

**Figure 7.** Number of used fissile U-235 for a different fraction of CFP
The number of fissile material used is one of the important parameters in the present study due to it gives a significant contribution to the fuel economic. Figure 7 and 8 show the number of fissile utilization for uranium dan thorium-based fuels. The number of fissile utilization is 82.7% for UO$_2$ and 83.1% for (Th-U)O$_2$. From this data, it could be said that the most used fissile material that leads to the highest fissile utilization obtained in the present study is (Th-U)O$_2$.

4. Conclusion
Focusing on the assembly level of a particular design of a prismatic-type 100 MWt HTGR, this study presents the optimal fissile enrichment value for UO$_2$ and (Th-U)O$_2$ are 15%. The optimal fraction of coated fuel particles obtained is 13000 for all two different fuels. The number of utilized fissile materials is 83.1% for UO$_2$ and 82.7% for (Th-U)O$_2$. It suggests that among those fuel options, the highest fissile utilization for prismatic-type 100 MWt HTGR design in the present study is (Th-U)O$_2$.

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