Study on Fissile Material Usage for 50 MWt High Temperature Gas Reactor using (Pu-U)O$_2$ Fuel

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Abstract. One of the most potential nuclear power plants is High Temperature Gas-cooled Reactor (HTGR). It is a reactor system designed using TRISO (Tristructural-Isotropic) coated fuel and has very high outlet temperature to produce electricity and many co-generation application processes. The present study aims to analyze fissile material usage for 50 MWt prismatic-type HTGR using (Pu-U)O$_2$ fuel. Calculations were performed using neutron diffusion method that applied in SRAC2006 code, and nuclear data based on JENDL 4.0. Selected neutronic parameters are analyzed to study the effect of the number of fissile enrichment and number of Coated Fuel Particle (CFP) to the reactor system. The results of the parametric survey show that for prismatic-type of 50 MWt HTGR, 10% of enrichment and 8950 of number CFP give the best performance in term of fissile material usage during reactor operation.

1. Introduction

In an archipelagos country like Indonesia, there are several scenarios and reactor types that could be implemented. In some area, such as a remote island, a long-life operation is an important factor, and several kinds of research have been conducted to find the optimal parameter design of this type of reactor [1,2]. In some other area, co-generation application such as desalination of seawater will be very beneficial, so that the High Temperature Gas-cooled Reactor (HTGR) becomes an interesting choice. HTGR is one of the Generation IV reactor technology with enhancing safety features, efficient utilization of fuel, nonproliferation attributes and improved economics. The HTGR is graphite-moderated, helium gas-cooled, and has high outlet temperature about 1000°C. The high outlet temperature may also be utilized for industrial applications like hydrogen production. Other than that, its outlet temperature potentially used to oil recovery, coal gasification, and purify the seawater, other than to generate electricity [3].

The two types of HTGR concepts are in their fuel form; pebble-type and prismatic-type. In the pebble-type, the coated fuel particle (CFP) embedded in spherical graphite. Whereas in prismatic-type, CFP embedded in graphite and then formed into cylindrical fuel compact to form the fuel rods. The CFP has a
function of preventing the release of fission products from the fuels [4]. The fuel kernels of HTGR are coated with inner low-density pyrolytic carbon (PyC), high-density pyrolytic carbon (PyC), silicon carbide (SiC), and outer high-density pyrolytic carbon (PyC) [5]. Figure 1 shows the difference between the two types of HTGR fuel form.

Study on neutronic parameters, including fuel utilization for pebble type reactor, have been conducted [7-9]. The present research aims to analyze fissile material usage for 50 MWt prismatic-type HTGR using (Pu-U)O₂ fuel. Selected neutronic parameters are analyzed to study the effect of the number of fissile enrichment and number of Coated Fuel Particle (CFP) to the reactor system. The usage of fissile material becomes an important factor in a reactor design utilized CFP concept such as HTGR system due to multilayered coatings that make it difficult to reprocess.

2. Design Parameters and Method

2.1 Design Parameters of 50 MWt HTGR

The HTGR design parameters and fuels specification used in the present study was adopted from High Temperature Test Engineering Reactor (HTTR) Japan [10] by increasing power from 30 MWt to 50 MWt. The reactor set to be operated for two years operation period. Detail specification is shown in Table 1 and 2. Japan’s HTTR-30 is representative of the HTGR concept that is operating today [11]. Its first criticality was attained in 1998. High temperature operation with an outlet temperature of 850°C and 950°C was achieved in December 2001 and April 2004, respectively [12].

| Design parameter       | Unit   | Value |
|------------------------|--------|-------|
| Thermal power          | MWt    | 50    |
| Equivalent core diameter | m   | 2.3   |
| Effective core height  | m      | 2.9   |
| Fuel enrichment        | wt%    | 1-20  |
| Outlet temperature     | °C     | 950   |
| Inlet temperature      | °C     | 395   |
| Core structure         | -      | Graphite |
| Coolant material       | -      | Helium gas |
| Burn-up period         | days   | 720   |

Figure 1. The two types of HTGR fuel form [6]
The HTGR structure consists of core components, including fuel assembly, control rod, reflector block, reactor pressure vessel and other components. The reactor core is constructed by stacking hexagonal blocks. The active hexagonal core consists of 30 columns for fuel blocks, 16 columns for control rods, three irradiation columns, and surrounded by permanent graphite reflector [13].

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

Table 2. Specification of fuel compact

In this study, (Pu-U)O₂ fuel are calculated and analyzed. Plutonium compositions used in this study were from reactor-grade Plutonium, as given in Table 3 [14].

| Pu     | Pu-238 | Pu-239 | Pu-240 | Pu-241 | Pu-242 |
|--------|--------|--------|--------|--------|--------|
| %      | 1.3    | 60.3   | 24.3   | 9.1    | 5.0    |

Table 3. Plutonium compositions [8]

2.2 Calculation Method

This research focused on analyzing neutronic parameters using deterministic methods to solve the diffusion equations applied to the SRAC2006 code [15] developed by JAEA (Japan Atomic Energy Agency). The nuclear data library used for calculation is based on JENDL (Japanese Evaluated Nuclear Data Library) version 4.0 [16].

The initial data is needed as input includes dimensions fuel block, atomic number density, cladding material, and coolant material. The calculation starts with calculating the parameter value in the form of atomic density with enrichment variants and number of CFP, geometric buckling, and reactor power level at assembly level using PIJ. Important neutronic parameters discussed in this study were obtained from the outputs of PIJ calculation.

3. Calculation Result and Discussion

3.1. Effect of fissile material enrichment

In order to characterize the effect of fissile material enrichment on the 50 MWt prismatic HTGR, sets of parametric surveys were performed. Typical fissile material enrichment varies from 1-20% for two years reactor operation period. The maximum enrichment value of 20% is based on the upper limit of enrichment can be used for a commercial nuclear power plant. Figure 2 shows the calculation result of the infinite multiplication factor (k-inf) as a function of burn-up period. Infinite multiplication factor (k-inf) is the ratio of the neutrons produced in one generation to the sum of neutrons absorbed in the preceding generation without leakage. Figure 2 shows that the enrichment value of at least 10% achieves two years of reactor operation target (k-inf higher than 1). Lower fissile enrichment values will make the reactor
reached a subcritical condition (k-inf less than 1) before the end of the operation target of two years. This 10% of enrichment considered to be the optimum value for this case because it meets the operation target while keeping enrichment value to as minimum as possible.

**Figure 2.** k-inf profiles vs burn-up period in parametric surveys for fissile material enrichment

Figures 3 depict the result of CR for the fuel calculated in this study. CR is the ratio between the fissile materials produced to the number of fissile materials consumed. It is found from the calculation that higher fuel enrichment will make lower CR values. This is due to the number of fissile materials and depletion processes that occur during reactor operation.

**Figure 3.** Conversion Ratio (CR) profiles vs burn-up period in parametric surveys for fissile material enrichment
3.2. Effect of Coated Fuel Particle

In addition to the calculation to get optimum enrichment, analysis of CFP value is needed for 50 MWt prismatic-type HTGR, which gives the highest used fissile material at the end of the reactor operation period. The limit given is the target operation for two years, and the enrichment value used is 10% obtained from the calculation of previous enrichment values. Number of CFP in HTTR30 is around 13000. In the present study, different number of CFPs, which lower and higher than HTTR30’s CFP, are also taken into consideration. The number of calculated coated fuel particles are 4500, 8950, 11200, 11500, 13000, 17900, 22380 and 268500.

Figure 4. k-inf profiles vs burn-up period for different number of CFP

Figure 4 shows the value k-inf for (Pu-U)O$_2$ fuel with different number of CFP. It could be seen that for 4500 number of CFP the reactor could not satisfy the two years of reactor operation target due to the insufficient number of fissile material needed for fission reaction. The number of CFP that meet the reactor operation target are the ones which have a higher number of CFP of 4500, that are 8950, 11200, 11500, 13000, 17900, 22380, and 26850.
Figure 5. Number of fissile material, Pu-239, usage for different number of CFP

Figure 5 depicts the number of fissile material (Pu-239) usage for different number of CFP. The optimal number of CFP obtained in this study is 8950 that meet reactor operation period target and give the highest number of fissile material usage at the end of reactor operation. For (Pu-U)O₂ fuel use in the present study, the highest number of fissile material used is 77.29%. It means that the optimal fissile material in this study that satisfies operation period target of two years could be achieved using 10% of enrichment and 8950 of the number of coated fuel particle.

4. Conclusion

Study of fissile material utilization on prismatic-type 50 MWt HTGR design in assembly level using (Pu-U)O₂ has been performed. Number of fissile enrichment at the beginning of reactor operation and the number of coated fuel particle inside fuel compact were analyzed by performing parametric surveys. It is found that for particular prismatic-type of 50 MWt High Temperature Gas Reactor calculated in the present study, 10% of enrichment and 8950 of number CFP give the best performance in term of fissile material utilization for two years of operation periods.

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