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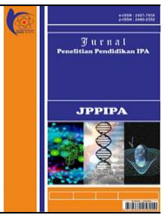

The Effects of the Number of Coated Fuel Particles on the Neutronic Aspects of 25 MWt Pebble Bed Reactor with Thorium Fuel

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Abstract: High-Temperature Gas Reactor (HTGR) is a type of reactor that continues to be developed because of its advantages in terms of economic aspects, proliferation resistance, and safety aspects. One of the safety aspect improvements is due to the use of the Coated Fuel Particle (CFP). A coated fuel particle is a fuel with a diameter smaller than 1 mm and is protected by several carbon layers. In the Pebble Bed Reactor (PBR) type of HTGR design, the CFP is placed in a 6 cm fuel ball. How much CFP is put into the fuel ball will determine the neutronic characteristics of the reactor. In this study, the effect of the amount of CFP in the fuel ball on the 25 MWt PBR design using Thorium fuel and its impact on several important neutronic aspects, such as the effective multiplication factor, the amount of fuel enrichment, the utilization of fissile material, and the density of the fissile material formed. The calculation was performed by the Monte Carlo MVP / MVP-BURN code. This study found that the coated fuel particle fraction of 15% was the optimum value for the studied neutronic parameters.

Keywords: Coated Fuel Particle; Neutronic; Pebble Bed Reactor.

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Introduction

The world's energy needs, which continue to increase along with the times, require as many alternative solutions as possible that can be immediately implemented. This is especially true for Indonesia, one of the most populous countries in the world, with such a large population that it is well known on various islands. For a densely populated area such as Java island, the need for electricity for both the community and industry requires power plants with large power without being too bothered by the supply of fuel because of the established infrastructure lines. It is different from areas located on small islands with a small population and a distribution channel infrastructure that is not as stable as the big islands. For such areas, a suitable power plant is a power plant with small or medium power, with a minimum refueling interval.

Small-power High-Temperature Gas Reactor (HTGR) is an alternative solution that can be implemented in a field like this. HTGR is one type of reactor with the characteristics of Generation-IV reactors, a type of future reactor with various advantages in terms of safety, proliferation resistance, and excellent economic value. Judging from how the fuel is used, there are two types of HTGR, as illustrated in Figure 1. The first is the prismatic type HTGR, where the fuel is formed into a fuel rod consisting of a compact in the form of a small cylinder, while the second type is HTGR pebble bed, in which the fuel is

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made in the form of balls with a diameter of 6 cm which is then fed into the reactor core.

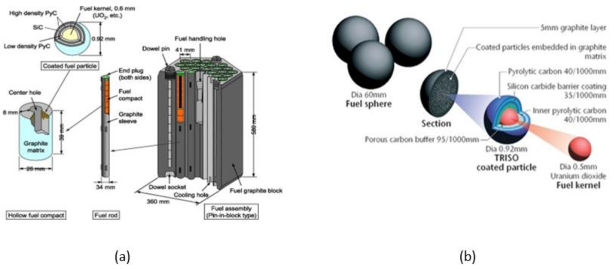


Figure 1. Types HTGR: (a) Prismatic type (Kuniyoshi, 2017); (b) Pebble bed type (Malin, 2013).

Fuels for prismatic and pebble beds HTGR both use the concept of coated fuel particle (CFP). The use of CFP will significantly increase the reactor's safety margin because uranium or thorium as a fuel will be made in particles of tiny dimensions, 0.5 mm in diameter. Each particle will be coated by three carbon layers, known as Tri- Structural-Isotropic (TRISO). These layers will keep the radioactive elements inside the fuel even in the event of an accident. Several studies regarding the neutronic review of the pebble bed-type HTGR and prismatic-type HTGR have been conducted (Irwanto et al., 2019; Pratama & Irwanto, 2020). The present study aimed to study the effect of the amount of coated fuel particles on the 25 MWt pebble-bed type HTGR reactor design using thorium fuel. Several important neutronic parameters in the operation of a reactor, such as the effective multiplication factor, the amount of fuel enrichment, the utilization of the fissile material, and the density of the fissile material formed, will be calculated and analyzed.

Method

here are currently two HTGR operating units, namely the High-Temperature Engineering Test Reactor (HTTR) in Japan and the High-Temperature Gas-cooled Test Reactor (HTR-10) in China. HTTR is a prismatic type of HTGR, while HTR-10 is a pebble bed type of HTGR. In this study, the design of the reactor was made by taking the basic design of HTR-10 (IAEA, 2003), which was then modified to obtained the desired characteristics. Table 1 shows the HTGR design used in this study.

Table 1. Reactor Design Specifications

Parameters	Value	Unit
Power reactor	25	MWt
Active core radius	90	cm
Active terrace height	180	Cm
Reflector thickness	100	cm

The coated fuel particle uses Thorium-based fuel with U-233 as the fissile material that will undergo fission reactions. This study assumed that the enrichment of U-233 was obtained from the reaction of Th-232 with neutrons, which were then used to enrich the fissile material in the fuel. Specifications for coated fuel particles can be seen in Table 2.

Table 2. Coated Fuel Particle Specifications

Parameters		Value	Unit
- Fuel kernel radius		0.25	mm
- The first layer (porous carbon buffer)	Thickness	0.09	mm
	Density	1.1	g/cm^3
- The second layer (inner Pyrolytic Carbon)	Thickness	0.04	mm
	Density	1.9	g/cm^3
- The third layer (SiC)	Thickness	0.035	mm
	Density	3.18	g/cm^3
- The fourth layer (PyC)	Thickness	0.04	mm
	Density	1.9	g/cm^3

To get the neutronic parameters from the HTGR design, the MVP / MVP-BURN computer code is used (Nagaya, et al., 2004; Nagaya et al., 2005). The MVP/ MVP-BURN computer code was developed by the Japan Atomic Energy Agency (JAEA) based on the Monte Carlo method for solving the neutron transport equation. The output of this code includes important neutronic parameters such as the effective multiplication factor, neutron flux, and material density based on the burnup chain used. The nuclear data used in this study is the Japan Evaluated Nuclear Data Library (JENDL) (Shibata et al., 2002).

Result and Discussion

To find out the characteristics of the system, especially the effect of the U-233 fissile enrichment- on the effective multiplication factor and the amount of burnup (GWD / Ton), a series of calculations were carried out with different enrichment values of 1-20%. The maximum limit of 20% is taken because it is a limit value for the enrichment of fissile material permitted in commercial reactors.

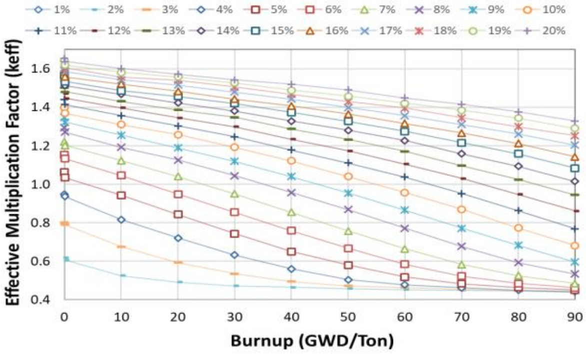


Figure 2. Parametric survey of the effect of the fissile enrichment on the effective multiplication factor and burnup value.

Data obtained from the calculations show that for the reactor specifications, as shown in table 1, at least 13% fissile enrichment is required to obtain a minimum burnup value of 80 GWD/Ton while maintaining the reactor critical condition, as shown in Figure 2. Fissile enrichment value less than 13% gave a reactor criticality value below 1.0 when it reached the burnup value of 80 GWD/Ton. Meanwhile, the fissile enrichment greater than 13% will provide a reactor criticality value above 1.0 when the burnup value is 80 GWD/Ton. Still, the enrichment process of fissile material is complicated and requires high costs. The smaller the enrichment value needed to meet the target of reactor operation, the better the economic value is obtained.

The calculation results provide important information on the effect of the amount of coated fuel particle fraction on important neutronic parameters, namely the effective multiplication factor and burn up. Figure 3 shows that the optimal value is the coated fuel particle fraction of 15%, which consistently provides the largest effective multiplication factor value for the average burnup level, ranging from 100MWD/Ton to 90 GWD/Ton.

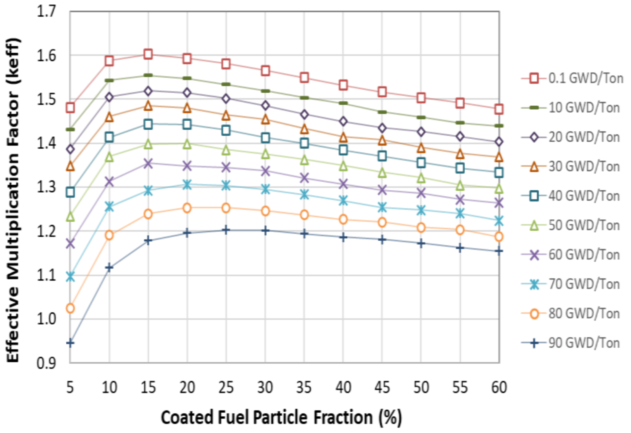


Figure 3. Effect of coated fuel particle on the effective multiplication factor and burnup value.

The high effective multiplication factor value for the coated fuel particle fraction of 15% is influenced by the composition of the fuel and the moderator. It is the fraction of coated fuel particles in the fuel ball that will determine the ratio of the amount of fuel and moderator in the reactor core, which will determine the level moderation of the fission product neutrons.

Naturally, neutrons produced from fission reactions have a high energy level. Sufficient moderation is required to reduce neutron's energy level to be classified as a low-value thermal energy level. Looking at the fission cross-section of U-233, the cross-section value will be high for low energy levels, meaning that fission reactions will be more likely to occur when neutrons have low energy levels.

For high energy neutrons, the fission reaction's cross-section value will be low, so that the fission reaction will be more difficult to occurs when the neutron has a high energy value. In this situation, the level of neutron moderation, which is also determined by the ratio of the amount of fissile material and the amount of moderating material (graphite), is important, so the composition of the amount of fissile material and the number of moderators is important to optimize the neuronic parameters of a reactor design. The reactor design with specifications, as shown in Tables 1 and 2, the value of the layered fuel particle fraction, which provides the optimal neutronic aspect value of 15%.

This fissile material utilization value, U-233, is an important parameter in the operation of the Pebble Bed Reactor, which uses the concept of coated fuel particles in its fuel. The large utilization value of the U-233 will increase the economical use of fuel in the reactor core, considering that coated fuel particle is difficult to reprocess.

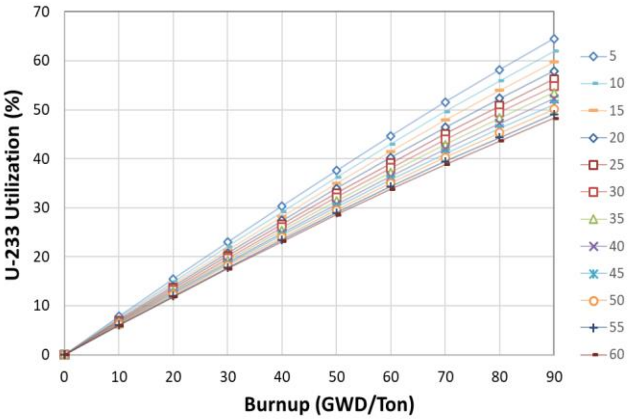
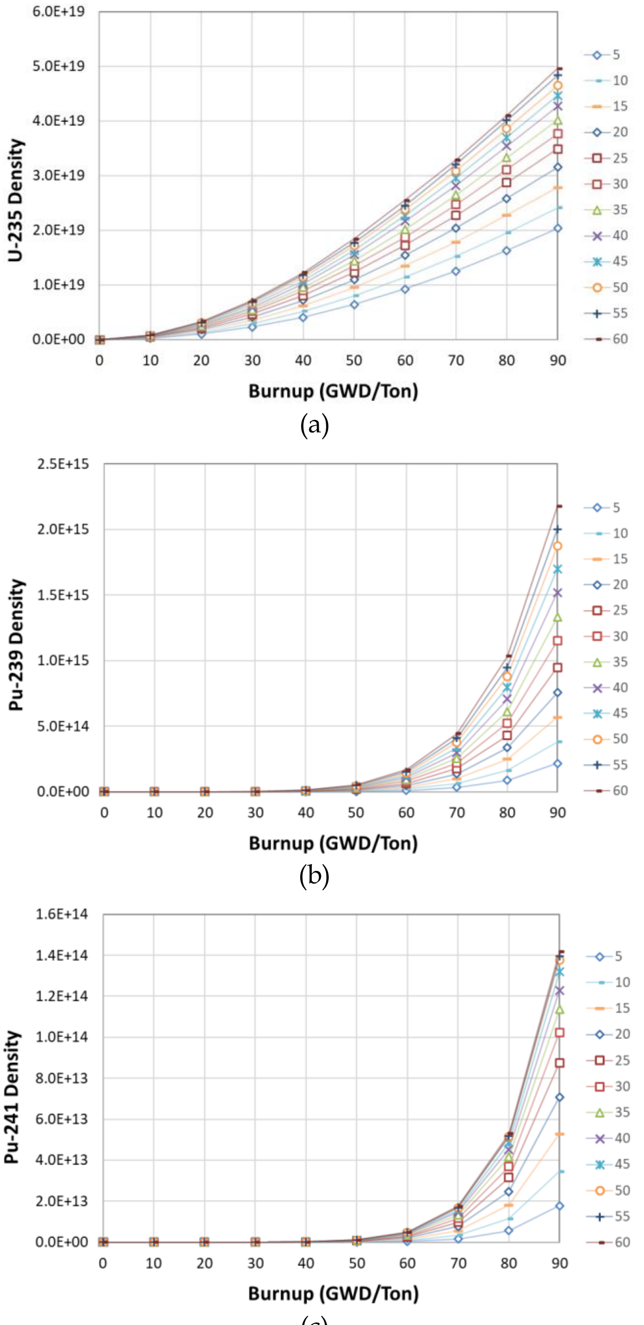


Figure 4. Utilization of U-233 fissile material against the number coated fuel particle and burnup values.

The total utilization of U-233 fissile material against the coated fuel particle fraction and the burnup value is shown in Figure 4. From this data, it is found that the coated fuel particle fraction is 15%, which is the optimal value giving the U-233 utilization value of 54% for 80 GWD burnup value/Ton and 59.8% for the burnup value of 90 GWD/Ton.

The utilization value of U-233 is more significant than all the utilization values produced by the coated fuel particle fraction of 20% - 60% and only smaller than the coated fuel particle fraction of 5% and 10%, which respectively provide a utilization value of 64.5% and 62.0%.



(a)

(b)

(c)

Figure 5. The density of the formed fissile material during the operating time of the reactor: (a) U-235, (b) Pu-239, (c) Pu-241.

Figure 5 shows the density data for the fissile materials U-235, Pu-239, and Pu-241. This fissile material is not provided at the beginning of the reactor's operating period. It can be seen from its density, which is zero at the beginning of the operation. U-235, Pu-239 and Pu-241 fissile materials were formed during reactor operation. This phenomenon is one of the advantages of nuclear reactor technology; the fuel needed to produce energy, namely fissile material required in fission reactions, can be formed during the reactor's operation. From the calculation, it was found that the fissile material of U-235, Pu-239, and Pu-241 began to form significantly when the burnup value was 50 GWD/Ton, then continued to increase. This happens because it takes time for Th-232, which is a fertile material to carry out the reaction, and the burnup chain through which it will turn into fissile material U-235, Pu-239, and Pu-241 after going through several reactions.

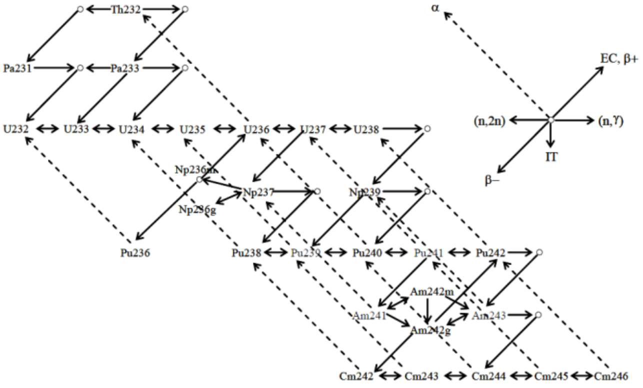


Figure 6. The burnup model for the Thorium chain (Okumura, 2007)

For the coated fuel particle fraction of 5%, it can be seen that number of the fissile materials U-235, Pu-239, and Pu-241 formed is small compared to the coated fuel particle fraction of 10%. It is because the smaller number of fertile material put into the fuel ball, the less fissile material formed from the fertile material. Likewise, on the other hand, the more significant the coated fuel particle fraction that is inserted into the fuel ball, the more fertile material will be available in the reactor core, and the more fissile material U-235, Pu-239, and Pu-241 will form. So it can be seen that the amount of fissile material formed will correspond to the value of the coated fuel particle fraction that is inserted into the fuel ball, starting from the smallest 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55% and the largest is 60%.

Conclusion

In this study, the effect of coated fuel particle fraction on the neutronic aspects of 25 MWt HTGR using thorium fuel has been calculated and analyzed. The parametric survey was conducted to determine the effect of the enrichment value of fissile material on the criticality of the reactor with an enrichment value between 1-20%. It gives an optimal value of enrichment of fissile material of 13%, which will maintain the criticality of the reactor until a burnup value of 80 GWD/Ton. Coated fuel particles were analyzed for a fraction of 5 - 60% at an enrichment value of 13% fissile material. The analysis found that the value of the coated fuel particle fraction of 15% gave the optimal value of the effective multiplication factor of this reactor with the utilization of U-233 fissile material of 59.8%. The knowledge gained from this research is expected to be valuable information in designing small power HTGR to be implemented in remote areas.

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