Neutron Fluence And DPA Rate Analysis In Pebble-Bed HTR Reactor Vessel Using MCNP

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Abstract. In the Pebble-bed HTR reactor, the distance between the core and the reactor vessel is very close and the media inside are carbon and He gas. Neutron moderation capability of graphite material is theoretically lower than that of water-moderated reactors. Thus, it is estimated much more the fast neutrons will reach the reactor vessel. The fast neutron collisions with the atoms in the reactor vessel will result in radiation damage and could be reducing the vessel life. The purpose of this study was to obtain the magnitude of neutron fluence in the Pebble-bed HTR reactor vessel. Neutron fluence calculations in the pebble-bed HTR reactor vessel were performed using the MCNP computer program. By determining the tally position, it can be calculated flux, spectrum and neutron fluence in the position of Pebble-bed HTR reactor vessel. The calculations results of total neutron flux and fast neutron flux in the reactor vessel of 1.82x10^8 n/cm^2/s and 1.79x10^8 n/cm^2/s respectively. The fast neutron fluence in the reactor vessel is 3.4x10^17 n/cm^2 for 60 years reactor operation. Radiation damage in stainless steel material caused by high-energy neutrons (> 1.0 MeV) will occur when it has reached the neutron flux level of 1.0x10^24 n/cm^2. The neutron fluence results show that there is no radiation damage in the Pebble-bed HTR reactor vessel, so it is predicted that it will be safe to operate at least for 60 years.

Keywords: Pebble-bed HTR reactor, fast neutron fluence, radiation damage, reactor vessel.

1. Introduction
Neutron flux and neutron spectrum and neutron fluence in the core and in the reactor vessel are the important parameters in reactor technology and safety. If the characteristics of these parameters have been determined accurately, the other important parameters of the nuclear reactor could be analyzed to ensure the sustainability and safety of the reactor operation. In this study is to analyze neutron fluence in the pebble-bed HTR reactor vessel using MCNP program [1]. In the previous research, neutron spectrum analysis has been done in the core and in the PWR reactor vessel using MCNP [2-4]. In addition, the neutron flux and the neutron spectrum analysis in the core and in irradiation facilities of the RRI-50 concept reactor have been conducted using MCNP program [5]. Based on this experience, this paper presents the results of research related to neutron fluence analysis in the pebble-bed HTR reactor vessel. This study has to be done because, like the PWR NPP reactor, the distance between the
vessel and the reactor core is very close, but the existing media are graphite and He gas, so it is estimated that there are still many fast neutrons reaching the reactor vessel. The fast neutrons with high-energy (E > 1 MeV) have enough energy to move or displace the reactor vessel material atoms from its lattice position and insert into the adjacent lattice. More and more atoms that move from their lattice positions when accumulated will cause vacancies and are inserted in the adjacent lattice when it accumulates into intertitions. This abnormal material condition at some point will degrade the properties of the material known as radiation damage [6-8]. The purpose of this study was to estimate the magnitude of neutron fluence in the pebble-bed HTR reactor vessel during its lifetime.

The Pebble-bed HTR reactor core is modeled into 5 (five) core segments in the axial direction according to burn-up level. The determination of the level of fuel burn-up is performed using the ORIGEN2.1 program [9]. The composition and geometry size of all components of the reactor becomes the main input in the MCNP. Based on the model, the calculation of neutron flux distribution and neutron spectrum from the reactor core to reactor vessel using MCNP has been carried out successfully. The calculation of the neutron flux distribution and the neutron spectrum is done by utilizing the F5 and/or F4 tally card in the kcode mode. The neutron fluence and atomic displacement rate per atom per year (dpa) were performed based on neutron flux calculation results in HTR Pebble-bed reactor vessel.

2. Methodology

2.1. HTR Pebble-bed Core Modeling

The composition and geometry data of each reactor core component is required to model 3-dimensional HTR Pebble-bed reactor core. The core composition and other components of the Pebble-bed HTR reactor are based on the reactor specification data contained in Table 1.

| Parameters                                      | Values   |
|-------------------------------------------------|----------|
| Core radius, cm                                 | 90       |
| Critical core height, cm                        | 123.06   |
| Height of core cavity, cm                       | 221.818  |
| Operational core height, cm                     | 197      |
| Height of conus, cm                             | 36.946   |
| Outer diameter of graphite reflector, cm        | 380      |
| Height of graphite reflector, cm                | 610      |
| Radius of fuel discharge tube, cm               | 25       |
| Height of fuel discharge tube, cm               | 610      |
| Diameter of fuel pebble, cm                     | 6.0      |
| Thickness of buffer layer, cm                   | 0.009    |
| Thickness of IPyC layer, cm                     | 0.004    |
| Thickness of SiC layer, cm                      | 0.0035   |
| Thickness of OPyC layer, cm                     | 0.004    |
| Uranium fuel loading, g/bola                    | 5        |
| Density of graphite matrix in fuel pebbed, g/cm³| 1.73     |
| Boron in fuel element, ppm                      | 1.3      |
| Density of graphite matrix in reflector, g/cm² | 1.76     |
| Density of boron in reflector graphite, ppm    | 4.8366   |
| Ratio of O to U in kernel                       | 2.0      |
| Density of buffer, g/cm³                        | 1.1      |
| Density of IPyC layer, cm                       | 1.9      |
| Density of SiC layer, cm                        | 3.18     |
| Density of OPyC layer, cm                       | 1.9      |
| Boron in kernel, ppm                            | 4        |
| Boron in dummy pebble, ppm                      | 0.125    |
Boron in carbon bricks, atom/b-cm | 3.46349e-3
---|---
Pebble packing fraction | 0.61

The reactor core with a nominal power of 10 MWth is divided into 5 (five) segments in the axial direction with the difference of the fuel burn-up level to approximate the actual conditions. Each segment at beginning of cycle (BOC) condition, starting from the uppermost segment is assumed as fresh fuel, then the second segment underneath has been burned 2320 mega watt days (MWD) and so on until the fifth segment has been burned as much as 9280 MWD. At the end of cycle (EOC), the top segment has been burned as much as 2320 MWD and so on until the fifth segment has been burned 11600 MWD. The calculation of the composition of the burned fuel including the activation, actinide and daughters and fission products corresponding to all segments is carried out using the ORIGEN2.1 program [9].

The calculation of the criticality and distribution of neutron flux and neutron spectrum is accomplished by meeting the success criteria of MCNP program results such as relative error (RE) <0.05, variance of the variance (VOV) <0.1 and figure of merit (FOM): fixed. If the criterion has not been reached, then the calculation is repeated by adding the number of particles or the cycle number on the kcode card until the criteria are met. Criticality calculations and the distribution of neutron flux and neutron spectrum on the Pebble-bed HTR reactor core using MCNP program with a cross-section library compiled from ENDF/B-VII.1 [10-15] for neutrons, protons and photo-nuclear interactions for up to 100 MeV.

2.2. Calculation of Neutron Flux Distribution and Spectrum
The neutron flux and neutron spectrum distribution analysis in HTR Pebble-bed reactor were conducted in radial direction starting from the reactor core axis. The neutron flux distribution analysis was carried out in 4 energy groups, i.e. thermal neutrons (E < 0.625 eV), epithermal neutrons (0.625 eV < E < 5.53 keV), advanced neutrons (5.53 keV < E < 0.1 MeV) and fast neutrons (E > 0.1 MeV). The analysis of the neutron spectrum was carried out as much as 640 [10,15-20] energy groups according to the structure of available energy groups in the cross-section library ranging from 10^{-11} MeV to 20 MeV. The calculation of the neutron flux distribution and the neutron spectrum is carried out by meeting the criteria of accuracy as described above. Analysis of neutron flux distribution and neutron spectrum is done by utilizing F4 and/or F5 tally cards in kcode mode. The results obtained from the MCNP are still in normalized flux values, and a conversion factor is needed to obtain the absolute neutron flux value. The magnitude of the conversion factor is obtained by the equation: [1]

\[ FM = 3.15E10 \times \frac{P \eta}{k_{eff}} \]  
(1)

with:
P = reactor power (10 MWth),
\( \eta \) = neutrons produce in one fission reaction,
k_{eff} = neutron multiplication factor,

2.3. Neutron Fluence and Displacement per Atom (dpa) Calculations
The neutron fluence in the reactor vessel is the multiplication between the neutron flux and the duration of the reactor operation. Radiation damage in stainless steel materials caused by high-energy neutrons (> 1.0 MeV) could occur when neutron fluence has exceeded the levels of \( 1.0 \times 10^{24} \text{n/cm}^2 \) [10,12]. Displacement per atom (dpa) is an atom that moves from its lattice position because it is exposed to radiation that has considerable energy. However, the calculation of the rate of dpa per second is theoretically carried out using the equation:

\[ dpa = \int_{0}^{\infty} \phi(E) \sigma_{dpa}(E) dE \]  
(2)
where:
\[ \phi(E) = \text{differential neutron flux density, } \text{n/cm}^2/\text{s}/\text{MeV}. \]
\[ \sigma_{dpa}(E) = \text{cross-section of displacement per atom, } \text{cm}^2. \]

3. Results and Discussion

3.1. HTR Pebble-bed Core Modeling

The results of tracing the HTR pebble-bed core data in the form of reactor specifications tabulated in Table 1 above. As can be seen in Table 1, the radius and height of the active core during operation and cone height underneath the pebble-bed HTR reactor is 90 cm, 197 cm, and 36.946 cm respectively. The 3-dimensional model of the pebble-bed HTR reactor core including reactor vessel can be seen in Figure 1. At BOC condition, the core segments burn-up have been calculated using the ORIGEN2.1 program, starting from the top position are the 1st, 2nd, 3rd, 4th, and 5th segments are 0%, 11.2%, 20.1%, 27.7%, and 34.5% respectively. At EOC condition, the 1st, 2nd, 3rd, 4th, and 5th segments burn-up are 11.2%, 20.1%, 27.7%, 34.5%, and 40.6%. All of these fuel compositions are taken into account in the analysis including activation, actinide and daughters and fission products are about 137 elements and actinide isotopes correspond to the level of its burn-up.

The 3-dimensional core model including reactor vessel has been made based on geometry data and composition of the core and other components. As shown in Figure 1, each reactor core segment is modeled in homogeneous form. The reactor core is surrounded by a neutron reflector made of graphite. The outside of reflector is covered with stainless steel barrel. All of the core components are inside the stainless steel reactor vessel.

![Figure 1. The model of the HTR Pebble-bed core to the reactor vessel.](image)

The result criticality calculations of HTR Pebble-bed in operational condition with 197 cm core height resulted in effective neutron multiplication factor at BOC and EOC are 1.08586±0.00018 and 1.04257±0.00017 respectively. This result can be reasonably believed to be true because the calculation of k-eff in critical condition with a 123.06 cm core height is 0.99673±0.00039 which is very close to 0.9973 of benchmark results for HTR-10 [21]. The above calculation still assumes that the entire control rod is pulled out from the reactor core. Thus it can be seen that the HTR Pebble-bed core model could be considered true.
3.2. Neutron Flux Distribution and Neutron Spectrum

Calculation of neutron flux distribution and neutron spectrum in Pebble-bed HTR reactor core using MCNP program based on the model that has been made. MCNP program simulation is conducted using kcode card option with 5000 particles as much as 5000 cycles with additional 100 cycles skipped to obtain good statistical accuracy and meet the success criteria of analysis result.

The calculation results of neutron flux distribution in the HTR pebble-bed reactor core with the power of 10 MWth is plotted in Fig. 2. The thermal and epithermal neutron flux value in the reactor core is around $3.5 \times 10^{13} \text{n/cm}^2\text{/s}$ and almost evenly distributed towards the radial direction. Fig. 2 shows that epithermal neutron flux with energy $0.625 \text{eV} < E < 5.53 \text{keV}$ is slightly higher than that of thermal neutron flux. It shows that neutrons in the reactor core are a little bit less moderated. The thermal neutron flux ($E < 0.625 \text{eV}$) is highest compared to the epithermal neutron flux and the fast neutrons in the reflector region. It shows that neutrons have been well moderated in the reflector region until a distance of about 170 cm from the core axis.

![Figure 2](image)

**Figure 2.** Radial neutron flux distribution from Pebble-bed HTR core to reactor vessel.

In Fig. 2 it can be seen that the thermal neutron flux has a considerable decrease in barrel media and so do in the reactor vessel. It is because of the stainless steel material in the core barrel and the reactor vessel has high neutron absorption cross-section. In the area between the barrel and the reactor vessel containing the He gas cooler, the thermal neutron flux is slightly increased. This is due to the accumulation of thermal neutron flux as a result of moderation of fast neutron, intermediate neutrons and epithermal in the reflecting medium entering the region between the core barrel and the reactor vessel.

In Fig. 2 it is also seen that the fast neutron flux that reaches the reactor vessel is still quite high. That is because the distance between the reactor core and the reactor vessel is relatively close so that many fast neutrons are not yet moderated perfectly become lower energy neutrons. The exposure of fast neutron fluence with energy more than 1.0 MeV during its lifetime when reaching the order of $1 \times 10^{24} \text{n/cm}^2$ [10,12] can cause radiation damage to the reactor vessel.
The results of neutron spectrum calculations in the core and in the Pebble-bed HTR reactor vessel using the MCNP program are plotted in Fig. 3. The calculation of the neutron spectrum uses a neutron energy group structure of 640 groups [10,15-20] taken from the energy distribution in the cross-section library. When compared to the neutron spectrum in the core (Fig. 3), the neutron spectrum in the reactor vessel has been distorted because it has been absorbed by the materials it passes including by the reactor vessel itself. The calculation results of thermal neutron flux and fast neutron flux in the reactor core are $3.5 \times 10^{15}$ n/cm$^2$/s and $1.5 \times 10^{13}$ n/cm$^2$/s respectively. While the thermal neutron flux and fast neutrons in the reactor vessel are $1.82 \times 10^8$ n/cm$^2$/s and $1.79 \times 10^8$ n/cm$^2$/s. The thermal neutron flux in the reactor vessel decreased more than the fast neutrons significantly. The greater amount of thermal neutron flux decreasing indicates that there are many thermal neutrons absorbed in the medium through which it travels. The fast neutron decreasing in the reactor vessel is not as much as the decreasing of thermal neutron flux which suggests that the process of moderation and fast neutron absorption is not as much as the absorption of thermal neutrons in the medium through which it travels. This is a characteristic of Pebble-bed HTR reactor core that uses graphite as a moderator. Compared with a water-based reactor (H2O) as a moderator, the moderation process of the fast neutron on the reactor core with graphite moderator is not as much as on the water-moderated reactor core.

### 3.3. Neutron Fluence and dpa rate Calculation Results in the Reactor Vessel

The calculation results of the thermal and fast neutron flux in the Pebble-bed HTR reactor vessel described above are $1.82 \times 10^8$ n/cm$^2$/s and $1.79 \times 10^8$ n/cm$^2$/s respectively. For 1-year reactor operation, the thermal and fast neutron fluence in the reactor vessel is $5.75 \times 10^{15}$ n/cm² and $5.65 \times 10^{13}$ n/cm² respectively. When the reactor is operated for 60 years, the fast neutron fluence in the reactor vessel is $3.4 \times 10^{17}$ n/cm². That neutron fluence is still very small compared to the fluence limit of $1.0 \times 10^{24}$ n/cm². That fact is making it safe to operate the reactor for 60 years or even longer.

The dpa cross-section for SS-316 stainless steel material is plotted in Fig. 4. In Fig. 4, the dpa cross-section is quite high at low energy and decreases sharply and rise again at higher energy with the lowest energy of about $5 \times 10^{-4}$ MeV. While the neutron flux in thermal energy in the reactor vessel (Fig. 3) is very low that the calculation results dpa rate becomes small. The result of calculation of annual dpa rate caused by fast neutron flux in reactor vessel using equation (2) is $2.6 \times 10^{6}$. The annual dpa rate contribution caused by the epithermal and thermal flux neutrons in the reactor vessel is $2 \times 10^7$. The magnitude of total dpa in the Pebble-bed HTR reactor vessel during even 60 years of operation is a very small ($1.7 \times 10^{12}$) for the occurrence of radiation damage.

![Figure 3. Neutron spectrum in the Pebble-bed HTR core and in reactor vessel.](image-url)
4. Conclusion
Fast neutron fluence with energy above 1.0 MeV in a Pebble-bed HTR reactor vessel during 60 years of operation is $3.4 \times 10^{17}$ n/cm$^2$ which is a small fraction of the threshold of radiation damage ($1.0 \times 10^{24}$ n/cm$^2$). The annual dpa rate in the Pebble-bed HTR reactor vessel is very small ($2.6 \times 10^{-6}$). The total dpa in the reactor vessel during 60 years of operation is $1.7 \times 10^4$ for the occurrence of radiation damage. It could be concluded that the Pebble-bed HTR reactor vessel is safe from radiation damage for the operation of 60 years or even more.

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![Figure 4. Dpa cross-section for SS316 stainless steel. [10]](image)
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