Impact of Different Nuclear Data Library on Control Rod Reactivity Worth Calculation of Small Pebble Bed Reactor

Suwoto*, H Adrial, T Setiadipura, Zuhair, and S Bakhri

Center for Nuclear Reactor Technology and Safety National Nuclear Energy Agency of Indonesia Kawasan Puspiptek Gd.80, Serpong, Tangerang Selatan, Banten, Indonesia
Phone:+62(21)7560912,
*Corresponding author: suwoto@batan.go.id

Abstract. One of the main critical issues on a nuclear reactor is safety and control system. The control rod worth plays an important role in the safety and control of nuclear reactors. The control rods worth calculation is used to specify the safety margin of the reactor. The main objective of this work is to investigate impact of different nuclear data libraries on calculating the control rod reactivity worth on small pebble bed reactor. Calculation of the control rod reactivity worth in small high temperature gas cooled reactor has been conducted using the Monte Carlo N-Particle 6 (MCNP6) code coupled with a different nuclear data library. Famous evaluated nuclear data libraries such as JENDL-40u, ENDF/B-VII.1 and JEFF-3.2 continuous cross-section-energy data libraries were used. The overall calculation results of integral control rod worth show that the ENDF/B-VII.1, JENDL-40u and JEFF-3.2 files give values of -17.814% k/k, -18.0204% k/k and -18.0267% k/k, respectively. Calculations using ENDF/B-VII.1 give a slightly lower value than the others, while the JENDL-4.0u file gives results that are close to JEFF-3.2 file. The different nuclear data libraries have a relatively small impact on the control rod worth of small pebble bed reactor. Accurate prediction by simulation of control rod worth is very important for the safety operation of all reactor types, especially for new reactor designs.

Keywords: Control rod worth, pebble bed reactor, MCNP6, ENDF/B-VII.1, JENDL-40u, JEFF-3.2

1. Introduction
One of the main critical issues on a nuclear reactor is safety and control system. In high temperature gas cooled reactor (HTGR) type small pebble bed reactor designs, only the reflector control rods are used for reactivity control [1]. The main purpose of a reactivity control system is to get the desired level of output power from the system, to maintain at the desired power level, and turn it off during routine reactor operation [2]. Neutron absorber rods are installed in most reactors to provide adjustable reactivity control. This absorber rod can be inserted or withdrawn from the reactor core [3].

The control rod has the maximum effect if it is placed in the reactor where the flux is maximum [2]. The exact amount of reactivity that is inserted per control rod depends on the design of the reactor. Changes in reactivity caused by control rod movements are referred to as control rod worth. Integral control rod worth is the total reactivity worth of the rod at a certain withdrawal level [3]. The differential control rod worth is the change in reactivity per unit of rod and is usually expressed as ρ/cm, and is measured by Δk/k per cm, or pcm/cm.
However, sufficient calculation efforts using sophisticated methods such as the Monte Carlo method have not been conducted in this small pebble bed reactor, especially in calculating the control rod worth. In this report, the Monte Carlo calculation for control rod worth of a small pebble bed reactor core will be presented, because one of the main issues of a nuclear reactor is safety and control system.

The main objective of this work is to investigate impact of different nuclear data libraries on calculating the control rod reactivity worth on small pebble bed reactor. In this paper, the control rod reactivity worth (CRW) of small pebble bed reactor is presented. All calculations were performed using the Monte Carlo N-Particle MCNP6[4] code combined with a variety of different continuous energy cross-sections taken from the ENDF/B-VII.1[5], JENDL- 40u [6]and JEFF-3.2 [7] files.

2. Description of Small Pebble Bed Reactor

Indonesia through BATAN and its stakeholders have been carried out the design a small pebble bed reactor called Reaktor Daya Eksperimental (Experimental Power Reactor), one of the GEN-IV type reactors. This type of small modular variety will be very suitable for remote islands in Indonesia. The RDE reactor is designed to generate 10 MW thermal power and produce a core output temperature of around 700 °C and around 3 MWe of electricity. The Indonesian Experimental Power Reactor (RDE) [8,9] is a type of the fourth-generation reactor, a type of high temperature reactor cooled by helium. RDE refers to the design and technology of the German High Temperature Gas-cooled Reactor (HTR-Module) which is applied to HTR-10 in China and has inherent safety features [10]. RDE is designed using TRISO coated fuel particles [11] which are dispersed in a spherical fuel with a radius of 3 cm known as pebble. Theoretically, RDE reactor can use TRISO-coated fuel particles with kernels containing uranium dioxide as well as thorium dioxide without changing the shape and size of the reactor geometry [9]. The fuel and core design parameters of small pebble bed reactor are displayed in Table 1.

**Table 1. Core and fuel data parameter of small pebble bed reactor (RDE) [9,13]**

| Reactor Core Parameter                             | Value                  |
|---------------------------------------------------|------------------------|
| Thermal Reactor Power, MW                         | 10                     |
| Equivalent Core Radius, cm                        | 90                     |
| Equivalent Core Height, cm                        | 197                    |
| Reactor Core Volume, cm3                          | 5                      |
| Volumetric filling fraction of balls in the core, %| 61                     |
| Height of the empty cavity above the pebble bed, cm| 41.7                   |
| Radius of fuel discharging tube, cm               | 25                     |
| TRISO Coated Fuel Particle (CFP)                  |                        |
| Fuel kernel material                              | UO₂                    |
| Kernel diameter, cm                               | 0.05                   |
| Enrichment of U-235, %                            | 17                     |
| Kernel density, g/cm³                             | 10.4                   |
| Coating layer material from inside                | C/IPyC/SiC/OPyC        |
| Coating layer thickness, cm                       | 0.095/0.040/0.035/0.04 |
| Coating layer density (g/cm³)                     | 1.1/1.90/1.38/1.90     |
| Spherical Fuel Pebble                             |                        |
| Diameter of fuel pebble, cm                       | 6                      |
| Diameter of fuel zone, cm                         | 5                      |
| Thickness of graphite outer shell                 | 0.5                    |
| Heavy metal (uranium) loading (weight) per ball, g | 5                      |
| Density of graphite in matrix and outer shell, g/cm³| 1.73                   |
2.1 Design and Modeling of Control Rod

One of the main safety components of RDE is the control rod. Ten control rods function to control the fission reaction in the reactor, where each control rod consists of five boron carbide ring segments [14]. Each control rod is located 102.5 cm from the center and placed on the side of the reflector. The inner and outer diameter of the ring is 6 cm and 12 cm. The reactor is designed with a high level of safety.

The RDE reactor has ten control rods located in ten channels on the side of the reflector in a vertical position and uniformly distributed encircling the reactor core. This control rod system is designed to work at high temperatures, high radiation and in the helium environment. Control rod material made from Boron Carbide (B₄C) with a density of 1.7 g/cc composed of Carbon 20 %w, B-10 15.84 %w and B-11 64.16 %w is used as neutron absorber [15].

| Table 2. Main data of detail geometry and material specification of control rod [14-16] |
|---------------------------------------------------------------|
| Number of Control Rod (identically) | 10               |
| Length of control rod, cm                      | 275              |
| Radial position of channel center, cm          | 102.1            |
| Control Rod channel diameter, cm               | 13               |
| Neutron absorber material                      | B₄C              |
| Density of Boron Carbide (B₄C), g/cm³          | 1.7              |
| Helium Channel radius, mm                      | 27.5             |
| ID ring Boron Carbide (B₄C), cm                | 6.0              |
| OD ring Boron Carbide (B₄C), cm                | 10.5             |
| Number of segments B₄C                         | 5                |
| Length of each segment B₄C, cm                 | 48.7             |
| length of each joint, cm                       | 3.6              |
| length of lower and upper metallic end, cm     | 4.5/2.3          |
| Density of steel sleeve (SS), g/cm³            | 7.9              |
| ID/OD inner part of steel sleeves, cm          | 5.5/5.9          |
| ID/OD outer part of steel sleeves, cm          | 10.6/11          |
| Thickness of steel sleeve, cm                  | 0.02             |
| Gap between steel sleeve and B₄C, cm           | 0.05%            |
| Radial zone/thickness, (from center), mm       | He/27.5; SS/2; Gap/0.5; B₄C/22.5; Gap/0.5; SS/2 |
| Axial coordinate of CR lower end → CR          | 394.2            |
| fully inserted, cm                              |                  |
| Axial coordinate of CR lower end → CR          | 119.2            |
| fully withdrawn                                 |                  |
| Chemical composition of steel sleeve SS (%w₀)  |                  |
| element composition                            | weight composition of Steel Sleeve (%w) |
| Cr                                              | 18               |
| Fe                                              | 68.1             |
| Ni                                              | 10               |
| Si                                              | 1                |
| Mn                                              | 2                |
| C                                               | 0.1              |
| Ti                                              | 0.8              |
Each control rod has five B$_4$C ring segments which are housed in the area between an inner and outer sleeve of stainless steel. The steel sleeves housing the neutron absorber material (B$_4$C) are assumed to have a density of 7.9 g/cc. The isotopes composition of steel sleeves are Cr-18%w, Fe-68.1%w, Ni-10%w, Si-1%w, Mn-2%w, C-0.1%w, and Ti-0.8%w. These are then connected together by a metallic joint [15].

The inner and outer diameters of the B$_4$C ring are 6.0 cm and 10.5 cm, respectively, while the length of each ring segment is 48.7 cm. The inner/outer diameters of the inner part steel sleeves are 5.5 cm/5.9 cm and of the outer part of steel sleeve are 10.6 cm/11.0 cm. The length of each joint is 3.6 cm. The length of lower and upper metallic end are 4.5 cm and 2.3 cm, respectively [16].

Detailed geometry and specification data of control rod are presented in Figure 1 and Table 2. Figure 1 illustrates the schematic geometry of the RDE control rod. The geometry of the complexity control rod is modeled in detail and explicitly by special treatment in Figure 2.

![Figure 1. Schematic geometry of RDE control rod [15],](image1)

![Figure 2. Modeling and placement location of control rod using MCNP6 code](image2)
3. Calculation Methodology

The calculation of control rod reactivity worth of a small pebble bed reactor performed using the Monte Carlo transport code MCNP6 coupled with several continuous energy nuclear data libraries such as ENDF/B-VII.1, JENDL-4.0u and JEFF-3.2 files. The MCNP6 code provides detailed description capabilities of geometrical elements and a very precise representation of the continuous energy nuclear data cross-sections. Whereas other code (diffusion code) that uses a geometry approach and uses a multi-group cross section library.

MCNP6 is capable of solving the double heterogeneity problem [17,18]. The double heterogeneity model in MCNP6 is built into regular TRISO particles in the pebble fuel and pebble arrangement in the core. The first step is to calculate the total reactivity of the control rod (control rod worth) using all the control rods inserted into the core and the second step is all the control rods withdrawn by the core to calculate the excess reactivity. All calculations use some original nuclear data taken from ENDF/B-VII.1, JENDL-4.0u and JEFF-3.2 files, and the next calculation is using substitution some nuclides such as Boron, Carbon, Oxygen and Uranium in the ENDF/VII.1 file as reference nuclear data library.

3.1. Reactivity coefficients

Core reactivity is the most global parameter that helps to understand the behavior of all types of nuclear reactor. The precise calculation of core reactivity is a major concern of neutron physicists and engineers and the branch of physics that deals with it must be well understood. Defining it is not as easy as it seems at first.

The amount of reactivity (q) in the reactor core determines the manner of neutron population. This term is defined as [19-20]

\[ a = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \]  

(1)

where \( k_{\text{eff}} \) is effective reactor multiplication factor. The reactivity is affected by many factors such as fuel depletion, temperature, or neutron poisons.

3.2. Control Rod Worth

The control rod worth is calculated using the excess reactivity \( q_{\text{es}} \) of the core configuration. The core excess reactivity is calculated according to the global multiplication factor with all control rods withdrawn completely from the core, this is expressed in equation (1)[19].

\[ q_{\text{es}} = \frac{k_{\text{eff}}-CR_{\text{out}} - 1}{k_{\text{eff}}-CR_{\text{out}}} \]  

(2)

Whereas CRW (Control Rod Worth) is calculated using the following formula [3,20-21]:

\[ CRW = q_{\text{es}} - \frac{k_{\text{eff}}-CR_{\text{in}} - 1}{k_{\text{eff}}-CR_{\text{in}}} \left( in \frac{0_k}{k} \right) \]  

(3)

Or simply equation (3) becomes:

\[ CRW = q_{\text{es}} - \frac{k_{\text{eff}}-CR_{\text{out}} - k_{\text{eff}}-CR_{\text{in}}}{k_{\text{eff}}-CR_{\text{out}} \times k_{\text{eff}}-CR_{\text{in}}} \left( in \frac{0_k}{k} \right) \]  

(4)

where:

\( k_{\text{eff}}-CR_{\text{out}} \) = reactivity of the core with all control rods fully withdrawn from the core

\( k_{\text{eff}}-CR_{\text{in}} \) = reactivity of the core with all control rods fully inserted in the core

When a control rod is inserted into a reactor core, it absorbs the surrounding neutrons and results in distortion of the neutron flux distribution. The effect of absorber control rod can be explained by considering a reactor in which the maximum neutron flux is maintained constant, with or without insertion of control rod, as illustrated in Figure 3.
4. Result and Discussions

In order to ensure reactivity control in reactor core operations, a full understanding of neutron physics needed. Achieving a full understanding of the complex physical mechanisms that occur in nuclear power reactor ensures good design and safe operation.

The control rod worth results calculated by MCNP6 combined with several different continuous energy nuclear data file such as ENDF/B-VII.1, JENDL-4.0u and JEFF-3.2 files for fresh core are presented in Table 3. All calculations run on MCNP6 code using 210 cycles including 10 cycles skipped of 5000 particles per cycle to obtain convergent results. The curve calculated from the integral control rod worth (CRW) of small pebble bed reactor (RDE) is particularly important in reactor operation as shown in Figure 4. In Figure 4, this phenomenon shows the reactivity change caused by moving the control rod with the unit distance at a certain height. when the control rod is inserted from the initial reference position to a certain height, the reactivity introduced in the process same as the control rod integral worth at the insertion height.

![Figure 4](image-url)  
**Figure 4.** Calculated curve of Control Rod Worth of small pebble bed reactor (RDE)
The calculation results shown in Table 3 use original data according to each of the mentioned nuclear data files. The results of all CRW calculations give relatively the same results, the ENDF / B-VII.1 file although the CRW value is slightly lower compared to JENDL-4.0u file which is close to JEFF-3.2 file.

Table 3. The global calculated value of effective multiplication factor and CRW from original nuclear data file

| Nuclear Data File Library | $K_{\text{eff}}$ | $K_{\text{eff}}$ | $\rho$ (%Δk/k) | CRW (%Δk/k) |
|-------------------------|----------------|----------------|----------------|--------------|
| ENDF/BVII.1             | 1.11678 ± 0.00084 | 0.93147 ± 0.00098 | 10.4568       | 17.8140373   |
| JENDL-4.0u              | 1.11679 ± 0.00079 | 0.92969 ± 0.00092 | 10.4577       | 18.0203869   |
| JEFF-3.2                | 1.11993 ± 0.00080 | 0.93181 ± 0.00088 | 10.7087       | 18.0267205   |

Meanwhile in Table 4 and Table 5, the results are calculated using the nuclide substitution for U-235, U-238 and O-16 taken from JENDL-4.0u and JEFF-3.2 files, while the rest of the nuclides are taken from ENDF/B-VII.1 file.

Table 4 shows the calculation results of the criticality and CRW values with the nuclide substitution in which the ENDF/B-VII.1 file is retained, while the JENDL-4.0u and JEFF-3.2 files are replaced for kernel fuel nuclides (UO$_2$) such as Uranium (U-235, U-238) and Oxygen (O-16) and other nuclides are taken from the ENDF/B-VII.1 file.

The differences in $K_{\text{eff}}$ value to the ENDF/B-VII.1 standard reference file is 0.073-0.102% and 0.0306-0.260% for the JENDL-4.0u and JEFF-3.2 files, respectively.

Table 4. The effect of nuclide substitution of UO$_2$ (kernel) on $K_{\text{eff}}$ and CRW

| Nuclear Data File Library | $K_{\text{eff}}$ | $K_{\text{eff}}$ | $\rho$ (%Δk/k) | CRW (%Δk/k) |
|-------------------------|----------------|----------------|----------------|--------------|
| ENDF/BVII.1             | 1.11678 ± 0.00084 | 0.93147 ± 0.00098 | 10.4568       | 17.8140373   |
| JENDL-4.0u              | 1.11564 ± 0.00084 | 0.93079 ± 0.00090 | 10.4577       | 17.800970    |
| JEFF-3.2                | 1.11636 ± 0.00087 | 0.92904 ± 0.00086 | 10.7087       | 18.0611529   |

Note: # only nuclides U-235, U-238 and O-16 taken from JENDL-4.0u, $ only nuclides U-235, U-238 and O-16 taken from JEFF-3.2

The fission cross-section of U-238 in the neutron energy region up to 1.9E4eV is no difference for JENDL-4.0u and 79.79% higher for JEFF-3.2 files, respectively, when compared to U-238 in ENDF/B-VII.1 file, as seen in Figure 5. Meanwhile, for the capture cross-sections there are relatively no significant difference between the three libraries on that neutron energy range.
Figure 5. Fission cross-section of U-238 and their % difference to ENDF/B-VII.1.

For the fission cross-sections of U-235 in the thermal neutron energy region up to the resonance energy region, there are no significant differences between another nuclear data libraries, while differences begin to occur in energy regions above 475eV, as seen on Figure 6. The difference respect to ENDF / B-VII.1 file is -9.6% to 14.75% and -6.7% to 12.85% for JENDL-4.0u and JEFF-3.2 files, respectively.

As for the elastic cross-section of O-16 in the thermal neutron energy region is lower by 58.6% for JENDL-4.0u and JEFF-3.2 files, respectively, when compared to the ENDF/B-VII.1 standard reference file, while for other neutron energy regions each about 83% lower.
Figure 6. Fission cross-section of U-235 and their % difference to ENDF/B-VII.1.

So, from the above explanation can illustrate the results of calculating the value of the effective multiplication factor with the ENDF/B-VII.1 standard reference file slightly higher than the JENDL-40u and JEFF-3.2 files as listed in Table 4. Differences in nuclear data library have little impact on the control rod worth (CRW) are shown around -0.07% to 1.39% differences.

Table 5 shows the results of the criticality and CRW calculations with nuclear data substitution, ENDF/B-VII.1 is maintained, while JENDL-4.0u and JEFF-3.2 are substituted for Carbon and Boron nuclides (B-10, B-11), and the remaining nuclides from the ENDF/B-VII.1 standard reference file.

Table 5. The effect of nuclides substitution of Carbon and Boron on $K_{eff}$ and CRW

| Nuclear Data File Library | $K_{eff}$-CRout | $K_{eff}$-CRin | $\rho$ (\%$\Delta k/k$) | CRW (\%$\Delta k/k$) |
|---------------------------|-----------------|----------------|-------------------------|---------------------|
| ENDF/B-VII.1              | 1.11678±0.00084 | 0.93147±0.00098 | 10.4568                 | 17.8140373        |
| JENDL-4.0u                | 1.11465±0.00090 | 0.92824±0.00085 | 10.4577                 | 16.86827744       |
| JEFF-3.2                  | 1.11885±0.00089 | 0.93202±0.00097 | 10.7087                 | 17.91634908       |

Note: # only nuclides U-235, U-238 and O-16 taken from JENDL-4.0u,
$ only nuclides U-235, U-238 and O-16 taken from JEFF-3.2
The change in CRW values in Table 5 that occurred in the JENDL-4.0u file is caused by the elastic cross section of the Carbon nuclide which is relatively lower by about 30% in the thermal energy region and increases to 326% in the energy of about 425 keV compared to the ENDF/B-VII.1 and JEFF-3.2 files without significant differences as seen in Figure 7. The different nuclear data libraries have a relatively small impact on the control rod worth (CRW) shown around -5.31% to 0.57% differences.

The differences in $K_{\text{eff}}$ value to ENDF/B-VII.1 is 0.073-0.102% and 0.0306-0.260% for the JENDL-u and JEFF-3.2 files, respectively. So that the impact of different nuclear data libraries has little effect on differences in the calculation of the control rod worth (CRW).

So, from the above explanation it appears that the quality of the cross-section data library affects the calculation results obtained. Therefore, because the difference in the value of CRM is very small (around 1% $\Delta k/k$) so shrewdness in selecting the right nuclear data library is needed in these calculations.
5. Conclusion
Accurate prediction of control rod worth is very important for the safety operation of all nuclear reactors. Investigation on the impact of different evaluated nuclear data libraries on the reactivity of control rod worth calculation on small pebble reactor has been performed. The results of the overall calculation of the integral control rod worth show that the file ENDF/B-VII.1, JENDL-40u and JEFF-3.2 give values of -17.814%dk/k, -18.0204%dk/k and -18.0267%dk/k, respectively. The calculation results show that different nuclear data libraries have a relatively small impact on the control rod worth (CRW) on small pebble bed reactor. This result implies that some differences on result calculation caused by some cross-sections that used in CR material especially in carbon and boron nuclides.

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12

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