Analysis of Heavy Metal Loading Optimization Through Criticality Calculation on RDE

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Abstract. The RDE (Indonesian Experimental Power Reactor) designed to produce 10 MW thermal with cylindrical core. The HGTR (High Temperature Gas-cooled Reactor) reactor technology with passive inherent safety is adopted. This RDE reactor core is designed to produce high temperature output range about 700°C, making it particularly suitable for cogeneration purposes such as electricity, desalination water production and industrial high temperature heat application. The improvement of performance and neutronic safety design parameter which strongly affects to the neutron moderation ratio such as the HM (Heavy Metal) loading optimization is important to ensure that. Therefore HM loading through the criticality calculation of the RDE reactor core using VSOP’94 code and MCNP6 coupled with ENDF/BII library is performed. Calculations using VSOP’94 code utilize DATA-2, ZUT-DGL, BIRGIT and VSOP-CITATION modules, whereas the calculations with MCNP6 start from the TRISO kernel modeling, fuel pebble and 3-D full core modeling. The optimization of HM loading calculation on core criticality is done through simulating of the heavy metal loading (HM) variation level from 1-15 gHM/pebble using several enrichment of $^{235}$U from 8%, 10%, 12% 14% and 17% using VSOP’94 and MCNP6 code through RDE core criticality with good results. The smallest difference of effective multiplication factor on RDE core criticality (below 1%) between two calculations with VSOP’94 and MCNP6 occurs at the HM loading level of 5 gHM/pebble at all $^{235}$U enrichment levels. At 17% enrichment, a similar trends to other enrichment, gives the maximum core criticality on HM loading of 8 gHM/pebble with effective multiplication factor of 1.17860 and 1.22458, respectively for VSOP’94 and MCNP6 with a difference of -3.75476%. As for HM loading 5 gHM/pebble calculations using VSOP’94 and MCNP6 each gives effective multiplication factor value of 1.16096 and 1.16666, respectively, with a difference of about -0.48857%.

Keywords: RDE, VSOP’94, MCNP6, heavy metal loading, criticality, ENDF/B-VII
1. Introduction

The RDE (Indonesian: Reaktor Daya Eksperimental) reactor is designed to generate 10 MW thermal power and produce core output temperature of approximately 700 °C and about 3 MW of electricity. The Indonesian Experimental Power Reactor (RDE)[1] is one type of the fourth generation reactor, a high-temperature reactor type that is helium-cooled. The RDE refers to the design and technology of Germany’s High Temperature Gas-cooled Reactor (HTR-Module) applied to HTR-10[2] in China and it has inherent safety feature[3]. The RDE is designed using TRISO coated fuel particle[4] spherical-shaped 3 cm diameter fuel known as pebble. Theoretically, RDE can use TRISO-coated fuel particle with kernels containing uranium dioxide[5], plutonium oxide[6] as well as thorium oxide[7-8] without changing the shape and size of reactor geometry.

Previous research has been carried out on neutronic calculations of HTGR pebble-fueled with a power of 200 MWth (RGTT200K) using VSOP’94 code with the results in accordance with comparative calculations using Monte Carlo MCNP5 code[9-10], with the difference of relatively small below than 1%. The effect of water ingress accident on HTGR pebble-bed type reactor has also been carried out[11-12] using MCNP code. The HM loading contain can be adjusted by volumetric packing fraction[13-14] of the coated particles in the fuel zone matrix. The improvement of performance and neutronic safety related to design parameter which strongly affects to the neutron moderation ratio is important through the HM loading optimization. Therefore HM (heavy metal) loading through the criticality calculation of the RDE reactor is done. Despite of previous research in the optimization of HM loading of HTGR in Indonesia, however this research themes have not much been done for RDE. The international collaboration research on loading HM for RDE reactors has not been much, one of which is the paper on alternative fueling schemes for RDE[15]. Therefore the objective of this research is to optimize the HM loading per pebble fuel used in RDE core fuel through calculation of core criticality with various enrichment variations and heavy metal loading per pebble fuel.

The RDE reactor is designed to produce high temperature used for industrial heat processes, in addition to the main product is electricity. The study on optimizing of heavy metal (HM) loading uranium in fuel pebble through criticality calculation only discusses of uranium dioxide (UO$_2$) kernel with $^{235}$U various enrichment of 8%, 10%, 12%, 14% and 17% with HM metal loading which varies from 1 gHM/pebble up to 15 gHM/pebble. All calculations are performed on RDE full core with fresh fuel using VSOP’94 and MCNP6 code owned by BATAN.

VSOP’94 code (Very Superior Old Program - 1994)[16] is a computer software developed in Germany to simulate the operation of high temperature reactors spherical fuel with kernel TRISO-coated fuel particle as well as in the form of prismatic blocks. While the Monte Carlo MCNP program which is now using version 6, is a very powerful computer program in solving various problems, such as reactor criticality, radiation shielding and other problems. Because of MCNP6 code in simulation uses actual geometry without any geometry approach in modeling, so that the results of MCNP6[17] calculations provide more accuracy than the calculations using other diffusion code.

HM loading optimization through RDE core criticality calculation starts from UO$_2$ kernel geometry modeling of TRISO coated particles in pebble fuel and 3-D core modeling along with cones and reflectors. Optimization of HM loading calculations through RDE criticality simulation with variations in UO$_2$ fuel enrichment varying from 8%, 10%, 12%, 14% and 17% with heavy metal (HM) loading ranging from from 1 gHM/pebble to 15 gHM/pebble.

2. Description of Fuel and Reactor Core

Illustrations and technical specifications of the RDE fuel, refer to the geometry of HTR-10[2] fuel of uranium dioxide kernels (UO$_2$) coated with TRISO layer such as porous carbon buffers, inner carbon pyrolytic (iPyC), silicon carbide (SiC) and the outer pyrolytic carbon (oPyC) as illustrated in Fig. 1 and Table 1[18].
Figure 1. Illustration of TRISO-coated fuel particle

| Coated Fuel Particles (cfp) | Remarks |
|-----------------------------|---------|
| Kernel material            | UO$_2$  |
| Kernel diameter, cm        | 0.05    |
| Enrichment, % ($^{235}$U)  | 17      |
| Kernel density, g/cm$^3$    | 10.4    |
| Total diameter of kernel + TRISO, cm | 0.091 |

| Coating layer               |         |
|-----------------------------|---------|
| Coating material layer (from inside) | C/iPyC/SiC/oPyC |
| Thickness of coating layer, cm | 0.009/0.0040/0.0035/0.004 |
| Coating layer density, g/cm$^3$ | 1.05/1.90/1.38/1.90 |

| Pebble Fuel                  |         |
|-----------------------------|---------|
| Pebble diameter, cm         | 6.00    |
| Fuel zone diameter, cm      | 5.00    |
| Thickness of outer shell graphite, cm | 0.50    |
| Density of outer shell graphite matrix, g/cm$^3$ | 1.75 |

3. Calculation Methodology
Calculation and analysis of HM loading optimization is done using VSOP'94 and MCNP6 code. The VSOP'94 modules used in the calculation are DATA2 module, ZUT-DGL module, BIRGIT module and VSOP-CITATION module.

RDE active core geometry modeling in VSOP'94 code is divided into five flow channels of pebble from top to down (downward flow), with each pebble flow channel containing the layers with the following specifications:
- Channel-1 (center channel) with 13 layers, (1 batch per layer),
- Channel-2 with 15 layers, (1 batch per layer),
- Channel-3 with 17 layers, (1 batch per layer),
- Channel-4 with 21 layers, (1 batch per layer),
- Channel-5 with 30 layers, (1 batch per layer).

The energy grouping structures used in RDE core criticality calculation were calculated using VSOP'94 code with four energy group structures as presented in Table 2.
Table 2. Four energy groups structure used in VSOP’94 calculation[16]

| Group No. | Energy group GAM (eV) | Upper Energy eV | Lower Energy eV |
|-----------|-----------------------|-----------------|-----------------|
| 1         | 1                     | 10.0E+6         | 1.0E+6          |
| 2         | 19                    | 1.0E+6          | 4.3E+3          |
| 3         | 52                    | 4.3E+3          | 1.86            |
| 4         | 63                    | 1.86            | 0               |

While the calculations using the Monte Carlo MCNP6 code that utilizes ENDF/B-VII nuclear data library with continuous-energy cross-section from 1E-5 eV to 20MeV. The 3-dimensional geometry modeling in accordance with actual geometry from the TRISO-coated fuel particles, pebble fuel and full core of RDE are done.

Optimization of HM calculation loading in RDE core through calculation of core criticality with UO$_2$ kernel TRISO-coated fuel particle is done at full core condition with various enrichment of $^{235}$U i.e. 8%, 10%, 12%, 14% and 17%. The simulation also use variations level of heavy metal loading per pebble (in gHM/pebble) are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15.

4. MCNP6 and VSOP’94 Code Modeling

4.1 TRISO, pebble and RDE kernel modeling with MCNP6

Heterogeneity modeling of TRISO-coated fuel particle with UO$_2$ kernel and pebble inserted into RDE core with MCNP6 code is presented in Fig. 2. TRISO-coated fuel particles are modeled with a simple cubic (SC) lattice with six zones to consider the existing double heterogeneity[19,20,21]. While the pebble fuel that contains thousands of TRISO-coated fuel particles kernels in the RDE core is modeled in two zones with BCC (Body Centered Cubic) lattice.

![Figure 2](image)

**Figure 2.** Schematic modeling of RDE core and UO$_2$ kernel with TRISO-coated fuel particles as well as pebble fuel with MCNP6 code.
4.2 Pebble Flow Channels Modeling on RDE core with VSOP’94

The modeling of the pebble fuel flow channel in the RDE core with the BIRGIT module in the VSOP’94 code is presented in Fig. 3. The RDE active core with a diameter of 180cm and the total height including the cone with a 30º slope is 217.64cm. So that the core volume used in the neutronik calculation is the sum of the cylinder volume above the cone and the conical volume is about 5.0147E+06 cm³.

![Figure 3. Modeling of pebble flow channel pattern in RDE core with VSOP’94](image)

The pebble fuel flow channel in the RDE active core is modeled with 5 channels and 96 layers. It is assumed that the movement of the pebble fuel at the peripheral (Channel-5) has the slowest drop speed. With the details of the division of layers in each channel are as follows: Channel-1, Channel-2 and Channel-3 are 13, 15 and 17 layers, respectively. While Channel-4 and Channel-5 each use 21 and 30 layers.

The pebble fuel in the RDE reactor core is modeled with the BCC lattice in such a way that the packing fraction\[13, 22\] of 61% of the optimum value for the pebble-fueled HTGR type will be used in critical calculations using MCNP6 and VSOP’94.

5. Results and Discussion

The calculation results of the HM loading optimization through the RDE core criticality using VSOP’94 and MCNP6 for 5 gHM/pebble with variation of $^{235}$U enrichment from 8% to 17% are presented in Table 3. While the calculation results for HM loading variations start from 1gHM/pebble up to 15 gHM/pebble are presented in Table 4 to Table 8.

Table 3. The calculation results of core criticality with variation of enrichment $^{235}$U, with HM loading 5 gHM/pebble

| No. | $^{235}$U enrichment (%) | Core criticality ($k_{eff}$) | % Diff. |
|-----|------------------------|-----------------------------|---------|
|     |                        | VSOP’94 | MCNP6          |         |
| 1.  | 8                      | 0.953576 | 0.94457±0.00238 | 0.95345 |
| 2.  | 10                     | 1.022070 | 1.01624±0.00222 | 0.57368 |
| 3.  | 12                     | 1.073760 | 1.06844±0.00243 | 0.49792 |
| 4.  | 14                     | 1.114240 | 1.11346±0.00238 | 0.07005 |
| 5.  | 17                     | 1.160960 | 1.16666±0.00280 | -0.48857 |

From Table 3 it appears that rising enrichment will increase the RDE core criticality, this is justified because the existing fissile material content also increases. The core is critical at the level of
heavy metal loading of 5 gHM/pebble when it reaches 10% enrichment and above it. As is evident in Table 3, the difference of the effective multiplication factor ($k_{\text{eff}}$) of the RDE core between the calculations using VSOP'94 and Monte Carlo MCNP 6 code is very small enough under 1%. So other calculations for enrichment variation and HM loading can be accounted for.

Table 4. The calculation result of effective multiplication factor with various HM loading at enrichment $^{235}$U - 8%

| No. | HM loading per pebble (gram) | Fissile mass per pebble (gram) | Effective Multiplication Factor ($k_{\text{eff}}$) | VSOP'94 | MCNP6 | % Diff. |
|-----|-----------------------------|-------------------------------|---------------------------------|---------|-------|--------|
| 1.  | 1                           | 0.07907                       | 0.471780                        | 0.44474±0.00147 | 6.07996 |
| 2.  | 2                           | 0.15814                       | 0.694611                        | 0.65966±0.00213 | 5.29834 |
| 3.  | 3                           | 0.23721                       | 0.829501                        | 0.79795±0.00214 | 3.95401 |
| 4.  | 4                           | 0.31627                       | 0.906412                        | 0.88807±0.00233 | 2.06538 |
| 5.  | 5                           | 0.39534                       | 0.953576                        | 0.94457±0.00238 | 0.95345 |
| 6.  | 6                           | 0.47441                       | 0.983612                        | 0.99938±0.00246 | -1.57778 |
| 7.  | 7                           | 0.55348                       | 1.003050                        | 1.02665±0.00259 | -2.29784 |
| 8.  | 8                           | 0.63255                       | 1.015610                        | 1.04601±0.00202 | -2.90628 |
| 9.  | 9                           | 0.71162                       | 1.023540                        | 1.06598±0.00238 | -3.98131 |
| 10. | 10                          | 0.79069                       | 1.028280                        | 1.07760±0.00263 | -4.57684 |
| 11. | 11                          | 0.86976                       | 1.030770                        | 1.08916±0.00259 | -5.36101 |
| 12. | 12                          | 0.94883                       | 1.031650                        | 1.09867±0.00248 | -6.10010 |
| 13. | 13                          | 1.02790                       | 1.031360                        | 1.10135±0.00284 | -6.35493 |
| 14. | 14                          | 1.10700                       | 1.032400                        | 1.101323±0.00251 | -7.20481 |
| 15. | 15                          | 1.18600                       | 1.028500                        | 1.11674±0.00279 | -7.90157 |

The calculation results of of RDE core criticality value for optimization of variation of heavy metal loading level from 1 gHM/pebble to 15 gHM/pebble for various enrichment of $^{235}$U from 8%, 10%, 12%, 14% and 17% are presented in Table 4 through Table 8.

Table 5. The calculation result of effective multiplication factor with various HM loading at enrichment $^{235}$U - 10%

| No. | HM loading per pebble (gram) | Fissile mass per pebble (gram) | Effective Multiplication Factor ($k_{\text{eff}}$) | VSOP'94 | MCNP6 | % Diff. |
|-----|-----------------------------|-------------------------------|---------------------------------|---------|-------|--------|
| 1.  | 1                           | 0.09886                       | 0.55091                         | 0.51577±0.00161 | 6.81311 |
| 2.  | 2                           | 0.19772                       | 0.77948                         | 0.74250±0.00223 | 4.98047 |
| 3.  | 3                           | 0.29659                       | 0.91037                         | 0.87388±0.00247 | 4.17563 |
| 4.  | 4                           | 0.39544                       | 0.98094                         | 0.95844±0.00227 | 2.34756 |
| 5.  | 5                           | 0.49431                       | 1.02207                         | 1.01624±0.00222 | 0.57368 |
| 6.  | 6                           | 0.59317                       | 1.04685                         | 1.05629±0.00242 | -0.89369 |
| 7.  | 7                           | 0.69203                       | 1.06182                         | 1.08429±0.00258 | -2.07232 |
| 8.  | 8                           | 0.79089                       | 1.07062                         | 1.10725±0.00248 | -3.30820 |
| 9.  | 9                           | 0.88975                       | 1.07538                         | 1.11198±0.00280 | -3.29143 |
| 10. | 10                          | 0.98862                       | 1.07744                         | 1.12961±0.00273 | -4.61841 |
| 11. | 11                          | 1.08750                       | 1.07766                         | 1.14023±0.00258 | -5.48749 |
| 12. | 12                          | 1.186300                      | 1.07658                         | 1.14836±0.00275 | -6.25065 |
| 13. | 13                          | 1.285200                      | 1.07464                         | 1.14856±0.00241 | -6.43588 |
| 14. | 14                          | 1.384100                      | 1.07208                         | 1.15796±0.00300 | -7.41649 |
| 15. | 15                          | 1.482900                      | 1.06910                         | 1.15884±0.00315 | -7.74395 |
Table 6. The calculation result of effective multiplication factor with various HM loading at enrichment $^{235}$U - 12%.

| No. | HM loading per pebble (gram) | Fissile mass per pebble (gram) | Effective Multiplication Factor ($k_{eff}$) | VSOP'94 | MCNP6 | % Diff. |
|-----|-----------------------------|--------------------------------|------------------------------------------|---------|-------|---------|
| 1.  | 1                           | 0.11866                        | 0.61519                                  | 0.57810±0.00166 | 6.41585 |
| 2.  | 2                           | 0.23733                        | 0.84869                                  | 0.80991±0.00221 | 4.78819 |
| 3.  | 3                           | 0.35599                        | 0.97379                                  | 0.94320±0.00241 | 3.24321 |
| 4.  | 4                           | 0.47465                        | 1.03806                                  | 1.02126±0.00249 | 1.64503 |
| 5.  | 5                           | 0.59332                        | 1.07376                                  | 1.06844±0.00243 | 0.49792 |
| 6.  | 6                           | 0.71198                        | 1.09406                                  | 1.10889±0.00275 | -1.33737 |
| 7.  | 7                           | 0.83065                        | 1.10539                                  | 1.13210±0.00271 | -2.35933 |
| 8.  | 8                           | 0.94931                        | 1.11124                                  | 1.14954±0.00287 | -3.31777 |
| 9.  | 9                           | 1.06800                        | 1.11356                                  | 1.16410±0.00296 | -4.34155 |
| 10. | 10                          | 1.18660                        | 1.11359                                  | 1.16967±0.00268 | -4.79451 |
| 11. | 11                          | 1.30530                        | 1.11212                                  | 1.18344±0.00290 | -6.02650 |
| 12. | 12                          | 1.42400                        | 1.10964                                  | 1.18717±0.00223 | -6.53066 |
| 13. | 13                          | 1.54260                        | 1.10650                                  | 1.19065±0.00293 | -7.06757 |
| 14. | 14                          | 1.66130                        | 1.10294                                  | 1.19308±0.00287 | -7.55524 |
| 15. | 15                          | 1.78000                        | 1.09912                                  | 1.19155±0.00270 | -7.75712 |

Increasing the HM content in pebble fuel greatly affects the level of core criticality. On enrichment of 8% with HM level 5 gHM and 6 gHM/pebble with the amount of each fissile material ($^{235}$U) of 0.39534 gr/pebble and 0.47441 gr/pebble has not made the reactive, as shown in Table 4. Usage the VSOP'94 code for the increase of core reactivity at 8% enrichment occurs optimally at HM loading level of 12 gHM/pebble with a core prediction value of 1.031650 and this value decreases in line with higher HM loading.

Table 7. The calculation result of effective multiplication factor with various HM loading at enrichment $^{235}$U - 14%.

| No. | HM loading per pebble (gram) | Fissile mass per pebble (gram) | Effective Multiplication Factor ($k_{eff}$) | VSOP'94 | MCNP6 | % Diff. |
|-----|-----------------------------|--------------------------------|------------------------------------------|---------|-------|---------|
| 1.  | 1                           | 0.13848                        | 0.66978                                  | 0.62876±0.00180 | 6.52395 |
| 2.  | 2                           | 0.27695                        | 0.90625                                  | 0.88650±0.00222 | 4.58742 |
| 3.  | 3                           | 0.41542                        | 1.02493                                  | 0.98997±0.00235 | 3.53142 |
| 4.  | 4                           | 0.55390                        | 1.08329                                  | 1.06956±0.00244 | 1.28371 |
| 5.  | 5                           | 0.69238                        | 1.11424                                  | 1.11346±0.00238 | 0.07005 |
| 6.  | 6                           | 0.83086                        | 1.13080                                  | 1.15234±0.00324 | -1.86924 |
| 7.  | 7                           | 0.96933                        | 1.13918                                  | 1.16658±0.00262 | -2.34875 |
| 8.  | 8                           | 1.10780                        | 1.14265                                  | 1.18303±0.00263 | -3.41327 |
| 9.  | 9                           | 1.24630                        | 1.14305                                  | 1.19412±0.00277 | -4.27679 |
| 10. | 10                          | 1.38480                        | 1.14153                                  | 1.20593±0.00295 | -5.34028 |
| 11. | 11                          | 1.52320                        | 1.13878                                  | 1.21249±0.00300 | -6.07923 |
| 12. | 12                          | 1.66170                        | 1.13526                                  | 1.21656±0.00271 | -6.68278 |
| 13. | 13                          | 1.80020                        | 1.13126                                  | 1.21645±0.00243 | -7.00316 |
| 14. | 14                          | 1.93870                        | 1.12699                                  | 1.21831±0.00311 | -7.49563 |
| 15. | 15                          | 2.07710                        | 1.12259                                  | 1.21445±0.00241 | -7.56392 |
Table 8. The calculation result of effective multiplication factor with various HM loading at enrichment $^{235}\text{U} - 17\%$

| No. | HM loading per pebble (gram) | Fissile mass per pebble (gram) | Effective Multiplication Factor ($k_{\text{eff}}$) | % Diff. |
|-----|-----------------------------|--------------------------------|-----------------------------------------------|--------|
| 1.  | 1                           | 0.16822                        | 0.74808±0.00191                               | 7.16012|
| 2.  | 2                           | 0.33643                        | 0.97648±0.00260                               | 4.82202|
| 3.  | 3                           | 0.50465                        | 1.08551±0.00280                               | 2.63511|
| 4.  | 4                           | 0.67285                        | 1.13600±0.00274                               | 0.71636|
| 5.  | 5                           | 0.84106                        | 1.16096±0.00280                               | -0.48857|
| 6.  | 6                           | 1.00930                        | 1.17300±0.00254                               | -2.00092|
| 7.  | 7                           | 1.17750                        | 1.17788±0.00254                               | -2.65052|
| 8.  | 8                           | 1.34570                        | 1.17860±0.00302                               | -3.75476|
| 9.  | 9                           | 1.51390                        | 1.17685±0.00254                               | -4.54387|
| 10. | 10                          | 1.68210                        | 1.17361±0.00303                               | -5.13446|
| 11. | 11                          | 1.85040                        | 1.16948±0.00291                               | -5.50191|
| 12. | 12                          | 2.01860                        | 1.16485±0.00256                               | -6.47081|
| 13. | 13                          | 2.18680                        | 1.15998±0.00297                               | -7.95666|
| 14. | 14                          | 2.35500                        | 1.15502±0.00263                               | -7.46441|
| 15. | 15                          | 2.52320                        | 1.15007±0.00302                               | -7.77306|

Figure 4. Simulation of HM loading on the value of RDE core criticality and difference between VSOP’94 and MCNP6 code
While the calculation results of coreity criteria using Monte Carlo MCNP6 code, shows an increase in the value of criticality in line with increasing HM load level given. The difference value of the criticality calculation result between VSOP94 and MCNP6 for the variation of HM loading values on each enrichment gives the same profile tendency, with a relatively small difference value (below 1%) at 5gHM/pebble for all enrichment level.

Other calculations do not differ much in enrichment of 10%, 12%, 14% and 17% using the existing HM loading variation giving the same profile trend of effective multiplication factor. Similarly, the value of the difference is almost similar to the result of effective multiplication factor calculation between using VSOP94 and MCNP6 with the value of difference below 1% occurs at HM loading level of 5 gHM / pebble, while for HM loading which is getting smaller or larger gives difference result an increasing value between the VSOP94 and MCNP6 codes.

At a 17% enrichment of $^{235}$U, the core criticality value of more than one is indicated by all HM loading levels, from 3 gHM/pebble to 15 gHM/pebble. The profile tendency shape or gradient of increased core criticality is similar to other enrichment, with maximum core criticality value at HM loading level of 8 gHM/pebble with effective multiplication factor of 1.17860 and 1.22458, respectively for VSOP94 and MCNP6 with difference of about -3.75476%.

In general, the value of RDE core criticality with various of HM loading, presented in Table 4 through Table 8 above, can be presented graphically in Fig.4. From this figure it appears that the rising enrichment will increase the criticality value RDE core, this is indeed justified because the existing fissile material content is also increasing.

The reactor core begin to be critical at the HM loading level of 5 gHM/pebble when enriched $^{235}$U over 10%. Reactivity change is very sharp for HM loading levels below 5 gHM/pebble for all enrichment level. The difference values between criticality calculations using the VSOP94 and MCNP6 code provide similar profiles tendency, with the least optimal difference values occurring at a HM loading level of 5 gHM/pebble at all enrichment levels.

6. Conclusion
Calculation of HM loading optimization through RDE core criticality using VSOP94 and MCNP6 with various enrichment of 8%, 10%, 12%, 14% and 17% as well as various of heavy metal loading ranging from 1gHM/pebble to 15gHM/pebble has well done. The differences of effective multiplication factor multiplication of the RDE core (below 1%) between the two calculations with VSOP94 and MCNP6 at the loading level of 5 gHM/pebble heavy metals at all $^{235}$U enrichment levels. At a 17% enrichment, increasing core criticality are similar to other enrichment level with maximum core criticality at a heavy metal loading of 8 gHM/pebble with effective multiplication factor of 1.17860 and 1.22458, respectively for VSOP94 and MCNP6 with difference of about -3.75476%.

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References

[1]. Topan Setiadipura, Syaiful Bakhri, Geni R. Sunaryo, Djaroit S. Wisnusubroto, 2018. Cooling Passive Safety Features of Reaktor Daya Eksperimental, AIP Conference Proceedings 1984, 020034. DOI: https://doi.org/10.1063/1.5046618

[2]. Meng-Jen Wang, et al., 2014. Criticality calculations of the HTR-10 pebble-bed reactor with SCALE6/CSAS6 and MCNP5. Annals of Nuclear Energy 64, 1–7.

[3]. Ohashi, H. et al., 2014. Concept on Inherent Safety in High-Temperature Gas-cooled Reactor. Transaction of the Atomic Energy Society of Japan 13(1), 17-26.

[4]. Kania, M. J., Nabielek, H. and Nickel, H., 2015. Coated Particle Fuels for High-Temperature Reactors, Materials Science and Technology, DOI: http://dx.doi.org/10.1080/1742-6596.1198/2/022004

[5]. Suwoto, H. Adrial, Zuhair, 2017. Analisis Kuat Sumber Neutron Dan Perhitungan Laju Dosis Neutron Teras Awal RDE, Urania Jurnal Ilmiah Daur Bahan Bakar Nuklir, 23(1), 33-44. DOI: https://doi.org/10.17146/urania.2017.23.1.3119

[6]. Zuhair, Suwoto, T Setiadipura, S Bakhri, GR Sunaryo, 2018. Study on Characteristic of Temperature Coefficient of Reactivity for Plutonium Core of Pebbled Bed Reactor, J. Phys.: Conf. Ser. 962 (1), 012058. DOI: https://doi.org/10.1088/1742-6596/962/1/012058

[7]. Allelein, H.J., Kania, M. J., Nabielek, H., Verfondern, K., 2014. Thorium Fuel Performance Assessment in HTRs, Nuclear Engineering and Design 271, 166–170.

[8]. Suwoto, W Luthfi, H Adrial, Zuhair, 2018. Study on Temperature Coefficient of Reactivity for Pebble Bed Reactor with Thorium Fuel, International Journal of Mechanical Engineering and Technology, 9(13), 1410-1419. https://doi.org/10.31227/osf.io/t4rh3

[9]. S. Suwoto and Z. Zuhair, 2016. Analysis of Neutron Dose Rates on RGTT200K Core Using MCNP5, Jurnal Sains dan Teknologi Nuklir Indonesia 17 (2), 107-121. DOI: http://dx.doi.org/10.17146/jstni.2016.2.2350

[10]. Suwoto, Zuhair, 2014. Analisis Sensitivitas Ketebalan Reflektor Grafit Teras RGTT200K Menggunakan Perhitungan Monte Carlo. Jurnal Pengembangan Energi Nuklir 16 (2), 73-83.

[11]. Zuhair, Suwoto, 2015. Analisis Efek Kecelakaan Water Ingress Terhadap Reaktivitas Doppler Teras RGTT200K. Jurnal Teknologi Reaktor Nuklir TRI DASA MEGA 17 (1), 31-40. DOI: http://dx.doi.org/10.17146/dm.2015.17.1.2238

[12]. Zuhair, Suwoto, T. Setiadipura, and Z. Su'ud, 2017. The effects of applying silicon carbide coating on core reactivity of pebble-bed HTR in water ingress accident. Kerntechnik 82 (1), 92-97. DOI: http://dx.doi.org/10.3139/124.110628

[13]. Zuhair, Suwoto, P Supriatna, 2011. Studi Efek Fraksi Packing TRISO Dalam Desain Kritikalitas RGTT200K Seminar Nasional ke-17 Teknologi dan Keselamatan PLTN serta Fasilitas Nuklir, Yogyakarta, 1 Oktober, 310-323.

[14]. Zuhair, Suwoto, PI Yazid, 2013 Investigasi parameter bahan bakar pebble dalam perhitungan teras thorium RGTT200K Jurnal Sains dan Teknologi Nuklir Indonesia 14 (2), 65-77. DOI: http://dx.doi.org/10.17146/jstni.2013.14.2.1263

[15]. T. Setiadipura, Suwoto, Zuhair, S Bakhri, GR Sunaryo, 2018. Power Peaking Effect of OTTO Fuel Scheme Pebble Bed Reactor, J. Phys.: Conf. Ser. 962 (1), 012065. DOI: https://doi.org/10.1088/1742-6596/962/1/012065

[16]. Teuchert et al., 1994. VSOP (‘94) Computer Code System for Reactor Physics and Fuel Cycle Simulation”, Germany Juelich, Juel-2897.

[17]. F.B. Brown, B.C. Kiedrowski, J.S. Bull, 2013. Verification of MCNP5-1.60 and MCNP6.1 for Criticality Safety Applications”, LA-UR-13-22196.

[18]. Suwoto, H Adrial, A Hamzah, Zuhair, S Bakhri, and, GR Sunaryo, 2018. Neutron dose rate analysis on HTGR-10 reactor using Monte Carlo code, J. Phys.: Conf. Ser. 962 (1), 012029. https://dx.doi.org/10.1088/1742-6596/962/1/012029
[19]. Z Zuhair, S Suwoto, P Supriatna, 2012. Studi Model Heksagonal MCNP5 Dalam Perhitungan Benchmark Fisika Teras HTR-10, Jurnal Matematika dan Sains, 17 (2), 61-70.

[20]. Zuhair, Suwoto, PI Yazid, JS Pane, 2016. Studi Model Benchmark MCNP6 Dalam Perhitungan Reaktivitas Butang Kendali HTR-10, GANENDRA Majalah IPTEK Nuklir, 19 (2), 95-103. DOI: http://dx.doi.org/10.17146/gnd.2016.19.2.2880.

[21]. Kim et al., 2017. Annals of Nuclear Energy 99, 124–135.

[22]. Türkmen, M., Çolak, U., 2012. Effect of Pebble Packing on Neutron Spectrum and the Isotopic Composition of HTGR Fuel, Annals of Nuclear Energy 46, 29–36.