Preliminary Analysis on Burnup Calculation of Several Arrangement of TRISO and Pebble inside an MCNP Model of HTR Core

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Abstract. Several studies related to simplifying the modeling of pebble bed High-Temperature Reactor core (HTR) has been developed before. From some calculation on several MCNP models with a fueled pebble to dummy ratio 57:43, using a combination of several types of TRISO (Tri-structural ISOtrpic particle fuel) unit and Pebble unit is modeled to achieve its first criticality. In this paper, some MCNP model that uses 27000 pebbles with a 57:43 ratio and 100% fueled pebble is created to be used on burnup calculation and to compare its k-eff and nuclide inventory. From this burnup calculation, it could be seen that SC (Simple Cubic) TRISO unit has faster calculation time followed by the HCP (Hexagonal Close Packed) TRISO unit and then the FCC (Face-Centered Cubic) TRISO unit. The BCC (Body-Centered Cubic) pebble unit had some consistent deviation from another pebble unit, and it still needs more study to know more about the reason behind it. It could be seen that if there are some dummy pebbles inside the reactor, then the deviation would be higher than if there is just fueled pebble inside the reactor. On the 57:43 ratio, the absolute average deviation of k-eff on burnup calculation is lower than 2% and 10% for nuclide inventory (mass). On 100% fueled pebble, it's below 0.15% on k-eff absolute deviation and below 8% on nuclide inventory deviation.

Keywords: HTR Modeling, TRISO, Fueled Pebble, Dummy Pebble, MCNP, Burnup.

1. Introduction

Previously on simplifying an MCNP model of a pebble bed HTR core, by modeling a homogenized coating or cover consists of buffer, PyC, and SiC on a Tri-structural ISotropic particle fuel (TRISO) can be used to boost up calculation time on the MCNP model of a TRISO without changing its result. Modeling a TRISO unit with SC (Simple Cubic) arrangement can be used as the initial approach on burnup calculation. By using a 1:1 ratio of fueled pebble and dummy pebble, each pebble model except ones that use SC (Simple Cubic) pebble arrangement gives a similar k-eff, because the SC pebble model has a maximum packing fraction below 61%. In addition, the SC TRISO arrangement inside the pebble will need additional calculation time compared to another TRISO arrangement. By using HCP (Hexagonal Close Packed) TRISO arrangement inside an HCP pebble arrangement into HTR core gives shorter calculation time, same as the FCC (Face-Centered Cubic) TRISO arrangement that gives faster calculation time compare to another TRISO arrangement. FCC and BCC (Body-Centered Cubic) pebble arrangement are also faster in calculation time when compare to HCP at the k-eff calculations. Then the model selected for TRISO unit...
and pebble units that could be used for k-eff calculation and also burnup calculation still requires further research [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

As part of RPJMN (National Medium-Term Development Plant), RDE (Reaktor Daya Eksperimental) is becoming one of the national programs [11]. The neutronic aspect of RDE is similar to HTR-10, a pebble bed High-Temperature Gas-cooled Reactor, then the reactor modeled in this study is called an HTR for its generality.

As part of HTGR Test Module Core Physics Benchmarks, the criticality calculation of HTR-10 using Monte Carlo and VSOP 2D has been done by INET [12]. Several criticality calculations have also been done by Tsinghua University using random geometry capability of their Monte Carlo code, RMC [13]. The previous HTR-10 calculation has been done using its standard core parameters. Several calculations have been done with two coolants, helium, and dry air, with an addition of boron inside several core components. The conclusion from those calculations is random geometry arrangement of TRISO and Pebble using RMC and MCNP are similar to the calculated result by INET using VSOP or MCNP, and their experimental result.

There are some trends from the last HTGR core model study on a k-eff calculation using some TRISOs and Pebbles dispersion mode. Faster k-eff calculating time is achieved by using HCP (Hexagonal Close Packed) TRISO unit configuration, followed by FCC (Face-Centered Cubic) TRISO unit and SC (Simple Cubic) TRISO unit, and BCC (Body-Centered Cubic) TRISO unit variation could be ignored, if necessary, because it couldn’t give us faster k-eff calculating time. But in this burnup study, BCC TRISO units are still being used to know more about its behavior in MCNP burnup calculation.

This study was part of a study to analyze the effect of HTGR core modeling using a combination of TRISO particle arrangement inside the fueled pebble and pebble arrangement inside the reactor core that uses approximately 27000 pebbles, with several fueled pebble to dummy pebble ratios on its burnup calculation and calculation time. The TRISO and pebble arrangement used in this study is Hexagonal Close Packed (HCP), Face-Centered Cubic (FCC), and Body-Centered Cubic (BCC). These calculations could help further HTR core modeling to make it faster in terms of calculation time when modeled using an MCNP, especially in burnup calculation. In general, this preliminary study is a sensitivity study on modeling TRISOs and Pebbles inside an HTR reactor core by using MCNP, so the result presented in this study is compared by each variance model that has been used.

2. Methods

2.1. General Parameter

Because this calculation is just a further analysis of our last calculation [10], so, our method is not so much different from our last calculation. The geometric of HTR used in this study could be seen in Figures 1 and 2. In Figure 2, the hexagonal lattice has been used as part of the HCP dispersion model for pebble inside the HTR reactor, and another pebble dispersion will also be used in this study, such as FCC and BCC.

Chosen TRISO modeling from the previous study is a TRISO with fuel kernel (250 mm) and its coating are homogenized into a cover material (455 mm). This fuel kernel homogenized coating consists of buffer, Pyrolitic Carbon, and SiC with the total mass of each component are conserve, also its outer radius of TRISO. The UO$_2$ density with 17% 235U enriched uranium is 10.4 gr/cc, and the TRISO homogenized coating has a 1.929 gr/cc density from its component density, buffer material, 1.04 gr/cc, Pyrolitic Carbon, 1.88 gr/cc, and 3.15 gr/cc of SiC.

In this study, two-reactor conditions were calculated on each variation, one using helium (4.848E-03 gr/cc) as a coolant combined with dummy pebbles density of 1.73 gr/cc, and another variation using dry air (1.175E-03 gr/cc) as a coolant combined with dummy pebble density of 1.84 gr/cc. The temperature for all MCNP cells was set into 27°C, calculated using a 3.4GHz quad-core processor and a 3.2GHz hexa-core processor, 16GB RAM, 1000 GB HDD.
2.2. Fuel and Dummy Pebble

TRISO particle arrangement inside fueled pebble model are using HCP, SC, FCC, and BCC that consist of 6, 1, 4, and 2 TRISO particles in each arrangement, respectively. 5.0248% TRISO volumetric packing fraction inside fuel pebble is chosen to achieve 8335 particles inside fueled pebble. This TRISO arrangement is then filled into the fuel region. This fueled pebble has a dimension of 2.5 cm on radii and 0.5 cm shell thickness. The dummy pebble has a 3 cm radius, and it's filled with graphite.

2.3. Pebble arrangement

Same as before, pebble dispersions are variated into several arrangements, the HCP is modeled using hexagonal type lattice, and FCC and BCC are modeled using hexahedral (6 sides) type lattice. For core modeling, the dimensions of each pebble arrangement are shown in Figure 3, for 61% packing fraction.

Using this pebble dispersion, 3 core configurations with 57:43 fueled pebble to dummy pebble ratio have been done. The configurations have been done by positioning the “pebble lattice filled with fueled pebble” and “pebble lattice filled with dummy pebble” inside the lattice. Within the simulation, it is called “X-version”.

The second pebble dispersion mode selected in this study is the positioning of fueled pebble and dummy pebble in the pebble lattice, using a 50:50 ratio of fueled and dummy pebble. Because the HCP unit consists...
of 6 pebbles inside its lattice, the HCP unit has additional variations of fueled and dummy pebble that called “HCP 3 center” and “HCP 2 center” to define a number of fueled pebbles on the center of the HCP unit, same like previous calculation [10]. Within the simulation, this second variation is called Xa-version and it could be seen in Figure 4.

Figure 4. The second variation of the pebble unit, Xa-version

Then, the third variation of the pebble configuration is also similar to the previous calculation, a reversed version of the second variation [10]. Each fueled pebble in Xa-version changed to dummy pebble and so on, as shown in Figure 5. This variation is called Xb-version.

Figure 5. The third variation of the pebble unit, Xb-version

Later, inside the reactor, for the second and third arrangement, “pebble lattice filled with fueled pebble” has been added to the reactor core to achieve a 57:43 fueled to dummy pebble ratio. Distribution of this unit in the core has been done layer by layer to make sure that those pebbles are uniformly distributed inside the reactor.

2.4. Simple Burnup Calculation

For burnup calculation, 27000 pebbles have been used as a control and there are 4 configurations in total. First, is 57:43 fueled pebble to dummy pebble ratio from flat section of the core to the top (in this paper, it is called “core”), and the remainder is using 27000 pebble 100% fueled pebble, one just in its core section to the top, then from cone section to the top, and the last one is filled from its bottom channel (on this paper, it called “down”) to the top. X-version configurations could be seen in Figure 6.

For some reason, terms like X-version, Xa-version, and Xb-version would be used in the analysis section, followed by the term HCP, FCC, BCC, and also HCP 3 center and HCP 2 center. As burnup calculation, there is only 1 material for all fuel material inside fueled pebble inside the reactor core, 17 time-steps using power 10 MWth, tier 1 of fission product content, and a kcode using 1000 neutron per calculation step with 50 inactive steps (skipped) from a total 200 steps.
Figure 6. HCP X-version pebble dispersion mode, 27000 pebbles from top to bottom: a. 57:43 ratio, b. 100% in the core, c. 100% in core and cone, d. 100% in core, cone, and bottom section
3. Results and Discussion

3.1. Burnup analysis of 27000 pebbles, 57:43 fueled pebbles to dummy pebbles ratio

As additional information, since every k-eff calculation of HTGR core using helium as coolant combined with 1.73 gr/cc dummy pebble density have a consistently lower k-eff compared to the core that uses dry air as coolant combined with 1.84 gr/cc dummy pebble density. So, the one that uses helium as a coolant will be analyzed, but the one that used dry air will mention in the resume section. In this section, burnup calculation has been done with 10 MWth power, and its first criticality when 27000 pebbles with a ratio of 57:43 are inside reactor could be seen in Table 1. Cells on this table and so on have been formatted by using a color gradient that in general means gradient from “low to high” or “fast to slow”, depending on each part.

| TRISO unit type | Pebble unit type | X-version with helium coolant | Xb-version with helium coolant |
|-----------------|------------------|-------------------------------|-------------------------------|
|                 |                  | k-eff                         | stdev                         | ctm              | k-eff                         | stdev                         | ctm              |
| HCP             | HCP              | 1.16682                       | 0.00221                       | 700.56           | 1.16579                       | 0.00219                       | 700.17           |
|                 | FCC              | 1.16570                       | 0.00224                       | 727.94           | 1.16812                       | 0.00246                       | 677.40           |
|                 | BCC              | 1.16755                       | 0.00221                       | 674.07           | 1.16374                       | 0.00216                       | 671.88           |
| SC              | HCP              | 1.15954                       | 0.00224                       | 676.69           | 1.16281                       | 0.00220                       | 670.97           |
|                 | FCC              | 1.15692                       | 0.00247                       | 624.08           | 1.16821                       | 0.00247                       | 626.38           |
|                 | BCC              | 1.17927                       | 0.00242                       | 626.81           | 1.16364                       | 0.00209                       | 663.27           |
| FCC             | HCP              | 1.16193                       | 0.00216                       | 747.18           | 1.16174                       | 0.00216                       | 745.00           |
|                 | FCC              | 1.15699                       | 0.00220                       | 707.97           | 1.16821                       | 0.00230                       | 713.33           |
|                 | BCC              | 1.16769                       | 0.00210                       | 722.19           | 1.16364                       | 0.00209                       | 715.63           |
| BCC             | HCP              | 1.16580                       | 0.00230                       | 775.69           | 1.16858                       | 0.00238                       | 782.64           |
|                 | FCC              | 1.16593                       | 0.00238                       | 782.64           | 1.16848                       | 0.00238                       | 743.08           |
|                 | BCC              |                               |                               |                  |                               |                               |                  |

Table 1. k-eff on day 0 and calculation time for 27000 pebbles, 57:43 ratio, with helium as a coolant.
Some cells on burnup calculation time didn’t have color gradient because when calculating burnup on parallel mode, some configuration had been finished before and it gives MCNPX free CPU to use compared to when all CPU had been used before. It will make some calculations finished faster and to make it tie, every pebble configuration in the same type to this will have no color gradient.

It could be seen that the k-eff of every BCC pebble unit variation have a bigger k-eff than another pebble unit, and the smaller one is all pebble units based on HCP. It all happened because the loading mass of uranium in the BCC pebble unit is slightly higher than others, for about 50gr more uranium than HCP-based pebble unit and 10 gr more uranium than FCC. On other variation, HCP has 350gr less uranium than BCC, where it is 340gr less uranium on FCC. It is all because our controlled configuration somehow didn’t perfectly conserve the ratio of fueled pebble and dummy pebble inside the reactor. Detailed core configuration could be seen in Table 2.

Table 2. Core configuration using 27000 pebbles, 57:43 ratio

| Pebble unit type | #Fuel  | #Dummy  | #Total  | %Fuel pebble | Height (cm) | Fuel volume (cc) | Total mass of uranium (gr) |
|------------------|--------|---------|---------|--------------|-------------|------------------|---------------------------|
| HCP              | 15306  | 11694   | 27000   | 0.566889     | 196.7944    | 8349.798         | 76529.73                  |
| FCC              | 15308  | 11692   | 27000   | 0.566963     | 196.7748    | 8350.889         | 76539.73                  |
| BCC              | 15376  | 11624   | 27000   | 0.569481     | 196.7303    | 8387.984         | 76879.73                  |
| HCP 3 Ctr        | 15381  | 11619   | 27000   | 0.569667     | 196.7944    | 8390.712         | 76904.73                  |
| HCP 2 Ctr        | 15381  | 11619   | 27000   | 0.569667     | 196.7944    | 8390.712         | 76904.73                  |
| FCC              | 15384  | 11616   | 27000   | 0.569778     | 196.7748    | 8392.349         | 76919.73                  |
| BCC              | 15392  | 11608   | 27000   | 0.570074     | 196.7303    | 8396.713         | 76959.73                  |

The plot of k-eff through time could be seen in Figures 7, 8, and 9 respectively for X-version, Xa-version, and Xb-version configurations that use helium coolant conditions. In Table 1, it could be seen that the SC TRISO unit has a shorter burnup calculating time compared to another TRISO unit, followed by the HCP TRISO unit and then the FCC TRISO unit. So %deviation that defined in further part in this section and so on is a deviation from it correspond variation on SC TRISO unit configuration. %Deviation of k-eff didn’t surpass 2.5% of the k-eff of SC TRISO unit that it means the k-eff of each configuration is close enough rather than saying that it's identically same.

As Figures 7, 8, and 9, the %deviation of this k-eff is relative to the SC TRISO unit, and it has some trend. On BCC pebble unit configuration, for every type of TRISO unit that has been used, it gives a consistently lower k-eff than SC TRISO unit type. So, it could be said that the SC TRISO unit gives the BCC pebble unit a higher k-eff.

The different aspect of modeling TRISO unit using SC (Simple Cubic), HCP (Hexagonal Close Packed), FCC (Face-Centered Cubic), and BCC (Body-Centered Cubic) is the method to distribute fuel pebbles and dummy pebbles inside the reactor and also fuel kernel (TRISO) inside the pebble because lattice method that could be used on MCNP.

In HCP, there are 6 TRISO per HCP unit modeled by 17 TRISO cells to make an HCP structure that has a ratio of 5.0248% TRISO volume inside the fuel zone of pebble. SC is a simple one, 1 TRISO each SC unit, that only 1 TRISO cell. On the other hand, FCC consists of 4 TRISO per FCC unit, 14 TRISO cells, and the last one, BCC is 2 TRISO per BCC unit, it will need 9 TRISO cells per unit.

The method to distribute fuel or TRISO inside the pebble seems to have no big deal on the whole core because it has the same deviation range as the last study on reactor height, about -2.5% to 2.5% from other variations [10]. This pattern is repeated on dry air mode and detailed figures or data on dry air is not going to appear in this section, its trend will appear in section 3.2 as part of the resume of this section.
Figure 7. $k$-eff (top) and its deviation over time (bottom) for X-version, 57:43 ratio, Helium coolant, legend: TRISO unit type – Pebble unit type

In cases where dry air is used as a coolant inside the reactor, it could be said that the shortest burnup calculation time is on the SC TRISO unit, followed by HCP, FCC and the last is BCC TRISO unit. The $k$-eff trend is consistently repeated where BCC Pebble has a lower unit $k$-eff deviation over time. Some other variance except the SC TRISO unit has the same trend as before when helium is used as a coolant. It could be used to make sure that modeling HTR using this configuration or by mixing some lattice for TRISOs inside pebble with another lattice for pebbles inside the HTR core is consistent enough. The method to model the dispersion of dummy pebbles inside the reactor core could be a mix of fueled pebble and dummy pebble on each pebble unit or just completely separated using another unit. The method to disperse pebble unit inside the reactor core didn’t have a special impact on the %deviation because it consistently fluctuates in the range of 2.5% to -2.5% of the SC pebble unit, but most of it is in the range of 1% to -1%.
Figure 8. $k$-eff (top) and its deviation over time (bottom) for Xa-version, 57:43 ratio, Helium coolant, legend: TRISO unit type – Pebble unit type

As an additional tool for analyzing the phenomena, the changes of some nuclide mass from SC TRISO unit through time on Figures 10 to 13. It could be seen that with less total fuel volume inside the reactor, X-version of HCP and FCC pebble unit gives significantly lower U-238 mass, but on U-235, the difference is too small to be seen in Figure 10.
Figure 9. \(k\)-eff (top) and its deviation over time (bottom) for Xb-version, 57:43 ratio, Helium coolant, legend: TRISO unit type – Pebble unit type

Somehow BCC pebble unit is consumed U-238 faster than other pebble configurations. Those phenomena also happened on dry air coolant mode, so it might be because of the difference in BCC total fuel volume, the bigger one, but on Xa-version of BCC pebble unit, the trend is the same as another non-BCC pebble unit. So, there are some inconsistencies in BCC pebble unit configuration and it needs more data to know more about the reasons behind it.

In Figure 13, it could be seen that Cs-137 is linearly increased over time, with also, some deviation from BCC pebble unit on X-version and Xb-version. Here, the mass of Xe-135 is decreasing over time and it could be noted because it has a different trend if compared to the 100% fueled pebble model that will be analyzed after this 57:43 ratio section.
Figure 10. Mass of U-235 on SC TRISO unit variance, 57:43 ratio, Helium coolant

Figure 11. Mass of U-238 on SC TRISO unit variance, 57:43 ratio, Helium coolant

Figure 12. Mass of Xe-135 on SC TRISO unit variance, 57:43 ratio, Helium coolant
Figure 13. Mass of Cs-137 on SC TRISO unit variance, 57:43 ratio, Helium coolant

The changes of mass for some nuclide on dry air coolant is had the same trends as helium coolant as a coolant variation, where X-version and Xb-version of BCC consume U-238 faster than other configurations. The Cs-137 and Xe-135 mass is also had the same trend by using dry air coolant of 57:43 ratio.

3.2. Resume of 27000 pebbles, 57:43 fueled pebbles to dummy pebbles ratio

Because there is so much variation in one section, then some simplification over whole data could be made into Figure 14 as an average deviation from all deviation of k-eff over time. From this figure, it could be seen easily that another TRISO unit combined with BCC pebble unit is consistently got lower k-eff than the SC TRISO unit, except the Xa-version of Helium coolant. It could be said that the average deviation is also lower than 2% and it could help us said that this whole configuration is consistent enough to be used to calculate k-eff.

Figure 14. Average %deviation of k-eff of all configuration on 27000 pebbles, 57:43 ratio
The chart that shows the distribution of average absolute-deviation of some nuclide mass over time is also presented in Figure 15. %deviation is also compared to the CS TRISO unit. The average %deviation is a lot bigger on nuclide mass because there are 8 isotopes that averaged here, U-235, U-238, Pu-239, Pu-240, Pu-241, Pu-242, Xe-135, and Cs-137, and some of it had a big deviation relative to others and it will sum up to the final average. From this figure, it could be seen that some combination gives us high deviation like FCC TRISO unit + BCC pebble unit, it has high deviation except on Xa-version. BCC TRISO unit + FCC and BCC pebble unit also give us higher deviation than other BCC TRISO unit variations. The lower deviation is achieved on the HCP-based pebble unit, especially on Xa-version followed by X-version.

![Figure 15](image-url)

**Figure 15.** Average absolute %deviation of all nuclides inventory of all configuration on 27000 pebbles, 57:43 ratio

3.3. Burnup analysis of 27000 pebbles, 100% fueled pebbles

By using helium as coolant and 1.73 gr/cc dummy pebble density, burnup calculation has been done with 10 MWth power and its first criticality when 27000 fueled pebbles are inside the reactor. It will have 14729.161 cc fuel kernel or 134,599.523 gr uranium inside the reactor core and there are 3 configurations that are varied in this section as the detail has been describing on the method.

The detailed pebble composition that has been used on those 3 configurations could be seen in Table 3. This variation could be used to observe the effect of dummy pebbles on the cone section or on the bottom channel (Down) as fuel volume is conserve in every variation. In this section, the HCP, FCC and BCC pebble unit will be at 100% fueled pebble, not the mixed one. This section also helps us to choose the best pebble unit to use with a minimum deviation than another pebble unit.

Initial k-eff of this variation using helium as coolant could be seen in Table 4, followed by burnup computing time and standard deviation (stdev). Stdev in burnup calculation is in order of 200-250 pcm (1.0E-5) or about 3 times bigger than the previous study. It happens because burnup calculation has been done using 1000 nps (number of particles per step) rather than 10000 nps on k-eff calculation, and the reason behind this is on the computing time. Same as before, the calculation time (ctm) that didn’t have a color gradient means that it could be used as a comparison because it uses more CPU power, so to fill in
the gap, the trend from the last section could be used. Then the 27000 Core+Cone model is somehow needed less duration of computing time because it uses other CPUs, so in this section, an only observed trend will be discussed, not the value itself.

Table 3. Pebble configuration of 27000 fuel pebbles inside the reactor, 100% fueled pebbles

| Configuration   | Pebble unit type | Core | Cone | Down | total | Fuel | Dummy | Height Cylinder (cm) |
|-----------------|------------------|------|------|------|-------|------|-------|---------------------|
| Core            | HCP              | 27000| -    | -    | 27000 | Cone | 2280  | 196.794             |
|                 | FCC              | 27000| -    | -    | 27000 | Cone | 2280  | 196.775             |
|                 | BCC              | 27000| -    | -    | 27000 | Cone | 2280  | 196.730             |
| Core+Cone       | HCP              | 24720| 2280 | -    | 27000 | Cone | 2280  | 180.176             |
|                 | FCC              | 24720| 2280 | -    | 27000 | Cone | 2280  | 180.158             |
|                 | BCC              | 24720| 2280 | -    | 27000 | Cone | 2280  | 180.118             |
| Core+Cone+Down  | HCP              | 22326| 2280 | 2394 | 27000 | Cone | 2280  | 162.727             |
|                 | FCC              | 22324| 2280 | 2396 | 27000 | Cone | 2280  | 162.696             |
|                 | BCC              | 22326| 2280 | 2394 | 27000 | Cone | 2280  | 162.674             |

Table 4. $k_{\text{eff}}$ on day 0 and burnup calculating time for 27000 pebbles, 100% fueled pebbles with Helium as coolant

| TRISO unit | pebble unit | 27000 Core | 27000 Core+Cone | 27000 Core+Cone+Down |
|------------|-------------|------------|-----------------|----------------------|
| HCP        | HCP         | 1.22579    | 0.00217         | 1.22219              | 0.00235              | 1.19862              | 0.00224            | 1070.97             | 1057.08 |
|            | FCC         | 1.22681    | 0.00234         | 1.2275              | 0.00220              | 1.20298              | 0.00226            | 1064.83             | 1048.16 |
|            | BCC         | 1.23196    | 0.00221         | 1.22465             | 0.00219              | 1.20586              | 0.00229            | 1072.52             | 1061.75 |
| SC         | HCP         | 1.22574    | 0.00233         | 1.21973             | 0.00232              | 1.20295              | 0.00234            | 995.95              | 980.86  |
|            | FCC         | 1.22351    | 0.00221         | 1.21825             | 0.00226              | 1.19892              | 0.00243            | 985.98              | 971.20  |
|            | BCC         | 1.23219    | 0.00228         | 1.22379             | 0.00248              | 1.21090              | 0.00214            | 799.59              | 974.04  |
| FCC        | HCP         | 1.22631    | 0.00224         | 1.22057             | 0.00201              | 1.20035              | 0.00244            | 1142.34             | 1126.50 |
|            | FCC         | 1.22080    | 0.00200         | 1.22091             | 0.00227              | 1.20522              | 0.00232            | 1126.35             | 1111.10 |
|            | BCC         | 1.22682    | 0.00200         | 1.22183             | 0.00215              | 1.20684              | 0.00246            | 1129.49             | 1116.04 |
| BCC        | HCP         | 1.22465    | 0.00238         | 1.21773             | 0.00241              | 1.20465              | 0.00219            | 1174.10             | 1161.77 |
|            | FCC         | 1.22572    | 0.00220         | 1.21910             | 0.00239              | 1.20150              | 0.00215            | 1167.55             | 1145.87 |
|            | BCC         | 1.22982    | 0.00231         | 850.97              | 1.22373              | 0.00233             | 597.94              | 1129.49             | 1116.04 |

It could be seen that there is some consistency that the SC TRISO unit is finishing burnup calculation faster than any other TRISO unit, followed by the HCP TRISO unit and then the FCC TRISO unit. Using BCC pebble unit gives higher k-eff than other pebble unit and because its fuel volume is same as other pebble unit variation, then it must be the effect of modeling itself, maybe because its effective height is lower than other pebble unit and it could affect pebble effective packing fraction. But this couldn’t be used as a reason because the difference is in the range of 0.4 to 0.6 mm, that so small and inconsistent where the FCC pebble unit didn’t repeat that trend with its effective height. Then, as long as the k-eff of the reactor is close enough, with similar reflectors and other parts, then it could be said that the profile of neutron flux inside the reactor is similar enough.
The plot of k-eff over time from burnup calculation of 27000 pebbles inside core and cone could be seen in Figure 16 and the k-eff plot through time for other variations had the same trend like this one. From this plot, it could be said that the k-eff is close enough to each other with the same up and down deviation from its corresponding SC TRISO unit variation. For the value, k-eff in this section is higher than the 57:43 ratio because this section is for 100% fueled pebble.

![Figure 16. k-eff (top) and its deviation over time (bottom) for 27000 pebbles on Core & Cone, 100% fueled pebbles, Helium coolant. Legend: TRISO – Pebble](image)

There is no repeated k-eff trend of BCC pebble unit like on 57:43 ratio in this section, but on the nuclide density, the trend is repeated clearly, as it could be seen in Figures 17, 18, 19, and 20. All BCC pebble unit shows that it consumes U-238 faster than other configuration and it affects the other heavy metal that produced, and also its fission product. From those phenomena, it could be said that our BCC pebble unit
didn’t consistent enough with other models. It may be something with our way of modeling BCC to achieve effective height as close to another pebble unit as possible when it uses the same number of pebbles in the core, further study is needed to know more about BCC pebble unit behaviors.

Another thing to discuss is Xe-135 mass over time that has a different trend in 100% fueled pebble compared to 57:43 ratio. In the 57:43 ratio, the Xe-135 has a trend in decreasing mass, but in 100%, it has an increasing trend. Maybe it’s something with more thermal neutron flux when using 43% dummy pebble inside reactor core because it has theoretically more fission reaction rate conducted by thermal flux on 57:43 ratio than on 100% fueled pebble models. So, it must be something with more moderators inside the 57:43 ratio model compared to more fuel in the 100% model that made the neutron flux became less thermal. So more thermal neutron makes more Xe-135 consumed inside reactor although production rate is still the same.
In the case of dry air as coolant combined with 1.84 gr/cc dummy pebble density, the initial core k-eff could be seen in Table 5 and it has the same trend as before where the SC TRISO unit is fastest than another TRISO unit in burnup calculation time, followed by HCP TRISO unit and then the FCC TRISO unit. In thin 100% fueled pebble, the trend of k-eff value under helium as a coolant that is higher than dry air as a coolant is repeated like 57:43 ratio. The absolute deviation is consistently lower than 1.5%, the same as 27000 fueled pebbles under helium as coolant condition.

The trend of nuclide mass over time is still the same as helium as a coolant condition. The trends consistently repeated to BCC pebble units that consume uranium faster than other models and some calculations using axial and radial material separation could be used to know more about the effect of this material separation on material composition after burned.

**Figure 19.** Mass of Xe-135 on SC TRISO unit variance, 100% fueled pebbles, Helium coolant

**Figure 20.** Mass of Cs-137 on SC TRISO unit variance, 100% fueled pebbles, Helium coolant
Table 5. Day 0 k-eff and burnup calculation time for 27000 pebbles, 100% ratio with dry air as coolant

| TRISO unit type | pebble unit type | 27000 Core k-eff | 27000 Core k-eff | 27000 Core+Down k-eff | 27000 Core+Cone k-eff | 27000 Core+Cone+Down k-eff |
|-----------------|-----------------|-----------------|-----------------|----------------------|---------------------|-----------------------------|
| HCP             | HCP             | 1.21455         | 0.00227         | 1073.70              | 1.21096             | 0.00220                     | 1060.26                     |
| FCC             | HCP             | 1.21571         | 0.00243         | 1072.92              | 1.21396             | 0.00226                     | 1056.65                     |
| BCC             | HCP             | 1.22526         | 0.00226         | 1077.45              | 1.21749             | 0.00223                     | 1064.38                     |
| SC              | HCP             | 1.21450         | 0.00244         | 1000.07              | 1.21269             | 0.00214                     | 989.07                      |
| FCC             | HCP             | 1.21394         | 0.00219         | 992.81               | 1.20880             | 0.00189                     | 970.65                      |
| BCC             | HCP             | 1.22379         | 0.00226         | 973.07               | 1.21716             | 0.00225                     | 979.22                      |
| FCC             | HCP             | 1.21913         | 0.00212         | 1149.10              | 1.21248             | 0.00224                     | 1143.27                     |
| BCC             | HCP             | 1.22233         | 0.00218         | 1131.20              | 1.21048             | 0.00222                     | 1115.90                     |
| BCC             | HCP             | 1.21402         | 0.00215         | 1178.10              | 1.21136             | 0.00214                     | 1164.44                     |
| BCC             | HCP             | 1.21489         | 0.00227         | 1168.02              | 1.21667             | 0.00252                     | 1145.93                     |
| BCC             | HCP             | 1.21763         | 0.00233         | 849.48               | 1.21834             | 0.00222                     | 874.19                      |

3.4. Resume of 27000 pebbles, 100% fueled pebbles

Same as before, because there is so much variation in one section, then to do some simplification over whole data that exist, Figure 21 is an average deviation from all deviation of k-eff over time. The distribution of the average absolute deviation of all nuclide mass over time could be seen in Figure 22.

Figure 21. Average %deviation of k-eff of all configuration on 27000 pebbles, 100% fueled pebbles
Figure 22. Average absolute %deviation of all nuclides inventory of all configuration on 27000 pebbles, 100% fueled pebbles

From Figure 21, it could be seen that almost every configuration of 27000 pebbles inside Core Cone and bottom channel using helium coolant is lower than it is corresponding CS TRISO unit. Interesting observation because on other configurations, it’s almost always higher than the corresponding SC TRISO unit. Another interesting thing is the BCC pebble unit is almost had a higher deviation in some cases, the FCC pebble unit is also high enough, but the absolute deviation is below 0.15%.

Average deviation on nuclide (U-235, U-238, Pu-239, Pu-240, Pu-241, Pu-242, Xe-135 and Cs-137) mass aspect have a lower absolute value than 57:43 ratio, below 8% rather than 10%. From Figure 22, it could be seen that some combination of FCC TRISO unit + BCC pebble unit gives us highest deviation and trend of BCC pebble unit gives higher deviation compared to other pebble unit is still repeated.

4. Conclusion

The burnup calculation of pebble-bed high-temperature reactor core has been done by combining four types of TRISO units (HCP, SC, FCC, and BCC) and three types of pebble units (HCP, FCC, and BCC), with TRISO modeled by using fuel kernels and homogenized buffer, PyC, and SiC as a cover. Burnup calculation using 27000 pebble 57:43 ratio and 27000 fueled pebble (100%) had also been done. From this burnup calculation, the SC TRISO unit gives us faster calculation time followed by the HCP TRISO unit and then-FCC TRISO unit. This finding is also made us sure that the BCC TRISO unit could be neglected from the further HTGR model because it couldn’t give us a faster calculating time. On the other hand, the BCC pebble unit had some consistent deviation from another pebble unit, and more studies needed to know the reason behind it. It could be seen that if there are some dummy pebbles inside the reactor, then the deviation would be higher than if there is just fueled pebble inside the reactor. On the 57:43 ratio, the absolute average deviation of k-eff on burnup calculation is lower than 2% and 10% for nuclide inventory (mass). On 100% fueled pebble, it's below 0.15% on k-eff absolute deviation and below 8% on nuclide inventory deviation.
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