Equilibrium Core Design of Reaktor Daya Eksperimental

T Setiadipura∗, Suwoto†, Zuhair‡

†Center for Nuclear Reactor Technology and Safety – National Nuclear Energy Agency of Indonesia (BATAN), Kawasan PUPSPITEK, Gd.80, Serpong, Tangerang Selatan 15310, Telp. +62 (21) 756-0912, Fax. +62 (21) 756-0913, Indonesia.

∗E-mail: tsdipura@batan.go.id

Abstract. A prototype of a high temperature gas-cooled reactor for electric and cogeneration application, called Reaktor Daya Eksperimental (RDE) is being developed at BATAN. RDE is developed to fulfill the huge yet distributed Indonesian energy demand, in particular for the eastern part of Indonesia. As a moving fuel core, analysis of the fuel management of PBR can be divided into the analysis of the start-up phase where the core composition, neutron flux, and power density profile still changing and equilibrium core. Equilibrium core design usually represent the general performance over the entire range of reactor operation. As part of the design development, current paper presents the equilibrium core design of RDE and depressurized-loss-of-forced-cooling (DLOFC) accident analysis. PEBBED code is utilized for the equilibrium core analysis. Results of this study include several possible equilibrium designs for RDE which then the design with 123 fuel pebble recirculated per day with equilibrium k_{eff} = 1.02571, discharge burnup of 79.36 and maximum power generation 0.66kW per pebble fuel is chosen. Maximum fuel temperature of this design under the DLOFC accident is 1015.9°C which occurred 8.5h after the initiation of the accident. Results of DLOFC accident shows the strong passive safety features of RDE.

Keywords: equilibrium core, RDE, VSOP94, MCNP6, heavy metal loading, criticality, ENDF/B-VII

1. Introduction

Specific Indonesian energy demand marked by its huge and distributed populations. In addition, that energy distribution is not only in a form of electricity but also in other form such as high temperature steam or gas to process the raw natural resources across the archipelago. To contribute to such a challenging demand, the proposed nuclear reactor system needs to have several characteristics. First, it is a small modular type reactor which fits for a remote area or island where e.g. there is an important natural resource to be processed. And to fulfill bigger demand, those small reactors can be modularized to supply the specific bigger demand. Second, besides supplying electricity it should also have the capability of supplying a high temperature steam or gas for cogeneration applications. Third, it should have a sound passive safety feature. As proposed solution, Indonesian National Nuclear Energy Agency (BATAN) proposed a 10MWh prototype of a pebble bed high temperature gas-cooled reactor for electric and cogeneration application, called Reaktor Daya Eksperimental (RDE). In further
phase, RDE-based technology is planned to be the master nuclear power plant to be upscaled and commercialize as one of contributions to overcome the national energy challenge [1]. Different from the Light Water Reactor (LWR) which is currently the most nuclear reactor type used, RDE is composed of TRISO-based fuel in the form of spherical pebble fuel which placed randomly in the active core. RDE composition from the active core to the TRISO coated fuel particle is shown in Figure 1.

The purpose of this paper is to analyze the optimum equilibrium design of RDE. Depressurized loss of forced-cooling (DLOFC) accident analysis also perform to check the performance of the equilibrium core in the DLOFC accident which is among the severest hypothetical accident. Previously, an initial equilibrium design study and DLOFC accident analysis was already performed [1], current study is an update which include a more complete and optimized equilibrium core. A PBR type reactor with a moving fuel core, such as RDE, provides flexibility in the fuel management of the core, including the advantage of online refueling. On the other hand, depletion analysis of this moving fuel core is especially challenging because the analysis must account for the movements of the fuel as well as the changes of nuclide composition. Analysis of the fuel management of RDE can be divided into the analysis of the start-up phase where the core composition, neutron flux, and power density profile still changing and equilibrium core. In the equilibrium core, the precious core parameter is already achieved an equilibrium core design usually represent the general performance over the entire range of reactor operation [2]. Design principle of the RDE core is given in the next section followed by the calculation method, results and discussion, and finally the conclusion.

![Figure 1. RDE composition from active core to TRISO coated fuel particle [1]](image)

2. Design Principles

Basically, HTR-10 design [3] is used as the reference design in the development of RDE. General parameter of the RDE design are given in Table 1. Taking consideration of the time needed to license and test a new fuel design, HTR-10 pebble fuel including its TRISO [4] design is adopted in RDE design. Capability of RDE design to passively dissipate the heat out of the core is establish due to the graphite-based material which is the majority of the material.
### Table 1. General parameter of RDE

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Reactor Power              | 10 MWt                 |
| Active Core Diameter       | 180 cm                 |
| Active Core Height         | 197 cm                 |
| Side Reflector Thickness   | 100 cm                 |
| Top Reflector Thickness    | 130 cm                 |
| Void thickness             | 40 cm                  |
| Bottom reflector thickness | 243 cm                 |
| Uranium enrichment         | 17%                    |
| Initial Uranium loading    | 5 g/pebble             |
| Fuel recirculation number  | 5 pass                 |
| Diameter of pebble balls   | 6 cm                   |
| Fuel kernel diameter       | 500 μm                 |
| Fuel kernel density        | 10.4 g/cm³             |
| TRISO layers               | buffer/I-PyC/SiC/O-PyC |
| Thickness                  | 90/40/35/40 [μm]       |
| Density                    | 1.05/1.9/3.18/1.9 [g/cm³] |
| Graphite reflector density | 1.75 g/cm³             |

### 3. Computational Method

Full lifetime of a pebble bed reactor starts from its initial criticality up to its equilibrium core can be seen in Figure 2. In general, computational method to analyse equilibrium core is divided into two methods. First, the non-direct method which simulate the actual core condition from its initial loading, running-in phase, and finally reach the equilibrium condition [5]. The VSOP [6] code is one of the standard software in pebble bed analysis which adopt this method. VSOP code use diffusion method for the neutron transport simulation. Another software is the MCPBR [2] code which based on Monte Carlo method for the neutron transport simulation. Second, the direct method which directly simulate the equilibrium condition without simulating the running-in phase condition. BATAN-MPASS [7] code apply this direct method. And the PEBBED [8,9] code which used in this study also performing the equilibrium analysis using direct method. Direct method in general have an advantage of faster analysis to achieve an equilibrium condition, however this method is not physically simulating the recirculating event in pebble bed reactor in particular mathematical method need to be develop to find the equilibrium condition.
To simulate a moving core of pebble bed reactor, the governing equation need to be solved [10]:

\[
\frac{\partial N_k}{\partial t} + \frac{\partial N_k}{\partial z} \nu = \phi \sum_{i=1}^{m} N_i \sigma_{fi} \gamma_{ik} + \phi \sum_{s=r}^{q} N_s \sigma_{as} \gamma_{sk} + \sum_{j=n}^{p} N_j \lambda_j \alpha_{jk} - \lambda_k N_k - \phi N_k \alpha_{jk}
\]  

(1)

where

- \( N_k \) = atomic concentration of isotope k,
- \( \nu \) = axial ball velocity
- \( \phi \) = flux of the core region
- \( \sigma_{fi} \) = fission cross section of isotope i
- \( \sigma_{as} \) = absorption cross section of isotope i
- \( \lambda_j \) = decay constant of isotope i
- \( \gamma_{ik} \) = yield of isotope k due to fission in isotope i
- \( \gamma_{sk} \) = probability that neutron absorption in isotope s produces isotope k
- \( \alpha_{jk} \) = probability that decay of isotope j produce isotope k

In solving the above equation, PEBBED converges directly to the equilibrium (or asymptotic) core solution and thus assumes that the first term on the left in Eq. 1 vanishes. Then by solving that new equation and the diffusion equation iteratively until burnup convergence is achieved which represent the static nuclide distribution in the core. The thermal-fluid and spectrum equations are also solved in in this loop to yield a fully consistent core solution [1,8]. Flowchart of the PEBBED code is shown in Figure 3.
Figure 3. Computational flow-chart for equilibrium cycle analysis of pebble bed reactor in the PEBBED code[1].

4. Results and Discussions

Results of the equilibrium core analysis in this study are given in Table 2.

Table 2. Equilibrium analysis results of RDE

| pebble per day | $k_{eff}$ | avg power density [W/cc] | Peak power density [W/cc] | Avg. BU [MWd/Kg] | Discharge BU [MWd/Kg] | Fuel Peak Temp [°C] | Mean Fuel Temp [°C] | Fuel Peak @DLOFC [degC] | Time to Peak @DLOFC (h) | Max Power/pebble [kW] | Max TRISO power [mW] |
|----------------|----------|--------------------------|---------------------------|------------------|-----------------------|---------------------|---------------------|-------------------------|--------------------------|-----------------------|----------------------|
| 109            | 1.00266  | 1.99                     | 3.02                      | 49.17            | 91.73                 | 897.8               | 498                 | 1010.7                  | 8.5                     | 0.695                 | 83.4                 |
| 110            | 1.00435  | 1.99                     | 3.02                      | 48.63            | 90.88                 | 897.9               | 497.9               | 1011.2                  | 8.2                     | 0.692                 | 83                  |
| 111            | 1.00567  | 1.99                     | 3.03                      | 48.26            | 90.25                 | 896.9               | 497.6               | 1011.4                  | 8.5                     | 0.689                 | 82.7                 |
| 112            | 1.00820  | 1.99                     | 3.03                      | 47.47            | 88.96                 | 896.2               | 497.3               | 1012.1                  | 8.5                     | 0.684                 | 82                  |
| 114            | 1.01167  | 2                        | 3.05                      | 46.37            | 87.14                 | 895                 | 496                 | 1012.9                  | 8.5                     | 0.677                 | 81.2                 |
| 115            | 1.01351  | 1.99                     | 3.06                      | 45.67            | 85.98                 | 895.2               | 498.8               | 1013.3                  | 8.5                     | 0.675                 | 81                  |
| 116            | 1.01571  | 1.99                     | 3.06                      | 44.99            | 84.85                 | 893.9               | 496.4               | 1013.8                  | 8.5                     | 0.672                 | 80.6                 |
| 120            | 1.02086  | 1.99                     | 3.08                      | 43.29            | 82                    | 893                 | 495.9               | 1015                    | 8.5                     | 0.666                 | 79.9                 |
| 121            | 1.02287  | 1.99                     | 3.08                      | 42.67            | 80.95                 | 891.8               | 495.5               | 1015.4                  | 8.5                     | 0.663                 | 79.6                 |
| 123            | 1.02571  | 1.99                     | 3.09                      | 41.73            | 79.36                 | 890.9               | 495.1               | 1015.9                  | 8.5                     | 0.66                  | 79.2                 |
| 125            | 1.02846  | 1.99                     | 3.1                       | 40.83            | 77.81                 | 890.1               | 494.8               | 1016.5                  | 8.5                     | 0.657                 | 78.8                 |

From the equilibrium results it is found that there several option of possible critical equilibrium core design of RDE based on its pebble per day parameter. Generally all the possible equilibrium core have almost same design characteristic, based on the target discharge burnup of the RDE of 80MWd/Kg the equilibrium design with 123 pebble per day recirculation is chosen. As graphically shown in Figure 4, discharge burnup is decreasing for higher pebble per day recirculation which is caused by shorter core residence time. As expected, more pebble per day will give a higher $k_{eff}$ of the equilibrium core, as shown in Figure 4, due to more fresh fuel in the core.
Figure 4. Discharge burnup and $k_{\text{eff}}$ of the equilibrium core for different pebble per day. Fuel temperature at equilibrium condition also affected by the pebble per day parameter although the temperature swing is not significant, as shown in Figure 5.

Figure 5. Peak and average fuel temperature of the equilibrium design for different pebble per day parameter.
Axial power density distributions of the equilibrium core are given in Figure 6. It shows the typical distribution of multipass pebble bed fuel in which the peak value is lower than the half core. This condition is due to non-fresh fuel which is re-inserted in the top of the core causing the fission reaction is scattered in the axial core and have it peaks below the half core. This condition is different compare to the once-through-then-out (OTTO) design in which only fresh fuels are inserted in the top of the fuel, causing most of the fission reaction occurred in the upper part of the core. Number of pebble recirculated per day gives a non-significant effect to the power density distribution.

![Axial power density distribution of the equilibrium cores.](image)

**Figure 6.** Axial power density distribution of the equilibrium cores.

Results of the DLOFC accident is graphically shown in Figure 7. It shows that the fission reaction, which generate power and will cause higher temperature, can be decreased and stop due to fuel temperature increase along the accident. This phenomenon shows the passive safety feature of the RDE design. The maximum fuel peak temperature for the 123 fuel per day is 1015.9°C which is far lower compare to 1620°C, the maximum temperature limit of the TRISO based fuel.

![DLOFC accident analysis of the RDE equilibrium design.](image)

**Figure 7.** DLOFC accident analysis of the RDE equilibrium design.
5. Conclusion
Equilibrium analysis of the RDE design is already performed. There are several option of possible equilibrium design of RDE, however, due to discharge burnup target of the RDE of 80 MWD/Kg the equilibrium design with 123 pebble per day recirculation is chosen. On steady-state condition the maximum and average fuel temperature of the equilibrium design is 890.9°C and 495.1°C, respectively. Under DLOFC accident, which conformed as one of the severest hypothetical accident, the maximum fuel temperature is 1015.9°C which shown the sound passive safety feature of RDE design.

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