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# Alternative Fueling Scheme for the Indonesian Experimental Power Reactor (10 MWth Pebble-Bed HTGR)

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# Abstract

The National Nuclear Energy Agency of Indonesia (BATAN) is launching a plan (2014) to build an 10 MWth Experimental Power Reactor (*Reaktor Daya Eksperimental*, RDE) in the Agency's largest Research Center site, i.e. the Puspiptek Complex, Serpong, South Tangerang, Banten, as a first strategic milestone for the introduction of large scale nuclear power plant fleets into the country. The main objective of the plan is to demonstrate safe and reliable electricity and process heat generation from a nuclear reactor. The RDE is a very small sized pebble-bed high temperature gas-cooled reactor (HTGR) with low enriched uranium (LEU) UO<sub>2</sub> TRISO fuel. Following our previous design study with multipass fueling scheme, a scoping study on fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment was conducted for the simpler once-through-then-out (OTTO) fueling scheme. No need of burnup measurement devices and refueling mechanism to send back discharged fuel pebbles into the core, low power and power density, and simple operation of the RDE become strongest motivation for the present work. The objective function for the optimization is the fissile loading requirement per energy generated (kg/GWd). The optimal heavy metal loading was found around 8 g/pebble while the uranium enrichment corresponding to the 80 GWd/t discharge burnup constraint is approximately 13.7 w/o. Compared with the burnup calculations results of multipass fueling scheme, OTTO fueling scheme burnup performance is slightly inferior in that slightly higher enrichment and fissile loading per pebble are required to achieved the same average discharge burnup.

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Keywords: Indonesian Experimental Power Reactor (RDE), Pebble-Bed Reactor, HTGR, OTTO, Multipass, uranium fuel cycle

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#### 1. Introduction

The National Nuclear Energy Agency of Indonesia (BATAN) is launching a plan (2014) to build an Experimental Power Reactor (*Reaktor Daya Eksperimental*, RDE) [1] in the Agency's largest Research Center site, i.e. the Puspiptek Complex, Serpong, South Tangerang, Banten, as a first strategic milestone for the introduction of large scale nuclear power plant fleets into the country. The main objective of the plan is to demonstrate safe and reliable electricity and process heat generation from a nuclear reactor. According to the User Requirement Document (URD) [1] together with its technical specification documents (TSD) issued by BATAN, the RDE adopted a very small sized pebble-bed high temperature gas-cooled reactor (HTGR) with a thermal output of 10 MWth, fueled with low enriched uranium (LEU) UO<sub>2</sub> TRISO fuel under multipass or once-through-then-out (OTTO) fueling scheme. The thermal heat generated in the core is transferred to steam generator (for electricity generation) and a heat utilization plant via an intermediate heat exchanger (IHX). The use of IHX is expected to ensure a high degree of plant safety especially the steam/water ingress events can be avoided.

In our previous design study [2], a scoping study on fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment was conducted for the multipass fueling scheme. In the present work, we extend our scoping study to include the once-through-then-out (OTTO) fueling scheme. The OTTO fueling scheme has several advantages over the multipass fueling scheme in that no need of burnup measurement devices and refueling mechanism to send back discharged fuel pebbles into the core. The low power and power density, and simple operation of the RDE are the strongest motivations for the present work.

As already shown and explored in Ref. [2], the URD and its TSD provide general main specifications of the RDE, however, many detail design parameters on the core dimension, fuel composition etc. are given in term of ranges of value which should be further optimized during the conceptual, basic and detail design phases. An optimal fuel composition in the operation of a pebble-bed HTGR is a very important design parameter since it will directly affect the fuel cost, new and spent fuel storage capacity as well as other back-end environmental burden.

Similar to our previous work, the present scoping study on the fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment is conducted. The main goal of this study is to obtain optimal ranges of HM loading per pebble and uranium enrichment for the RDE design. HM loading per pebble strongly affects the neutron moderation (core neutron spectrum) while uranium enrichment is correlated directly with the achievable discharge burnup. The present work is expected to contribute in providing an optimal fuel composition under OTTO fueling scheme which can be directly compared with the results of the multipass fueling scheme.

Design Parameters	Specifications Issued by URD/TSD	Present Analysis
Thermal Power (MW)	10	10
Core Diameter (m)	< 2.5	1.8 [3]
Core Height/Diameter Ratio	>1.1	1.1 (Height = 1.97 m)
Ave. Core Power Density (PD, W/cm <sup>3</sup> )	$2.0 \le PD \le 3.0$	2.0 (Max. Core Vol.)
Upper Core Void Height (m)	-	0.4 [3]
Radial Reflector Thickness (m)	-	0.5
Upper and Lower Reflector Thickness (m)	-	1.0
<sup>235</sup> U Enrichment (w/o)	≤ 17	10 – 20 (LEU)
HM Loading (g/pebble)	$\leq 20$	4 - 10
Ave. Discharge Burnup (GWd/t)	80	80
Fueling Scheme	Multipass/	OTTO
	OTTO	(10 flow paths)
He Inlet/Outlet Temp. (C)	250/700	250/700
He Inlet Pressure (MPa)	3	3

Table 1. Main design parameters and constraints of the 10 MWth RDE.

#### 2. RDE Technical Specifications

In Table 1, the main design parameters and constraints of the RDE are listed. The parameters and constraints shown in the second column of the table were taken from the URD/TSD issued by BATAN. The thermal output, discharge burnup and the coolant inlet/outlet temperature and pressure are already fixed. As for the core dimension, three design constraints are imposed, that is, the maximum core diameter, minimum height/diameter ratio and average core power density. On the other hand, as for the fuel composition, only the maximum uranium enrichment (17 w/o) and maximum HM loading (20 g/pebble) are imposed. The third column of Table 1 gives the design parameters taken for the present scoping study. The core diameter is set to 1.8 m (derived from the Chinese 10 MWth HTR-10 [3]) while the core height/diameter ratio and average power density are set to its minimum and maximum value, i.e. 1.1 and 2 W/cm<sup>3</sup>, respectively, to obtain good neutron economics. The void cavity at the top of the core is necessary and its height is set to be approximately 40 cm [3]. As for the fresh fuel composition, the scoping study is conducted over uranium enrichment in the range of 10 to 20 w/o and HM loading in the range of 4 to 10 g/pebble. Cases of uranium enrichment higher than the maximum design constraint (17 w/o) are also considered for the sake of completeness since the possible maximum uranium enrichment for LEU is 20 w/o. Cases with HM loading less than 4 or higher than 10 g/pebble are excluded through preliminary screening calculations.

The URD issued by BATAN allows the RDE to be operated under the once-through-then-out (OTTO) fueling scheme, however no detail specification on the radial zoning is given. In the present work, the pebble flow is simulated with 10 flow paths (flow path index of 1 to 10, index=1 is in the core center and index=10 is adjacent to the radial reflector). Since detail fuel specification and core-reflector structures and dimensions etc. are not presently available, as in our previous work [2] we assume no boron (equivalent) impurity in the fuel, 50 cm (radial) and 100 cm (axial) thickness of pure graphite reflectors with graphite density of 1.75 g/cm<sup>3</sup>.

# 3. Analytical Code and Group Constants

The pebble fuel movement, burnup, core criticality calculations and core equilibrium search are carried out by an upgraded version of BATAN-MPASS [4], a general in-core fuel management code for pebble-bed HTGRs, featured with many automatic equilibrium and criticality searching options as well as thermal-hydraulic calculation capability. The code has been validated with the German HTR-Module design, the validation results have also been used as a comparative solution for other code [5]. The TRISO coated particle fuel and pebble fuel element specifications are shown in Table 2. The microscopic cross-sections (4 energy groups, Table 2) and their self-shielding factors as a function of temperature and composition were prepared using several parts of the VSOP code system [6]: ZUT-DGL, THERMOS and GAM. In the upgraded version, amongst other additional options, users may specify a different fissile enrichment for each flow path.

In Table 3, the heavy metals, fission products, moderators and poisons nuclides used in the burnup chain of BATAN-MPASS are listed. Group constants for the cavity at the top of the core are determined according to the method developed by Gerwin and Scherer [7]. Using their method, different axial and radial diffusion coefficients can be obtained. The detail discussion of the in-core thermal-hydraulic model used in the BATAN-MPASS code was already given by Liem and Sekimoto [8]. By using the core equilibrium search option, all calculation cases converged to an equilibrium core with effective multiplication factor (keff) equals to 1.0 (critical).

# 4. Results and Discussion

The scoping analysis results are shown in Figures 1 and 2. Figure 1 (a) shows the fissile loading requirement as a function of HM loading for 4 values of uranium enrichment. The results for multipass fueling scheme are also shown for comparison. For both fueling schemes, the fissile loading requirement per unit energy generated (kg/GWd) decreases as the uranium enrichment increases. For all values of uranium enrichment, one can find an optimal value of HM loading per pebble, which is around 8 g/pebble for both fueling schemes. These optimal compositions also indicate the optimal moderation for the reactor.

Figure 1 (b) shows the pebble fuel element discharge burnup as a function of HM loading for 4 values of uranium enrichment. The results for multipass fueling scheme are also shown for comparison. From the figure, it can be

observed an almost linear proportionality of discharge burnup to uranium enrichment for both fueling schemes. Similar to Figure 1(a), for a particular value of uranium enrichment one can find an optimal value of HM loading per pebble, which is also around 8 g/pebble. If the design constraint of 80 GWd/t discharge burnup is imposed then for the optimal HM loading of 8 g/pebble case, the uranium enrichment is found to be around 13.7 w/o and 13.1 w/o for OTTO and multipass fueling scheme, respectively. For the case of optimal HM loading and uranium enrichment of 13.7 w/o, the pebble fuel residence time in the core is around 4.6 years (cf. Figure 2(a)).

r	TRISO coated particle fuel	
Kernel	material	( <sup>235</sup> U/ <sup>238</sup> U)O <sub>2</sub>
	diameter (µm)	500
	density (g/cm <sup>3</sup> )	10.9
Coatings	material	PyC/PyC/SiC/PyC
(from inner)	thickness (µm)	90/40/35/35
	density (g/cm <sup>3</sup> )	0.9/1.85/3.2/1.85
	Pebble fuel element	
Fuel matrix	material	graphite
	diameter (cm)	5
Outer layer	material	graphite
	thickness (cm)	0.5
Fuel element	diameter (cm)	6
	Few group structure	
Upper bound (eV)	Lower bound (eV)	Range
107	1.11×10 <sup>5</sup>	fast fission
$1.11 \times 10^{5}$	2.90×101	slowing down
$2.90 \times 10^{1}$	2.38	resonance
2.38		thermal

Table 2. Standard data for pebble fuel element cell calculation.

Table 3. Nuclides used in BATAN-MPASS code

Heavy metals	<sup>232</sup> Th, <sup>233</sup> Pa, <sup>233</sup> U, <sup>234</sup> U, <sup>235</sup> U, <sup>236</sup> U, <sup>237</sup> Np, <sup>239</sup> Np,
-	<sup>239</sup> Pu, <sup>240</sup> Pu, <sup>241</sup> Pu, <sup>242</sup> Pu
Fission products	<sup>83</sup> Kr, <sup>95</sup> Zr, <sup>95</sup> Mo, <sup>97</sup> Mo, <sup>99</sup> Tc, <sup>101</sup> Ru, <sup>103</sup> Ru,
-	<sup>103</sup> Rh, <sup>105</sup> Rh, <sup>105</sup> Pd, <sup>106</sup> Pd, <sup>109</sup> Ag, <sup>113</sup> Cd, <sup>131</sup> I,
	<sup>131</sup> Xe, <sup>133</sup> Xe, <sup>135</sup> Xe, <sup>136</sup> Xe, <sup>133</sup> Cs, <sup>134</sup> Cs, <sup>141</sup> Pr,
	<sup>143</sup> Pr, <sup>143</sup> Nd, <sup>145</sup> Nd, <sup>146</sup> Nd, <sup>147</sup> Pm, <sup>148m</sup> Pm,
	<sup>148</sup> gPm, <sup>147</sup> Sm, <sup>148</sup> Sm, <sup>149</sup> Sm, <sup>150</sup> Sm, <sup>151</sup> Sm,
	<sup>152</sup> Sm, <sup>153</sup> Eu, <sup>154</sup> Eu, <sup>155</sup> Eu, <sup>155</sup> Gd, <sup>156</sup> Gd,
	<sup>157</sup> Gd, Non-saturating FP
Moderators	$^{12}C, ^{16}O$
Poisons	B, Impurity in C

Figure 2(b) shows the maximum power density as a function of HM loading. This parameter is sensitive to both uranium enrichment and heavy metal loading per pebble. It can be observed that abrupt changes in the maximum power density curves for uranium enrichment values of 15.0, 17.5 and 20.0 w/o. These trends can be explained from the fact that higher HM loading will result in a longer pebble fuel residence time and the axial power density profile will produce higher peak toward the core top. Nevertheless, even for 10 g/pebble HM loading cases the maximum power density is still lower than 4 W/cm<sup>3</sup> which is still smaller than the maximum allowable value.

Figure 2(c) shows the conversion ratio as a function of HM loading. As expected, lower uranium enrichment gives better conversion ratio. Higher HM loading per pebble also significantly increases the conversion ratio. With higher HM loading, the pebble fuel resides longer in the core and the fertile to fissile conversion is enhanced.



Fig. 1. (a) Fissile loading requirement; (b) Average discharge burnup as function of heavy metal loading and uranium enrichment (O=OTTO, M=multipass).

For the optimal HM loading and uranium enrichment of 13.7 w/o, the fissile nuclide distributions are shown in Figures 3 and 4, for <sup>235</sup>U, <sup>239</sup>Pu, and <sup>241</sup>Pu, <sup>237</sup>Np, respectively. From Figure 3(a), it can be observed that <sup>235</sup>U is depleted more in the outer pebble flow paths than the inner ones since the pebble flow velocities in the outer paths are slower. Consequently, the discharged burnup levels are also higher for pebbles discharged from the outer flow paths.



Fig. 2. (a) Pebble fuel average residence time; (b) Maximum power density; (c) Conversion ratio as function of heavy metal loading and uranium enrichment.

Figures 3(b) and 4(a) show that fissile plutonium is produced and accumulated along the pebble flow paths, however, at core lower regions the consumption rates are greater than the production rates so that the fissile plutonium nuclide densities decrease. Figure 4(b) shows the <sup>237</sup>Np nuclide densities as function of pebble flow path and axial positions. For pebble flow path index 1 to 8, <sup>237</sup>Np is produced and accumulated along the pebble flow paths, however, for flow path index 9 and 10 near the radial reflector where the pebble flow velocities are slower, the consumption rates are greater than the production rates at the core lower regions and their trends are similar with the fissile plutonium shown in Figures 3(b) and 4(a).



Fig. 3. Nuclide densities as function of pebble flow index and axial position (core top = 209.0 cm, core bottom = 419.7 cm).



Fig. 4. Nuclide densities as function of pebble flow index and axial position (core top = 209.0 cm, core bottom = 419.7 cm)

For the optimal HM loading and uranium enrichment of 13.7 w/o, the group neutron flux distributions are shown in Figure 5, and the power density distributions are shown in Figure 6. High thermal neutron peaks appear at the radial and axial reflector regions adjacent to the core. From Figure 6, one can observed that typical OTTO power density distributions where the power peaks are located in the upper regions of the core.

#### 5. Concluding Remarks and Future Works

A scoping study on the optimal fuel composition (heavy metal loading per pebble and uranium enrichment) for the 10 MWth RDE, with LEU UO<sub>2</sub> TRISO fuel under OTTO fueling scheme, was conducted using an upgraded version of BATAN-MPASS code. The objective function for the optimization is the fissile loading requirement per energy generated (kg/GWd). The optimal heavy metal loading was found around 8 g/pebble while the uranium enrichment corresponding to the 80 GWd/t discharge burnup constraint is approximately 13.7 w/o. Compared with the burnup calculations results of multipass fueling scheme [2], OTTO fueling scheme burnup performance is slightly inferior in that slightly higher enrichment and fissile loading per pebble are required to achieved the same average discharge burnup. However the optimal fuel compositions for the two fueling scheme are close to each other, i.e. identical 8 g/pebble and uranium enrichment of 13.7 and 13.1 w/o for OTTO and multipass, respectively.



Fig. 5. Group neutron flux distribution for the optimal fuel composition case

The results of the present scoping study can be improved in the future when other detail design parameters become available in the basic and detail design phases. These include the detail core-reflector structures and dimensions, control rod and reserved shutdown absorber in the radial reflectors, impurities in fuel and graphite etc.

The results of safety evaluation in the future may provide feedback to the present scoping study and the optimal composition of the fuel may slightly shifts from the above mentioned values.



Fig. 6. (a) Power density spatial distribution; (b) Power density along the pebble flow path for the optimal fuel composition case

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#### References

- [1] User Requirement Document Reaktor Daya Eksperimental -. BATAN, 2014.
- [2] Liem PH, Sembiring TM, Arbie B, Subki I. Analysis of the Optimal Fuel Composition for the Indonesian Experimental Power Reactor (10 MWth Pebble-Bed HTGR). To be published in Kerntechnik 2016.
- [3] Xu Y, Zuo K. Overview of the 10 MW High Temperature Gas Cooled Reactor Test Module Project. Nuclear Engineering and Design 2002; 218: 13-23.
- [4] Liem PH. BATAN-MPASS: A general fuel management code for pebble-bed high-temperature reactors. Annals of Nuclear Energy 1994; 21 (5): 281-290.
- [5] Tery WK, Gougar HD, Ougouag AM. Direct deterministic method for neutronics analysis and computation of asymptotic burnup distribution in a recirculating pebble-bed reactor. Annals of Nuclear Energy 2002; 29: 1345-1364.
- [6] Teuchert E et al. VSOP Computer Code System for Reactor Physics and Fuel Cycle Simulation. Jul-1649 1980.
- [7] Gerwin H, Scherer W. Treatment of the Upper Cavity in a Pebble-Bed High Temperature Gas-Cooled Reactor by Diffusion Theory. Nuclear Science and Engineering 1987; 97: 9-19.
- [8] Liem PH, Sekimoto H. Neutronic and Thermal Hydraulic Design of the Graphite Moderated Helium-Cooled High Flux Reactor. Nuclear Engineering and Design 1993; 139 (2): 221-233.