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## Criticality Safety Analysis of the Dry Cask Design with Air Gaps for RDNK Spent Pebble Fuels Storage

Pungky Ayu Artiani<sup>1</sup>, Yuli Purwanto<sup>1</sup>, Aisyah<sup>1</sup>, Ratiko<sup>1</sup>, Jaka Rachmadetin<sup>1</sup>, Kuat Heriyanto<sup>1</sup>

<sup>1</sup>Center for Radioactive Waste Technology, National Nuclear Energy Agency of Indonesia (BATAN), 15314 Tangerang Selatan, Indonesia

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### ABSTRACT

Reaktor Daya Non-Komersial (RDNK) with a 10 MW thermal power has been proposed as one of the technology options for the first nuclear power plant program in Indonesia. The reactor is a High Temperature Gas-Cooled Reactor-type with spherical fuel elements called pebbles. To support this program, it is necessary to prepare dry cask to safely store the spent pebble fuels that will be generated by the RDNK. The dry cask design has been proposed based on the Castor THTR/AVR but modified with air gaps to facilitate decay heat removal. The objective of this study is to evaluate criticality safety through  $k_{\text{eff}}$  value of the proposed dry cask design for the RDNK spent fuel. The  $k_{\text{eff}}$  values were calculated using MCNP5 program for the dry cask with 25, 50, 75, and 100% of canister capacity. The values were calculated for dry casks with and without air gaps in normal, submerged, tumbled, and both tumbled and submerged conditions. The results of calculated  $k_{\text{eff}}$  values for the dry cask with air gaps at 100% of canister capacity from the former to the latter conditions were 0.127, 0.539, 0.123, and 0.539, respectively. These  $k_{\text{eff}}$  values were smaller than the criticality threshold value of 0.95. Therefore, it can be concluded that the dry cask with air gaps design comply the criticality safety criteria in the aforementioned conditions.

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## 1. INTRODUCTION

In order to achieve country's electrification and renewable energy targets, the Government of Indonesia considered nuclear as one of the energy sources in the national energy mix. Among many reactor systems, Reaktor Daya Non-Komersial (RDNK) with a 10 MW thermal power has been proposed as one of the technology options for the

national first nuclear power plant. The RDNK is a High Temperature Gas-Cooled Reactor (HTGR) with helium gas as its coolant[1]. This type of reactor is attractive because, in addition to efficient electricity production, it could offer the possibility to provide heat for cogeneration processes[2]. Furthermore, this reactor is considered to have a good safety level[3]. Similar to other types of reactor, one of the major issues in the RDNK program is the management of spent fuel[4]. The spent fuel typically contains over 95% of the total radioactivity in the radioactive waste generated from nuclear power plant operation[5, 6]. Due to unavailability of geological disposal, dry cask

\* Corresponding author. Tel./Fax.: (021) 7563142

E-mail: [pungky@batan.go.id](mailto:pungky@batan.go.id)

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storage became an emerging option to safely store of the spent fuel in many countries[7, 8].

The RDNK uses  $UO_2$  spherical fuel elements called pebbles[9]. Several dry casks have been designed for this type of fuel, one of which is Castor THTR/AVR. The proposed dry cask for the spent fuel from the RDNK is based on the same design but modified with air gaps. The function of air gaps is to improve the removal of decay heat generated by radionuclides decay reaction in the spent fuel. The presence of the air gaps may provide advantages as many processes in dry cask storage are temperature dependent[10]. For example, high temperature may accelerate deformation of dry storage materials as well as corrosion process[11]. It was reported that the decay heat could generate hot spots due to heat accumulation in dry cask without air gaps. The hot spots could damage canister material structures which subsequently increasing the risk of radionuclides release from spent fuel to environment[12]. Therefore, the air gaps are not only facilitating the decay heat removal but also improving the integrity of the dry casks.

Beside the above-mentioned thermal aspect and mechanical integrity, the dry cask storage shall comply many other rigorous criteria and standard requirements, one of them is the safety of nuclear criticality[13, 14]. It is dedicated to prevent nuclear and radiation accidents from an inadvertent, self-sustaining nuclear chain reaction that is shown as  $k_{eff}$  value[15]. The purpose of this study is to assess the criticality of the dry cask designs to be used for RDNK spent fuel through determination of their  $k_{eff}$  values. The values were calculated using MCNP5 program which had already been used in analyzing the criticality both at the nuclear reactor and at the non-nuclear reactor facility[16–19]. The calculations were performed for the dry cask designs with and without air gaps in normal and abnormal conditions. Finally, the calculated  $k_{eff}$  values were compared to the threshold value ( $k_{eff} < 0.95$ ) to determine the safety margin of the nuclear criticality for the dry cask under different conditions.

## 2. METHODOLOGY

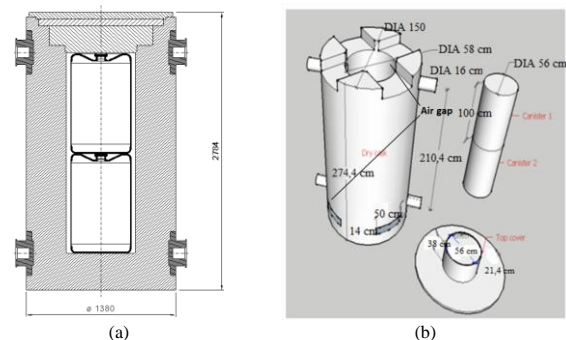
### 2.1. FUEL AND DRY CASK PROPERTIES

The RDNK uses pebble fuels with an approximate diameter of 6 cm, the composition of which is shown in Table 1. For conservative result, the calculation of the  $k_{eff}$  values were based on new unirradiated pebble fuel because it has higher reactivity compared to the irradiated one.

**Table 1.** Material composition of one pebble fuel of the RDNK reactor[9].

No.	Isotope	Weight (gram)
1.	U-235	0.749
2.	U-234	0.00022
3.	U-238	3.657
4.	C-12	195.538
5.	Si-28	0.407
6.	O-16	0.594

The dry cask for RDNK spent fuel is developed using similar dimensions of that of Castor THTR/AVR [20] which are shown in Fig. 1. It is designed to accommodate two canisters arranged one above the other, each of which has a capacity of 950 spent fuels. The canister is made of stainless steel, whereas the cask overpack is made of carbon steel. The dry cask is equipped with four openings at near the top and bottom of the cask for air ventilation.

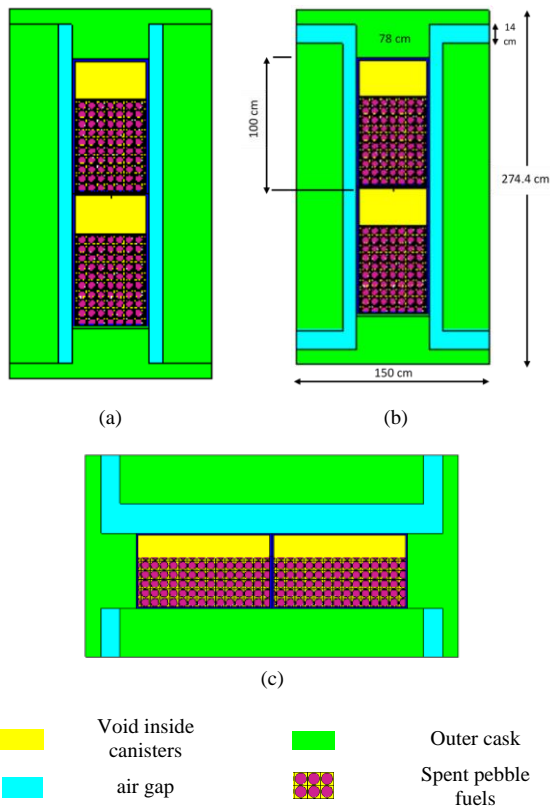


**Fig. 1.** Illustration of (a) Castor THTR/AVR dry cask [20], (b) the proposed dry cask design.

### 2.2. CRITICALITY EVALUATION

Fig. 2 shows the example representation of geometry model for criticality evaluation. The  $k_{eff}$  values were calculated for the dry cask with different spent fuel loading percentages of the canister capacity, i.e., 25, 50, 75 and 100%. These  $k_{eff}$  values were calculated for the dry cask design with and without air gaps. Furthermore, the  $k_{eff}$  values for both designs with different spent fuel loading percentages were calculated in normal and abnormal conditions. Three conditions of the latter were evaluated: (1) The dry cask is submerged in water, (2) tumbled in rotating horizontal cylinder, and (3) both tumbled and submerged in water. These abnormal conditions were selected for safety assessment in the case of flooding, tsunami, and/or earthquake occur. In the case of submersion in water, it was assumed that the water fill the whole space in the air gaps for dry cask with air gaps design. On the other hand, in the tumbled condition, the dry cask was assumed to maintain its integrity and the spent fuel is horizontally distributed inside the two canisters. In all cases, the dry cask was

modeled as three dimensions cylindrical layer. The spent fuels are arranged in simple cubic packing. At full capacity, the packing fraction for this type of arrangement which was calculated from the ratio of the volume occupied by the spent fuels to the volume of canister is 0.49. It was assumed that the spent fuels maintain their simple cubic arrangement, thus the packing fraction was assumed to be constant. The  $k_{eff}$  values were calculated using 5000 number of neutrons and 250 iterations. The first 50 iterations were used to obtain the convergence in the MCNP5 calculation.

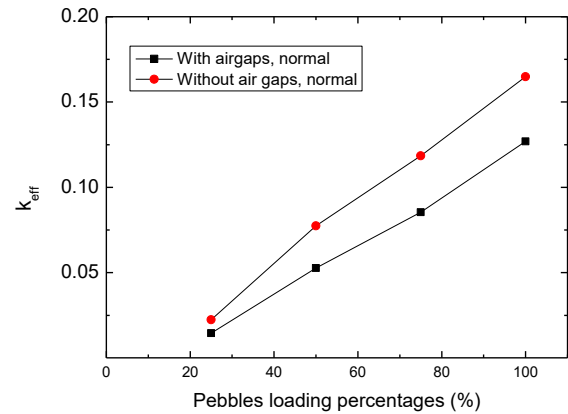


**Fig. 2.** Representation of geometry models for the criticality calculation for (a) a dry cask without air gaps, (b) a dry cask with air gaps, and (c) a dry cask with air gaps tumbled in rotating horizontal cylinder. All the representative models were for dry casks with 75% spent fuel loading of the canister capacity.

### 3. RESULTS AND DISCUSSION

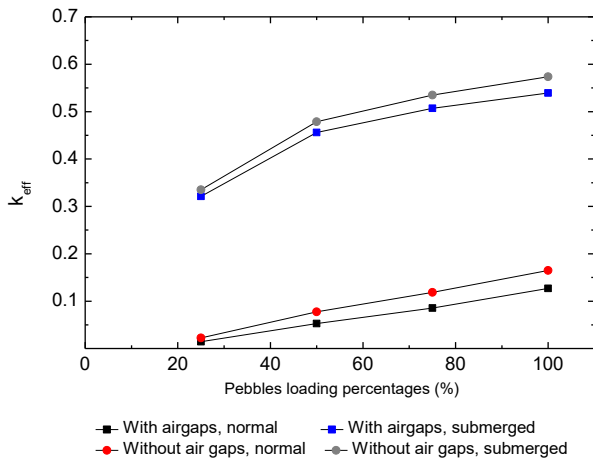
Fig. 3 shows the  $k_{eff}$  values of the dry casks with air gaps at different spent fuel loading percentages of the canister capacity in normal condition compared to those of without air gaps. As can be seen in the figure, the  $k_{eff}$  values increased linear to the spent fuel loading increased. At the same loading percentages, the  $k_{eff}$  values of dry casks with air gaps were lower than those without air gaps.  $k_{eff}$  values for dry casks with and without air gaps at full capacity were 0.127 and 0.165,

respectively. These values were lower than that of the permitted threshold ( $k_{eff} < 0.95$ ).



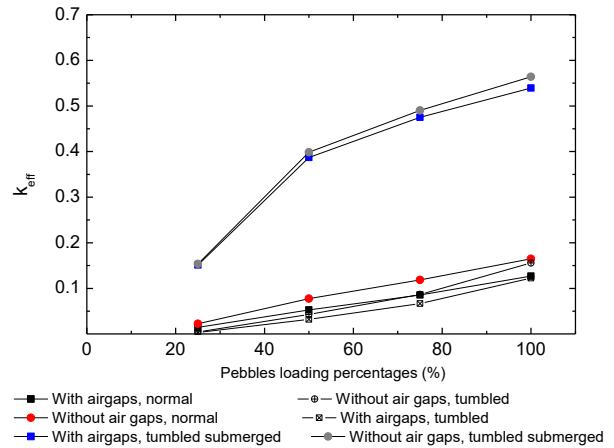
**Fig. 3.**  $k_{eff}$  values of the dry casks with and without air gaps at different spent fuel loading percentages of the canister capacity in normal condition.

Fig. 4 illustrates  $k_{eff}$  values of the dry casks with and without air gaps at different spent fuel loading percentages of the canister capacity in submerged compared to those in normal condition. For both dry casks with and without air gaps,  $k_{eff}$  values of dry casks submerged in water were higher than those in normal condition. This is because water act as a moderator. Thus, the presence of water increases the  $k_{eff}$  values of the dry casks. The same phenomenon also makes the dry cask with air gaps is more vulnerable to criticality because the water may fill the air gap through the opening at the top and bottom of the cask. Indeed, if the water fills the air gap, it become closer to the canister containing the spent fuel which subsequently affect the  $k_{eff}$ . However, the calculation result showed that the increase of  $k_{eff}$  of the dry casks with and without air gaps from normal to submerged conditions were similar. At full capacity,  $k_{eff}$  values of the dry casks with and without air gaps were 0.539 and 0.576. Although the values were significantly higher than those in normal condition, they were still lower than that of the permitted threshold ( $k_{eff} < 0.95$ ).



**Fig. 4.** The  $k_{eff}$  values of the dry casks with and without air gaps at different spent fuel loading percentages inside the canister in normal and submerged condition.

Fig. 5 shows the  $k_{eff}$  values of the dry casks with and without air gaps at different spent fuel loading percentages of the canister capacity in tumbled, and simultaneously tumbled and submerged compared to those in normal conditions. The figure implies that  $k_{eff}$  values for dry casks with and without air gaps at the same pebbles loading in tumbled condition were similar than those in normal conditions. The  $k_{eff}$  values for the tumbled dry casks with and without air gaps at full capacity were 0.127 and 0.165, respectively, which were the same to those of in normal condition. On the other hand,  $k_{eff}$  values of the tumbled dry casks submerged in water were higher than those of not submerged. At full capacity, the  $k_{eff}$  values of the submerged dry casks with and without air gaps were 0.539 and 0.564, respectively. These values were similar to those of submerged dry casks in normal position which also lower than that of the permitted threshold ( $k_{eff} < 0.95$ ). These results also show that the air gaps and the geometry of the dry cask, i.e., in normal or tumbled position, does not affect the criticality of the dry casks both in normal and submerged conditions.



**Fig. 5.** The  $k_{eff}$  values of the dry casks with and without air gaps at different spent fuel loading percentages of the canister capacity in normal, tumbled, and tumbled and submerged conditions.

## 5. CONCLUSION

Criticality safety assessment has been carried out for evaluation of dry cask design equipped with air gaps. The dry cask is intended to be used for spent fuel from RDNK. The result shows that  $k_{eff}$  values of the dry casks in normal, submerged, tumbled, and both tumbled and submerged were 0.127, 0.539, 0.123, and 0.539, respectively. These values were approximately the same to those of without air gaps in the same conditions. All the calculated  $k_{eff}$  values were smaller than the criticality threshold value of 0.95. Therefore, it can be concluded that the dry cask with air gaps design for the RDNK spent fuel comply the criticality safety criteria in the aforementioned conditions.

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## AUTHOR CONTRIBUTION

All authors equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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