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Assessment of Radiological Impacts from Postulated Accident Conditions of HTGR: A Case Study in Serpong Nuclear Area

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ABSTRACT

High-temperature gas-cooled reactor (HTGR) design has improved safety which relies on its TRISO-coated fuel particles that are considered as no failure even in accident conditions. However, the radiological impacts of accident conditions in HTGR are still important to be assessed. This research is aimed to perform a radiological impacts assessment of two postulated accidents of HTGR, which are depressurization and water ingress accidents. As a case study, a 10-MWt pebble-bed HTGR design named Reaktor Daya Eksperimental with the planned site located in Serpong Nuclear Area was chosen. The source terms from the accident conditions were estimated using the mechanistic source term model and the dose consequences were calculated using PC-COSYMA. The input data for PC-COSYMA, consisting of meteorological, population distribution, agricultural, and local farm data, were compiled based on the site data of the Serpong Nuclear Area. The radiological impacts were assessed based on individual and collective doses. The results showed that the highest dose will be received by the community within a radius of 250 m to the south from the reactor, amounting to about 7.22E-02 mSv and 3.04E-03 mSv from depressurization and water ingress accidents, respectively. It was also found that these accidents only result in minor radiological impacts since the highest dose obtained is still below the limit set by the national nuclear regulatory agency (BAPETEN) and do not require any countermeasures (iodine thyroid blocking, sheltering, evacuation, food ban, decontamination, and relocation).

1. INTRODUCTION

High-temperature gas-cooled reactor (HTGR) is an advanced nuclear reactor design that offers many excellent features compared to the existing conventional nuclear power reactors. Many countries, including Indonesia through its National Nuclear Energy Agency, have been performing research and development activities on HTGR to support its commercial use. During the past few years, Indonesia has completed detailed in-core fuel management of a 10-MWt pebble-bed HTGR named Reaktor Daya Eksperimental (RDE) [1, 2]. The planned site of the RDE is in South Tangerang, Indonesia.

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One of the advantages of the HTGR is the high safety performance of its fuels which relies on TRISO-coated fuel particles. The TRISO-coated fuel particles in HTGR are resistant to high temperature and undego no damage even during beyond design basic accidents (BDBAs) [3]. However, even though the fuel integrity can be maintained and the probability of large release is minor during accident, the assessment of radiological impacts arising from the accident condition still has to be performed to ensure the public safety around the reactor and to fulfil the regulation issued by the national nuclear regulatory body regarding the emergency preparedness and accident management.

Numerous studies regarding the radiological impacts assessment have been performed on many types of reactors [4–11]. Those research are dominantly performed on light water reactor (LWR)-type or research reactor, while for HTGRs-type several studies have also been performed [12–13]. The works regarding the radiological impact assessment are usually performed for a specific site and specific type of reactor. This is due to the unique characteristic of each site such as the meteorological condition, population density, consumption rate, etc. Each type of reactor also gives rise to different source terms which contribute to dose calculation.

The aim of this study is to perform radiological impact assessment of two postulated accident conditions of RDE in the chosen site of South Tangerang, Indonesia. The two postulated accidents used are depressurization and water ingress accidents. The radiological impacts were assessed in terms of short-term and long-term individual doses, collective doses, risk, and the necessary countermeasures based on the criteria issued by the Indonesian Nuclear Energy Regulatory Agency (BAPETEN). The calculation was started from the source term determination using mechanistic source term model. The calculation of atmospheric dispersion, surface deposition, and radiation doses were performed using PC-COSYMA. The obtained results of radiation doses were then evaluated based on the criteria for countermeasures, and the conclusion of the overall radiological impacts arising from the accident conditions were drawn from those results.

2. METHODOLOGY

The methodology approach used in this work is shown in Fig. 1. In general, the calculation of radiological impacts consists of two steps, which are the source term determination and the radiation doses calculation. The source terms from the two postulated accident conditions, which are the depressurization and water ingress accident, were determined using the mechanistic source term model [14]. The radiation doses calculation was performed using PC-COSYMA. All input data for PC-COSYMA consisting of meteorological and spatial data were taken from the site data of Serpong, South Tangerang. The radiological impacts are evaluated based on the short-term and long-term individual effective doses, the collective doses to 50 years, and the mean long-term individual risk of incidence.

2.1 The source terms determination

Source term is a specific parameter which depends on the type of reactor and can be different for each postulated accident. The calculation of source term of RDE in the depressurization and water ingress accident has been performed in our previous work which was based on the reactor parameter shown in Table 1. The lists of the source term considered in this work are shown in Table 2.

The source term was calculated based on the radionuclide inventory from the previous work [15, 16]. The inventory of radionuclide was calculated using ORIGEN 2.1 code, while the source terms were estimated using mechanistic source term model. Mechanistic model is an approximation model for estimating the release of radioactive material starting from the fuel element, reactor cooling system, reactor building and finally the environment. The failure and release fraction for each subsystem parameters used in this model were taken from experimental and simulation data performed by other researchers, for example the failure fraction used was in the range of 1.0E-04 and 1.0E-03.

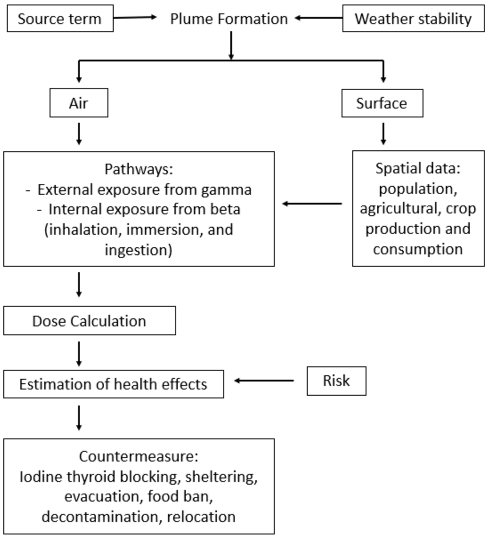

Fig 1. The methodology approach used for radiological impacts assessment

Table 1. The reactor parameters [2]

No	Parameters	Value
1	Thermal power	10 MW
2	U-235 fissile content	17%
3	HM loading per pebble	5 grams
4	Fuel loading scheme	Multipass
5	Average discharge burnup	80 GWd/t
6	Fuel kernel coating	IPyC/SiC/OPyC
7	Density of IPyC/SiC/OPyC	1.9/3.18/1.9
8	Thickness of IPyC/SiC/OPyC	0.004/0.0035/0.004 cm
9	Mass of one pebble	200 grams
10	Number of fuels in equilibrium state	27000 pebbles

2.2 The radiation doses calculation

The calculation of radiation doses using PC-COSYMA was started with the preparation of all input data including source term, meteorological data, and spatial data (population, consumption rate, and local production of agriculture and livestock). In this work, all pathways of radionuclide release were considered. The release of radioactive materials into the atmosphere gives rise to the exposure to human populations through several pathways. Radionuclides in the air can increase the exposure through two main paths, which are external exposure and internal exposure following inhalation of the radionuclides. Radionuclides dispersed in puffs of smoke in the air (plume) will go through a process of deposition to the ground surface.

Table 2. Source term for HTGR postulated accidents [15, 16]

Nuclide	Inventory activity (Bq)	Source term activity (Bq)	
		water ingress accident	depressurization accident
H-3	6.27E+12	1.87E+08	8.15E+08
Kr-83m	1.77E+15	5.29E+11	2.30E+12
Kr-85	1.04E+14	3.11E+10	1.35E+11
Kr-85m	3.85E+15	1.15E+12	5.01E+12
Kr-87	7.39E+15	2.21E+12	9.61E+12
Kr-88	1.04E+16	3.11E+12	1.35E+13
Xe-131m	1.49E+14	4.46E+10	1.94E+11
Xe-133	3.00E+16	8.97E+12	3.90E+13
Xe-133m	9.35E+14	2.80E+11	1.22E+12
Xe-135	1.46E+16	4.37E+12	1.90E+13
Xe-135m	5.94E+15	1.78E+12	7.72E+12
I-131	1.45E+16	4.34E+10	1.89E+10
I-132	1.93E+16	5.77E+10	2.51E+10
I-133	2.99E+16	8.94E+10	3.89E+10
I-134	3.02E+16	9.03E+10	3.93E+10
I-135	2.80E+16	8.37E+10	3.64E+10
Sr-89	1.06E+16	3.17E+08	1.38E+08
Sr-90	1.33E+16	3.98E+08	1.73E+08
Cs-134	8.06E+14	2.41E+07	1.05E+07
Cs-137	1.51E+15	4.51E+07	1.96E+07
Ag-110	1.20E+15	3.59E+07	1.56E+07

Radionuclides can be re-inhaled by human due to interference caused by wind and human. In addition, the deposition of radionuclides into plants and soils will cause the transfer of radionuclides to human through food chain. In general, the calculation of doses received by human was obtained by considering the sources of exposures which can be divided into cloud-shine, ground-shine, inhalation, and ingestion [17].

The calculation of the consequences on PC-COSYMA software uses a segmented Gaussian model based on the Eq. (1). PC-COSYMA calculates the radioactive distribution in the atmosphere according to the wind direction with a minimum of 8 wind directions or sectors, divided according to the spatial angle. In this calculation, the wind direction was divided into 16 sector angles with each angle of 22.5 degrees starting from the North. The radial area around the reactor was divided into 12 areas at the radial distance of 0.25; 0.5; 0.75; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5; 4.0; 4.5 and 5.0 km.

$$X = \frac{Q}{2\pi\sigma_y\sigma_z}\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

where X is the concentration in air (Ci/m^3) on the x-axis in the direction of the wind, y is distance perpendicular to the direction of the wind (m), and z is the height above the ground surface (m); Q is radioactive release from the chimney (Ci/s); μ is average wind speed (m/s); horizontal dispersion coefficient (m) σ_y, ; vertical dispersion coefficient (m) σ_z ; H is effective chimney height (m).

The input for the consumption of agricultural and livestock products are shown in Table 3. The parameters for the radionuclide deposition process at ground level for dry deposition and wet deposition rate for the aerosol group are 1.00E-03 m/s and 8.00E-05 m/s, respectively. For iodine element, the dry and wet deposition rate are 1.00E-02 m/s and 8.00E-05 m/s, respectively. The parameter for the effective radiation dose calculation was taken from the IAEA ICRP-60 for the respiratory rate which is 2.67E-04 m^3/s. The location factors used are 0.14 for groundshine; 0.16 for radioactive clouds, 0.55 for inhalation, 0.55 for the resuspension process, and 0.55 for depositions on the surface of the skin and clothing.

3. RESULTS AND DISCUSSION

3.1 Source term evaluation

From the list of radionuclides in Table 2, the dominant radionuclide obtained as source term are the noble gases Xe and Kr, Cs-134, Cs-137, the iodine group, Ag-110, H-3 and Sr. Those radionuclides generally have long half-life except for I-131 whose half-life is only 8 days. Radionuclides which have a significant impact on radiation doses are I-131, Cs-134, Cs-137, Sr-90 and Ag-110. The noble gases Xe and Kr have an insignificant effect on the internal exposure since they do not react with matter (inert). Noble gases will exert an influence on external doses if the activity is exceedingly high. The same argument for H-3, which is a weak β-emitter.

Table 3. The food stuff and the consumption rate input for PC-COSYMA

Food stuff	Consumption (kg/year)
cow milk	50
meat	25
grain	90
potatoes	50
sweet potatoes	50
green vegetables	30
non-leaf vegetables	25

3.2 Atmospheric dispersion and surface deposition

The atmospheric dispersion and surface deposition of radionuclide are influenced by weather stability, rainfall, wind speed, and the radionuclide characteristics. The contribution of the radionuclides dispersed in the atmosphere is in form of external irradiation (cloud-shine) or internal irradiation when inhaled by human. On the other hand, the contribution of the radionuclides deposited on the ground is in form of external irradiation (ground-shine) and internal irradiation when they are transferred to the food ingested by human. Different radionuclide has different contribution to the internal and external radiation dose.

Table 4. Air activity concentration in the depressurization and water ingress accident

Distance (km)	Time Integrated Radioactivity (Bq s/m^3)							
	Noble Gases		I-131		Cs-137		Other nuclides (Ag-110m, Sr-90)	
	Depress.	W. Ing.	Depress.	W. Ing.	Depress.	W. Ing.	Depress.	W. Ing.
0.250	1.48E+10	9.00E+07	1.82E+05	4.18E+05	1.98E+02	4.55E+02	1.90E+03	4.38E+03
0.500	8.72E+09	5.41E+07	1.05E+05	2.40E+05	1.18E+02	2.72E+02	1.14E+03	2.62E+03
0.750	5.07E+09	3.21E+07	5.93E+04	1.36E+05	7.00E+01	1.61E+02	6.73E+02	1.55E+03
1.000	3.30E+09	2.13E+07	3.79E+04	8.70E+04	4.64E+01	1.07E+02	4.46E+02	1.03E+03
1.500	1.80E+09	1.21E+07	2.01E+04	4.62E+04	2.63E+01	6.04E+01	2.53E+02	5.81E+02
2.000	1.18E+09	8.20E+06	1.29E+04	2.96E+04	4.08E+01	4.08E+01	1.70E+02	3.92E+02
2.500	8.87E+08	6.23E+06	9.41E+03	2.16E+04	3.08E+01	3.08E+01	1.32E+02	2.97E+02
3.000	6.97E+08	4.90E+06	7.19E+03	1.65E+04	1.05E+01	2.42E+01	1.01E+02	2.33E+02
3.500	5.00E+08	3.85E+06	5.56E+03	1.28E+04	8.30E+00	1.91E+01	7.98E+01	1.84E+02
4.000	3.78E+08	3.00E+06	4.28E+03	9.84E+03	6.49E+00	1.49E+01	6.24E+01	1.44E+02
4.500	3.11E+08	2.50E+06	3.54E+03	8.14E+03	5.39E+00	1.24E+01	5.19E+01	1.19E+02
5.000	2.55E+08	2.05E+06	2.87E+03	6.58E+03	4.41E+00	1.01E+01	4.24E+01	9.76E+01

Table 5. Surface activity concentration in the water ingress and depressurization accident

Distance (km)	Radioactivity (Bq/m^2)							
	Sr-90		I-131		Cs-137		Ag-110m	
	Depress.	W. Ing.	Depress.	W. Ing.	Depress.	W. Ing.	Depress.	W. Ing.
0.250	1.75E+00	4.01E+00	1.80E+03	4.14E+03	1.98E-01	4.55E-01	1.57E-01	3.62E-01
0.500	1.05E+00	2.40E+00	1.04E+03	2.38E+03	1.18E-01	2.72E-01	9.41E-02	2.17E-01
0.750	6.18E-01	1.42E+00	5.87E+02	1.35E+03	7.00E-02	1.61E-01	5.57E-02	1.28E-01
1.000	4.09E-01	9.42E-01	3.75E+02	8.61E+02	4.64E-02	1.07E-01	3.69E-02	8.49E-02
1.500	2.32E-01	5.33E-01	1.99E+02	4.57E+02	2.63E-02	6.04E-02	2.09E-02	4.80E-02
2.000	1.56E-01	3.60E-01	1.27E+02	2.92E+02	1.77E-02	4.08E-02	1.41E-02	3.24E-02
2.500	1.18E-01	2.72E-01	9.29E+01	2.13E+02	1.34E-02	3.08E-02	1.07E-02	2.45E-02
3.000	9.28E-02	2.14E-01	7.09E+01	1.63E+02	1.05E-02	2.42E-02	8.36E-03	1.92E-02
3.500	7.32E-02	1.69E-01	5.48E+01	1.26E+02	8.30E-03	1.91E-02	6.60E-03	1.52E-02
4.000	5.73E-02	1.32E-01	4.23E+01	9.70E+01	6.49E-03	1.49E-02	5.16E-03	1.19E-02
4.500	4.76E-02	1.10E-01	3.49E+01	8.02E+01	5.39E-03	1.24E-02	4.29E-03	9.87E-03
5.000	3.89E-02	8.95E-02	2.83E+01	6.49E+01	4.41E-03	1.01E-02	3.51E-03	8.07E-03

Tables 4 and 5 show the concentration of time-integrated air activity (Bq-s/m^3) dispersed in the atmosphere and deposited in the ground, for water ingress and depressurization accident condition, respectively. From Table 4, it can be seen that the activity of noble gases is high, but due to their inert characteristic, they are not absorbed into the body when inhaled and will only contribute to the external radiation dose through cloud-shine. While from Table 5, it can be seen that none of the noble gases are deposited on the ground. This is also due to their inert characteristics so that they are not influenced by dry and wet deposition. For the other radionuclides, there are about 0.01 fraction of the activity dispersed in the atmosphere which then deposited into the ground.

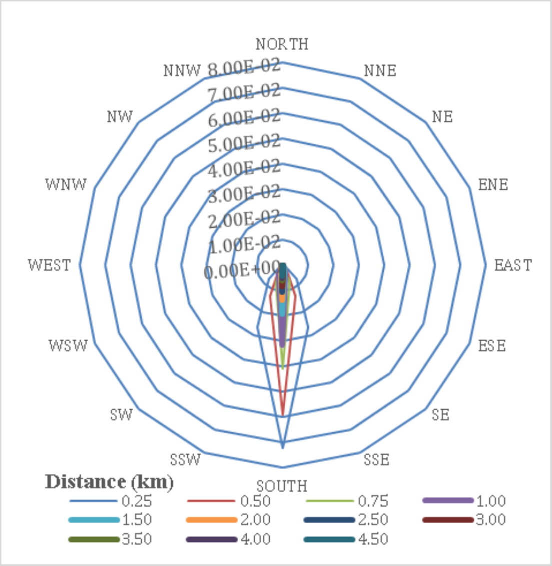

Fig. 2. Short-term individual effective dose for the depressurization accident

Those radionuclides will contribute to the internal radiation dose when inhaled from the air and ingested from the foods, especially for I-131 in spite of its short half-life. Other radionuclides, due to itslong half-life, will remain on the ground for a long time and have a higher probability to enter the food chain pathways.

From the results in the Table 4 and 5, it can be seen that the concentration of radionuclide activity decreases with the increasing of the distance radius from the reactor. The region in the radius of less than 250 m from the reactor will receive the highest radiation dose.

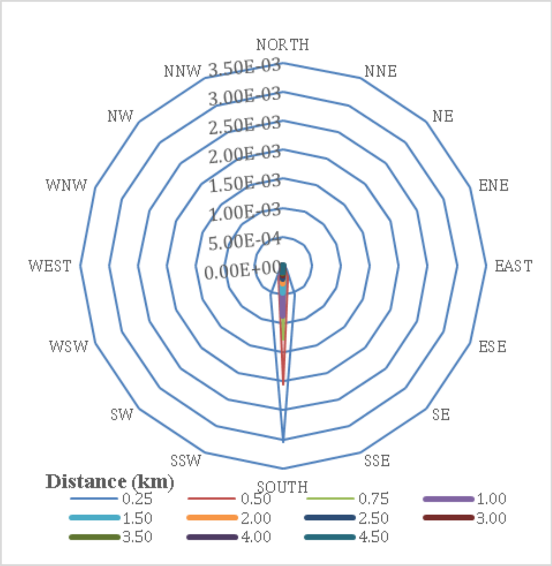

Fig. 3. Short-term individual effective dose for water ingress accident

3.3 Short-term Individual Doses

Short-term individual doses originate from external irradiation (cloud-shine and ground-shine) and internal irradiation (inhalation from the air, ingestion of contaminated food and drinks. Figure 2 and Figure3 show the short-term individual doses (1-

day doses) for all directions and distances from depressurization and water ingress accident, respectively. It can be seen that the highest radiation dose from depressurization accident is about 7.22E-02 mSv and from water ingress accident is about 3.04E-03 mSv. These dose values are obtained within the radius of 250 m to the South of the reactor. Compared to the national regulation issued by BAPETEN and GSR Part 3 of the IAEA standard regarding criteria for accident condition, these dose values are still significantly below the limit for emergency workers in the precautionary action zone, namely that doses above 50 mSv is a voluntary task after obtaining clear information regarding radiological risk for the task.

Figure 4 shows the comparison of short-term doses from depressurization and water ingress accident. The dose received from depressurization accident is higher than the one from water ingress accident. This is in accordance with the source terms from depressurization accident which is higher than the source term from water ingress accidents. Since the calculation was carried out on the same site, the local weather conditions generate the same effect on the two accidents condition.

Short-term countermeasure is estimated based on the short-term doses. Short-term countermeasures include iodine thyroid blocking, sheltering, and evacuation. According to IAEA and BAPETEN regulation, the iodine thyroid blocking, sheltering, and evacuation are implemented if the individual effective radiation dose reaches 10 mSv, 20 mSv, and 50 mSv, respectively. Based on the individual radiation dose obtained from both postulated accident conditions, no short-term countermeasure measures are needed for the people who live outside of the exclusion area.

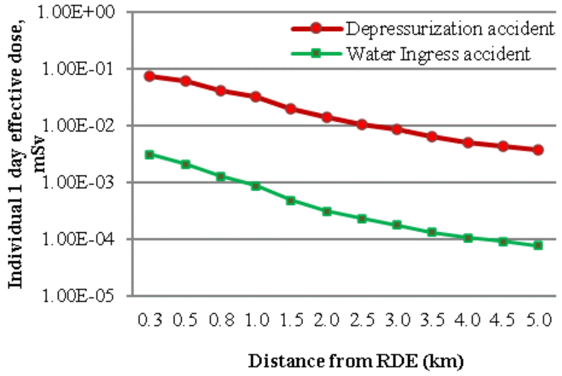

Fig. 4. Short-term individual effective dose within a radius of 250 m to the South from the reactor

3.4 Long-term Individual Doses

Figure 5 shows the results for the long-term individual effective doses arising from both depressurization and water ingress accident conditions. The long-term individual effective doses were calculated for the time of 50 years after the accident. The highest doses are obtained in the area of 250 m southward the reactor, which is almost the same as the short-term individual effective doses results.

The long-term doses are predominantly contributed by the long-lived radionuclide cesium which deposited on the ground surface. The doses received by the human are originated from the consumption of contaminated agricultural and livestock products from the contaminated areas. Dose contributions also come from the exposure to the radionuclides deposited on the soil surface that enter the food chain. From the results shown in the Table 5, it can be concluded that the doses arising from the radionuclide deposition are insignificant, both from depressurization and water ingress accident conditions.

The long-term countermeasures were decided based on the long-term doses. It consists of two actions, evacuation and food banning. According to the IAEA and BAPETEN regulations, evacuation is carried out if the individual effective radiation dose reaches 50 mSv. Food banning of contaminated products are decided based on the level of contamination and the type of consumption. Food consumption restrictions according to ICRP-60 for milk, beef, grain products, potatoes, leafy and non-leafy vegetable, and root vegetable are for an effective dose of 5 mSv. From the results for long-term doses obtained, no long-term countermeasures are needed for the people who live in the exclusion area of the reactor.

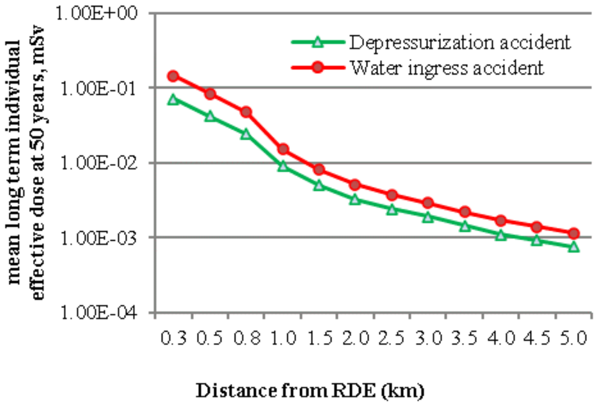

Fig. 5. Long term individual effective dose at 50 years within a radius of 250 m to the south from the reactor

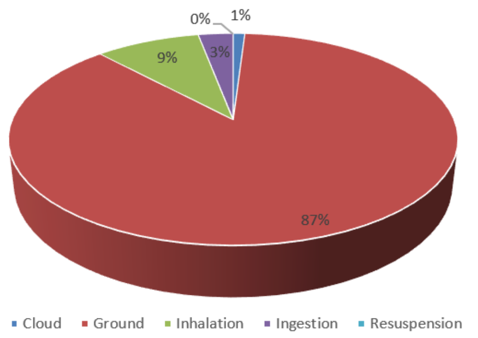

Fig. 6. The collective doses to 50 years by pathway for the depressurization accident

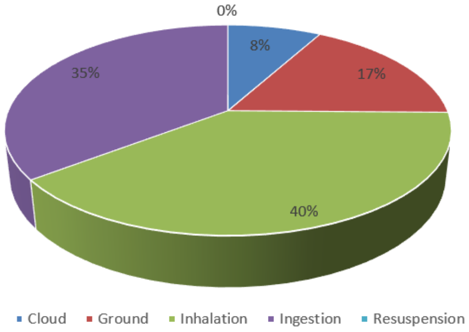

Fig. 7. The collective doses to 50 years by pathway for water ingress accident

3.5 The collective doses to 50 years by pathway

The calculation of collective doses involved the number of individual doses and population density residing in the contaminated areas. The results of collective doses calculation are shown in Figure 6 and 7 for the depressurization and water ingress accidents, respectively. The effective collective dose for the depressurization accident in Figure 6 is 3.98E-01 man-Sv, with the highest contribution of 87.87% coming from the surface deposition. For water ingress accident in Figure 7, the collective dose is 4.88E-02 man-Sv, with the highest contribution of 40% coming from inhalation. Each design option has a level protection cost and corresponding collective dose. By examination of cost analysis, a selection of options based on these two factors can be performed. The collective dose is useful to define optimum solution in radiological protection design for the NPP.

3.6 The mean long-term individual risk of incidence

The results for the long-term individual risk of incidence for depressurization and water ingress accidents are shown in Figure 8, which shows the risk acceptance for total of the body versus distance. From these results, it can be seen that the possibility of contracting a disease due to radiation arising from the accidents to the people who live around the site is very small, far below the limit set by BAPETEN regulations. The risks are in accordance with the long-term doses received. It can also be seen that the risks decrease along with the increasing radius from the reactor.

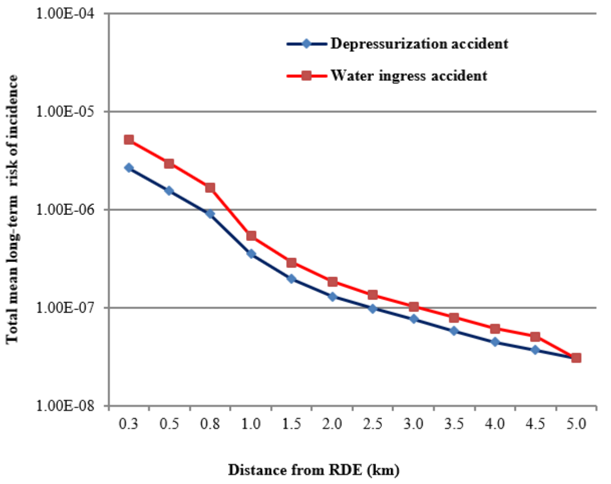

Fig. 8. Total mean long term individual risk of incidence

4. CONCLUSION

The radiological assessment of two postulated HTGR accident conditions, depressurization and water ingress accident, in the Serpong Area, South Tangerang has been performed. The assessment includes the calculations of the atmospheric dispersion and surface deposition, the radiation doses received form all pathways, by using the data of meteorological, weather conditions, population density, agricultural and livestock production in the site considered. The highest doses were obtained in the radius of 250 m to the south of the reactor. All calculation results of the short-term doses and the long-term doses obtained are still below the limit set by BAPETEN. The obtained radiation doses also showed that no countermeasures are needed for both the depressurization and water ingress accident conditions. Finally, it can be concluded that the two aforementioned postulated accident condition of HTGR have low radiological impacts.

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AUTHOR CONTRIBUTION

M. Budi Setiawan, Ihda Husnayani and Heni Susiati are equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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