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Radiation Shielding Optimization of ADS-SAMOP Reactor Test Facility

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Abstract

The accelerator driven system subcritical reactor assembly for Molybdenum-99 or ^{99}Mo isotope production (ADS-SAMOP) reactor test facility is located at the Kartini research reactor complex. The direct exposure at the ADS-SAMOP reactor facility system can reach 1600 mSv/h at a distance of 1 meter from the center of the reactor core. The minimum ordinary concrete shielding required in the radial direction is 2 m thickness with 3-meter height to qualify the maximum dose for radiation workers of 7 μSv/h. The aim of this study is to improve shielding configuration to achieve safety requirements. The method used is a calculation using computer code based on Monte Carlo. The results show that, by using barite concrete with 3 m in height, the thickness of radiation shielding at radial direction of ADS-SAMOP facility can achieve an optimum of only 1.5 m. The analysis results also concluded that the additional radiation shielding to the top of reactor tank must be added if the radial shielding is ordinary concrete.

Keywords: subcritical assembly, test facility, radiation, shielding, safety requirement.

1. Introduction

The ^{99}Mo radioisotope (also known as molly) is indispensable as a ^{99m}Tc generator, of which ^{99m}Tc radioisotope is the most widely used radioisotope for diagnostics in nuclear medicine [1, 2, 3]. However, the increased need for the ^{99m}Tc isotope can't be fulfilled because the ^{99}Mo commonly used as a ^{99m}Tc generator can only be produced in a nuclear reactor. The half-life of ^{99}Mo which is only 66 hours is also a factor making it difficult to store and its distribution process to consumer. This problem can be solved by shortening the ^{99}Mo radioisotope production process as well as shortening the distribution distance.

In general, the ^{99}Mo production is by splitting the ^{235}U nuclide, which ^{235}U is irradiated with thermal neutrons inside a nuclear reactor so that a critical reactor is required. The licensing issues for critical reactors are complex because they have to fulfill strict safety requirements. This problem requires a lot of funds to realize, excluding the cost of waste management products. To solve this problem, Research Organization for Nuclear Energy designed a system that could produce ^{99}Mo without a critical reactor and without using high-enriched uranium [4, 5]. This reactor is simple and safer than critical reactor systems. The

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reactor applies the subcritical reactor method with an external neutron source or an isotropic neutron source, known as SAMOP or subcritical assembly for ^{99}Mo production [4]. The SAMOP system was actually designed to be driven using a neutron source from a neutron generator, as an accelerator-driven system or ADS-SAMOP.

This study referred to previous studies of ADS-SAMOP design and safety analysis as well as its external neutron sources [6, 7, 8]. The ADS-SAMOP experimental facility is a test facility that uses an external neutron source from the beam-port of the TRIGA Kartini reactor, which has been identified as suitable for this purpose [8]. ADS-SAMOP is similar to an Aqueous Homogenous Reactor (AHR) but it operates in a subcritical condition. AHR is a reactor type in which uranium is dissolved in water. The fuel used is a mixture of uranium salt and coolants such as water which also act as a moderator and are often referred to as homogeneous reactors. The high negative temperature reactivity coefficient makes the AHR more stable than conventional reactors. Another positive aspect of AHR is its small size and can operate at much lower power than required for a reactor irradiating targets to produce the same quantity of isotopes [9, 10]. In the AHR system, other isotopes can be extracted from solutions other than ^{99}Mo [10, 11].

The modeling of the ADS-SAMOP reactor has been done using the MCNPX radiation transport code. MCNPX is a Fortran-90 Monte Carlo radiation transport computer code that transports nearly all particles at nearly all energies, developed by Los Alamos National Laboratory [12]. The radiation doses around the ADS-SAMOP reactor core and the effect of shielding from barite concrete and other materials to reduce radiation dose outside the reactor shielding system have been studied in the previously developed configuration [13, 14, 15]. From the final design, it is known that the optimum shape, size, and configuration of the ADS-SAMOP reactor core system are as follows: the annular cylindrical core of 32.4 cm in diameter and 45 cm in height, filled by 38 cm height of uranyl-nitrate (UN) or UN volume as fuel and target is 29.549 cm^3. The annular cylindrical core is surrounded by a ring containing 12 holes which can be filled by UN tubes or TRIGA reactor fuels. The mechanical construction of the ADS-SAMOP experimental test facility has been finished.

The previous study shown that the radiation dose of the ADS-SAMOP reactor from all its radioactive material produced can reach 1600 mSv/h at a distance of 1 meter from the subcritical reactor core without a radiation shield (direct exposure) [15]. To achieve the current safety requirements, the dose around the ADS-SAMOP reactor should always below the maximum allowed dose limit. The analysis of ADS-SAMOP radiation shielding which have been done formerly needed to be improved for comprehensiveness. Therefore, this research concerning the radiation shielding optimization analysis for the ADS-SAMOP reactor experimental test facility is considered necessary.

2. Materials & Methods

2.1 Materials

The reactor configuration, material and technical specifications of ADS-SAMOP experimental test facility are shown in Table 1, Figure 1 and Figure 2. The fuel and target for ^{99}Mo production is uranyl-nitrate (UN) or $UO_2(NO_3)_2$ with 19.75 % ^{235}U enrichment. Detail configurations of ADS-SAMOP reactor core is described in Figure 1 with configuration settings of $UO_2(NO_3)_2$ contained in annulus cylindrical tank surrounded by 12 holes of $UO_2(NO_3)_2$ tubes [4, 5].

Table 1: ADS-SAMOP reactor material specifications

Component	Materials	Density	Note
Fuel and target	$UO_2(NO_3)_2$	1.319 g/cc, (300g U/L)	^{235}U enrichment: 19.75 %
Reflector	Graphite	1.710 g/cc	C
Coolant	H2O	0.958 g/cc	Demineralized water
Structure	SS304	8.030 g/cc	Stainless-steel
Gas (in the fuel gap)	Helium	1.29 10-04 g/cc	He
Control Element	Boral®	2.530 g/cc	Al (65%wt); B4C (35%wt)

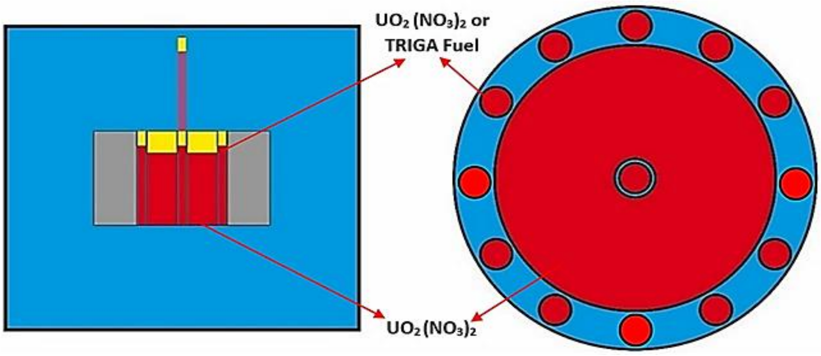

Figure-1: ADS-SAMOP reactor core configuration

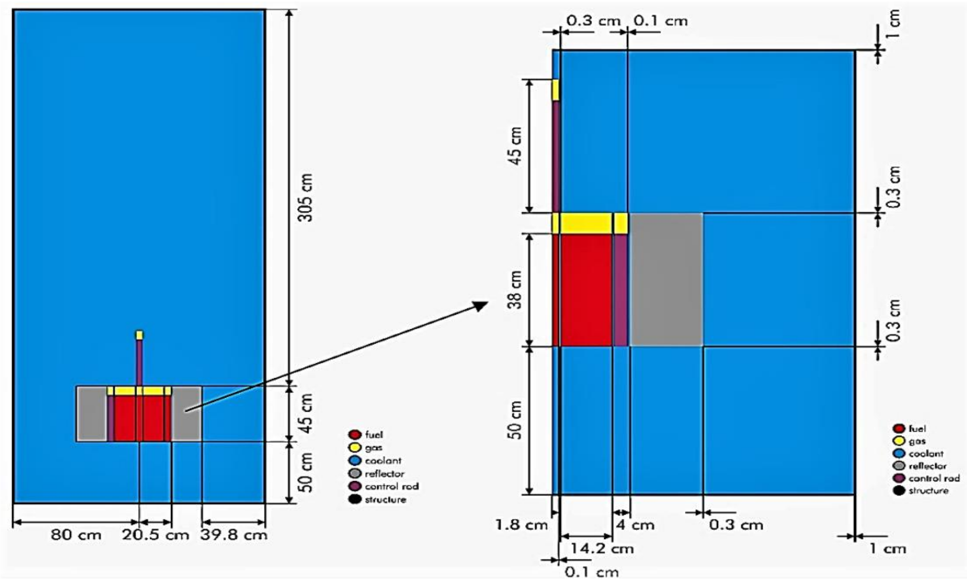

Figure 2: ADS-SAMOP reactor technical configurations: reactor core and water coolant tank

2.2 Methods

The method used is a computation of radiation dose for several position surrounding ADS-SAMOP reactor core using MCNP computer code. MCNP is a general-purpose Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies. The MCNPX is the next generation in the series of Monte Carlo transport codes that began at Los Alamos National Laboratory. The MCNPX program began in 1994 as an extension of MCNP4B in support of the Accelerator Production of Tritium Project. The work envisioned a formal extension of MCNP to all particles and all energies; improvement of physics simulation models; extension of neutron, proton, and photonuclear libraries to 150 MeV [12]. The calculation consists of two following steps: calculation of radiation dose without shielding, and dose calculation with configurations of radiation shielding.

Using burnup calculations and tallies provided by MCNPX to calculate radiation dose without shielding for certain position of ADS-SAMOP reactor, then it could be seen the distribution of radiation dose on every position all over the operating time. In this calculation, can be used tally 2 to calculate dose over an interest surface and DF (dose function or effective-dose conversion function) i.e. a command in MCNPX to find energy deposition tallies and provides the dose in units of Gy or Rad, to convert radiation flux to dose using standard dose function ICRP-21 1971 [16]. The calculations will be done for operation period of the reactor over 3 years. Several positions of the reactor that will be focused in this calculation is on radial section which is divided by 4 sections, i.e.: Level 1 is from ground or bottom to 1 meter above ground, then Level 2 is 1-2 meter above ground, Level 3 is 2-3 meter above ground and Level 4 is 3 meters above ground to the level of the top of the water coolant tank. Then, radiation dose for Top of the reactor (on the surface of water coolant tank), Bottom level of the reactor and Underground part or below the reactor concrete base.

The radiation dose after shielding is installed is then calculated with MCNPX using the same tallies. Radiation shielding configurations are varied and then the radiation dose at several sections i.e. Level 1 up to Level 4, Top, Ground and Bottom are calculated. The configuration of shielding materials and thicknesses are varied, the thickness variation until its radiation dose is below the limit 7 μSv/h with increment of 50 cm. The shielding materials are varied among others: ordinary concrete, barite concrete and paraffin to have deal with thermalization of the neutron. The ordinary concrete used with the mass composition of cement as commonly used for gamma shielding [17, 18, 19], whiles the mass composition of barite concrete is taken from Ref [20].

3. Results and Discussion

The optimum radiation shielding configuration of ADS-SAMOP calculated in this research is depicted in Figure-3, the reactor shielding configuration consists of 50 cm of paraffin, 50 cm of barite, and 50 cm ordinary concrete as radial shielding. The calculations were done for various shielding materials configurations described in the methodology. The calculation results on the radiation doses surrounding ADS-SAMOP reactor without shielding installed as well as with various configuration of shielding is shown in Table 2.

Table 2: The neutron dose and photon dose for various configuration of shielding over 3 years operation at any positions around ADS-SAMOP

Configuration		Top	level 4	level 3	level 2	level 1	Bottom	Ground
		Neutron dose (mSv/h)						
without shielding		0.00E+00	0.00E+00	0.00E+00	2.99E+01	2.32E+02	3.99E+02	0.00E+00
radial shield configuration	100 cm concrete	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.62E+02	0.00E+00
	50 cm paraffin			5.44E-06	8.12E-02	1.40E-01		
	+50 cm concrete	0.00E+00	7.19E-07	0.00E+00	0.00E+00	0.00E+00	3.33E+02	0.00E+00
	150 cm concrete	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.65E+02	0.00E+00
	+ 100 cm to Top	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.65E+02	0.00E+00
	50 cm paraffin			0.00E+00	2.12E-05	1.94E-05		
	+ 100 cm concrete	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.59E+02	0.00E+00
	100 cm barite	0.00E+00	0.00E+00	0.00E+00	6.19E-01	0.00E+00	3.83E+02	0.00E+00
	150 cm barite	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.83E+02	0.00E+00

Configuration		Photon dose (mSv/h)						
without shielding		5.33E-01	1.69E+00	4.01E+01	1.03E+03	2.95E+03	3.88E+03	2.13E+00
radial shield configuration	100 cm concrete	4.15E-01	1.47E+00	7.37E-02	8.35E-01	1.85E+00	3.90E+03	2.56E+00
	50 cm paraffin			1.89E+01	1.81E+02	3.47E+02		
	+50 cm concrete	5.46E-01	1.42E+00	7.92E-01	5.85E+00	9.76E+00	3.92E+03	2.41E+00
	150 cm concrete	8.85E-01	1.23E+00	1.49E-09	7.06E-02	1.84E-01	3.93E+03	1.16E+00
	+ 100 cm to Top	0.00E+00	6.09E-01	1.49E-09	7.06E-02	1.84E-01	3.93E+03	1.16E+00
	50 cm paraffin			1.67E+01	1.77E+02	3.50E+02		
	+100 cm concrete	1.14E+00	6.42E-01	2.04E-02	3.03E-01	4.25E-01	3.87E+03	8.81E-01
	100 cm barite	0.00E+00	4.68E-01	0.00E+00	1.52E-01	3.01E-02	3.78E+03	1.38E-01
	150 cm barite	0.00E+00	4.68E-01	0.00E+00	0.00E+00	0.00E+00	3.78E+03	1.38E-01

It can be seen that radiation dose from ADS-SAMOP reactor is not increasing till its end on the steady condition but it is actually fluctuating along operation time period that might be caused by the random particle interaction by MCNPX [12]. The average and maximum radiation dose from neutron and photon along 3 years or 1080 days operating time is shown in Table 3.

Table 3: Average and maximum radiation dose (mSv/h) over 3 years at any positions on ADS-SAMOP

	Neutron dose (mSv/h)						
	Top	**Level 4**	**Level 3**	**Level 2**	**Level 1**	**Bottom**	**Below concrete**
Average	0.00	0.00	0.12	34.68	259.62	360.59	0.00
Max	0.00	0.00	4.49	120.80	373.96	608.27	0.00
	Photon dose (mSv/h)						
	Top	**Level 4**	**Level 3**	**Level 2**	**Level 1**	**Bottom**	**Below concrete**
Average	0.50	1.89	40.57	1008.35	3032.48	4163.65	2.41
Max	1.74	3.81	48.59	1055.17	3089.48	4285.94	4.46

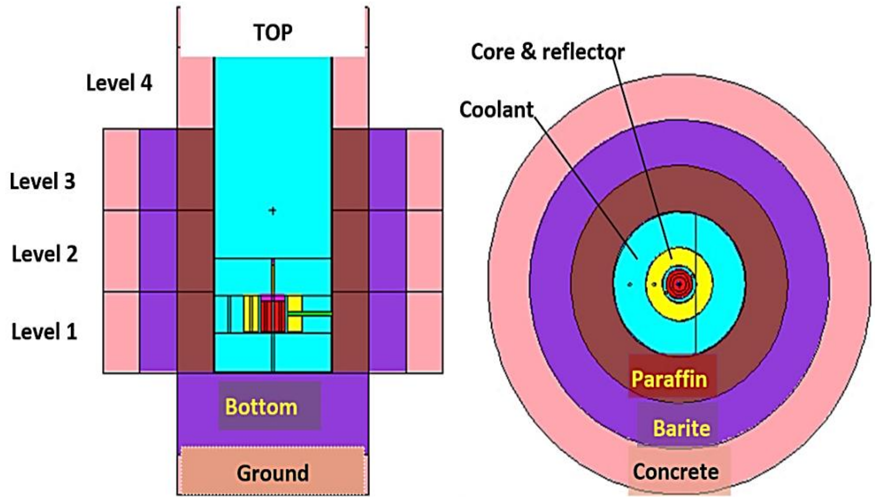

Figure 3: ADS-SAMOP reactor configuration using 50 cm of paraffin, 50 cm barite and 50 cm ordinary concrete as radial shielding

As shown in Table 2 and Table 3 or described in Figure 4, radiation dose caused by neutron is only found in Level 1 and Level 2 of axial direction or from Ground Level to 2 meters above ground. Then in the bottom of the reactor, neutron radiation dose is high enough, this phenomenon is realistic because the location is on the bottom of the reactor core, and by using 1 meter of concrete, this radiation vanished. Then highest neutron radiation dose is found on Level 1 because this position is parallel to the reactor in the ADS-SAMOP cooling tank. In another location, neutron has faded because interaction of neutron with another material is occurred more compared to interaction of photon with material.

The photon radiation dose is as much as 10 times higher than neutron radiation dose such as seen from Table 2 and Table 3. Dose distribution caused by photon radiation is also more spread over ADS-SAMOP reactor that its radiation could be experienced in the top of the reactor and the soil after the bottom of concrete shielding. The result shows that all radiation exposures in the working areas i.e. Level-4, and Top Level, (see Figure-3) are all still below the permission dose constraint of 7 μSv/h for radiation worker at the Kartini research reactor according to the Act of Indonesian Nuclear Regulator Regulatory Agency (BAPETEN) No. 04/2013 [21, 22]. Therefore, be concluded that the optimum shielding configuration is such as shown in Figure 3, by using 50 cm paraffin, 50 cm barite, and 50 cm of ordinary concrete as radial shielding. The ordinary concrete used was of NSI and NIS standards [18, 19].

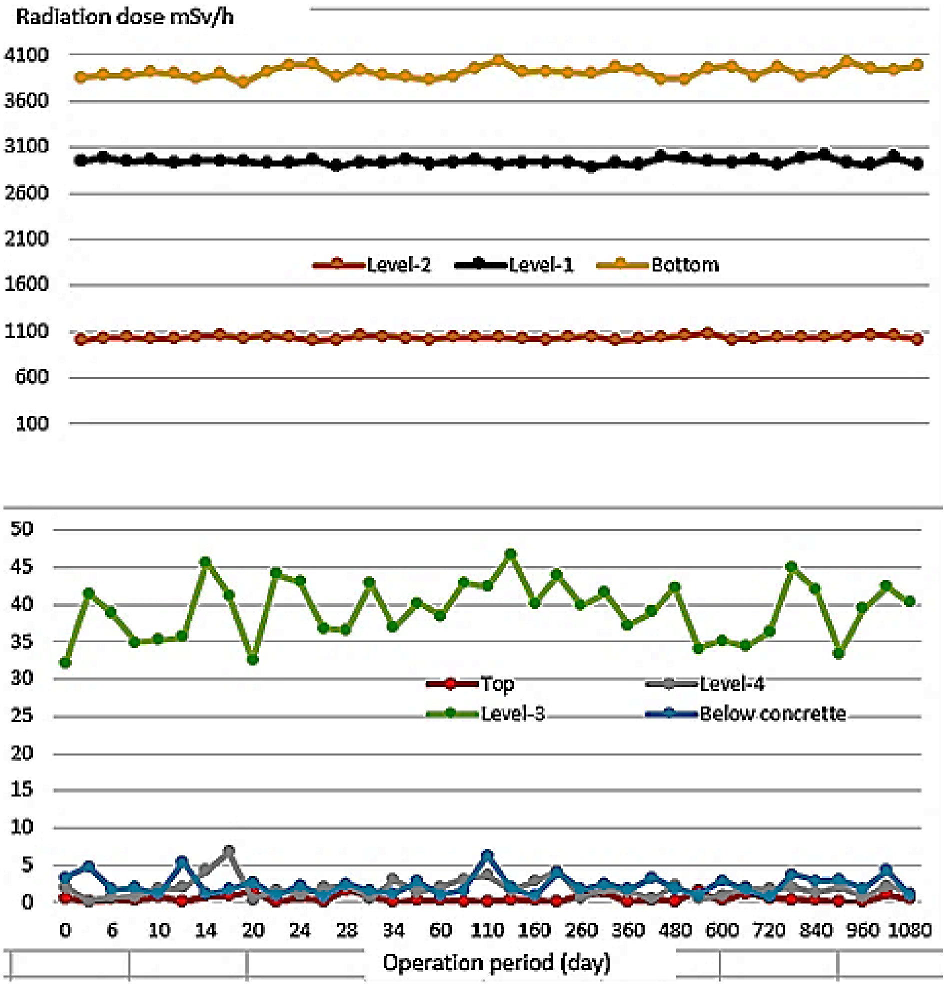

Figure 4: Photon radiation dose (mSv/h) at certain position during 3 years ADS-SAMOP operating time

It can be seen from Table 2 that 100 cm thickness of ordinary concrete of NIST standard could vanishing neutron radiation to zero. Then using barite concrete of 150 cm thickness could eliminate all radiation of photon and neutron. Barite concrete somehow could eliminate photon radiation at the top of the reactor. It could be happening because the presence of barite, one of the heavy elements in the concrete, could attenuate photons and minimize the scattering effect of the radiation to the top of the reactor. This scattering effect will appear when using a concrete wall that somehow increases photon dose in the top of the reactor when its thickness is about 150 cm compared to the configuration without shielding. The utilization of paraffin as neutron moderator is not so good from the photon radiation shielding aspect because it makes photon dose on radial section is higher than without paraffin (only concrete), but using paraffin as radial shielding will help neutron dose in the bottom of the tank decreases, that also occurred when using barite concrete as radial shielding, but not as low as combining paraffin with concrete. This result in agreement with the research result by Chichester, D. L. and Blackburn, B. W. [23] where they found that the composite materials such as a mixture of regular concrete, are ideal shield materials for neutron generator radiation because of their ability to attenuate internally generated photon radiation resulting from neutron scattering and capture within the shields themselves. Whiles, the result on using barite concrete is in accordance with the research results done by Hoang Quoc Vu et al [24] and Shouop et al [25] and [26], where it shows that the higher the thickness and percentage of barite powder, the higher is the radiation resistance.

The analysis results show that the optimum radiation shielding for the radial direction is 1.5 m barite concrete with 3 m in height. The radiation dose in the surrounding will be much lower than the permitted dose limit if the ADS-SAMOP tank is higher than 3 m. The analysis results have met the criteria determined by the national nuclear regulatory body (BAPETEN), the dose rate of all soft tissue does not exceed the limit value of 10 μSv/h or still bellows the radiation dose limit of 7 μSv/h for radiation workers at the Kartini research reactor area where the ADS-SAMOP experimental test facility was located. The optimum shielding configuration is as follows: by using 50 cm paraffin, 50 cm barite, and 50 cm of ordinary concrete as radial shielding.

4. Conclusion

The analysis results show that the optimum radiation shielding for the radial direction is 1.5 m barite concrete with 3 m in height. The radiation dose in the surrounding will be much lower than the permitted dose limit if the ADS-SAMOP tank is higher than 3 m. The analysis results have met the criteria determined by the national nuclear regulatory body (BAPETEN), the dose rate of all soft tissue does not exceed the limit value of 10 μSv/h or still bellows the radiation dose limit of 7 μSv/h for radiation workers at the Kartini research reactor area where the ADS-SAMOP experimental test facility was located. The optimum shielding configuration is as follows: by using 50 cm paraffin, 50 cm barite, and 50 cm of ordinary concrete as radial shielding.

5. Conflict of Interest

The authors declare that they have no conflict of interest that could affect the work reported in this paper.

6. Acknowledgement

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