Regulatory Assessment on a New utilization of SAMOP Test Facility: Determination on Fission Power

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Abstract. SAMOP test facility is a subcritical solution of uranyl nitrate to produce Mo$^{99}$ that is connected with external neutron source from one of Kartini reactor beam ports. Determining the SAMOP fission power is a critical step toward thermal hydraulic calculation ensuring the adequacy of cooling and to calculate the fission product inventory without modelling the Kartini reactor geometry. As part of regulatory assessment, the analyses were intended to determine the power level of SAMOP and its distribution in its solution tubes using MCNP5 code. Two cases of Kartini reactor power 100 % and 110 % of nominal power were simulated. The results showed that SAMOP can produce fission power ranging from 563.2 up to 860.8 watt. Taking uncertainties into account, it is recommended to conduct thermal hydraulic calculations on SAMOP test facility based on minimum total power of 1000 W.

Keywords: Subcritical solution, fission power, uranyl nitrate, SAMOP.

1. Introduction

Fission process is one of the techniques to produce Mo$^{99}$ which is used for nuclear medicine. The common application to produce Mo$^{99}$ is by irradiating U$^{235}$ target in a critical research reactor core. The critical system can sustain the fission reaction by itself. The fission product of Mo$^{99}$ is then extracted from the target and is sent to the medical facilities.

Another idea to produce Mo$^{99}$ from fission is using subcritical system incorporated with external neutron source [1]. SHINE (Subcritical Hybrid Intense Neutron Emitter) is developed to produce Mo$^{99}$ using subcritical uranyl sulfate solution driven by accelerator [2][3]. The similar idea is applied by Kartini reactor of BATAN by inducing neutron source from one of its beam ports to uranyl nitrate subcritical solution located outside the reactor concrete shielding. As, the so-called Subcritical Assembly for Mo$^{99}$ Production (SAMOP), is located separately from reactor primary cooling system, it has to be submersed in water which functions as natural convection cooling, moderator and radiation shielding as well.

In order to ensure the adequacy of cooling, the fission power of the subcritical solution has to be determined[4]. In addition, the fission power can also be used to calculate the fission product inventory such as Mo$^{99}$ activity, without being integrated with reactor core geometry. In such a case where burnup calculation is calculated without modelling the reactor core, it will significantly reduce the number of cells and consequently much less time consuming. These analyses focused on determining the fission power of SAMOP test facility and its distribution in the 8 solution tubes.

The Assessment Centre of BAPETEN is responsible for conducting safety assessment of any nuclear facilities for all stages from siting, construction, operation, modification and decommissioning. These calculations were part of the regulatory assessments by the Centre to support licensing decision making process on a new utilization of the Kartini research reactor. The calculations employed a Monte Carlo method of MCNP5 [5] code intended to determine the level of SAMOP fission power to ensure sufficient cooling system.

2. Description of SAMOP test facility

The SAMOP test facility consists of central cylinder containing uranyl nitrate (UO$_2$(NO$_3$)$_2$) solution. The upper part of the tube is connected to neutron absorber of B$_4$C, in such that they can move up and down to control the neutron flux when necessary. The central moveble tube is laterally surrounded by
annular cylinder which also contains uranyl nitrate solution. The annular cylinder is surrounded with water where six holes, that can be filled with similar uranyl nitrate tubes or standard TRIGA fuel elements, exist. Radial graphite reflector is used. A hole of 4 cm penetrating the reflector is a collimator channel where external neutron source from Kartini reactor beam port passes through. The SAMOP system is submersed in water tank that functions both cooling and radiation shielding, as shown in Fig.1.

![3-D SAMOP geometry](image)

**Figure 1.** 3-D SAMOP geometry

The uranyl nitrate solution has uranium density of 300 gU/l enriched by 19.75 % of U^{235}. From the pervious calculation, the 300 gU/l has been confirmed to be under moderated region [6], which ensures the negative void reactivity feedback. The central cylinder contains 226 ml of uranyl nitrate solution. On the other hand, the annular cylinder contains 22382 ml of the same solution. The six holes in peripheral region can be inserted with cylindrical tube of the same solution, or alternatively with standard TRIGA fuel elements.

**3. MCNP calculation model**

As the external neutron source of SAMOP comes from Kartini reactor, both geometries have to be interconnected through one of its beam ports. Fig.2. shows the MCNP geometrical model of integration between Kartini reactor and SAMOP test facility.
The outer part connecting beam is shielded with high density polyethylene (HDPE). HDPE has low neutron capture cross section and high elastic scattering cross section which could improve the moderation of fast neutrons [7]. The SAMOP core consists of central tube connected to absorber B$_4$C that can be moved up and down. The tube is filled with uranyl nitrate solution (white colour) of 300 gU/l, where the upper part is left empty to contain gaseous fission product and radiolytic gas. The central cylinder is surrounded by annular cylinder and 6 cylinders, as shown in Fig. 3, containing the same solution. The SAMOP system is reflected with graphite material (yellow colour).

**Figure 2.** MCNP model of integration between Kartini reactor core and SAMOP
The neutron fluxes both in the reactor core and SAMOP core can be calculated by applying tally F4. The absolute fluxes in unit neutron/cm$^2$s are then calculated based on the following formula [8]:

$$\Phi = \frac{P_{\text{core}} \times \nu \times 10^{-13} \times w_f}{1.6022} \times \frac{1}{k_{\text{eff}}} \times F_4$$  \hspace{1cm} (1)

Where $P_{\text{core}}$ is the total power of both Kartini reactor and SAMOP core in unit watt. The $\nu$ is the number of neutron produced per fission. The $\nu$ value is calculated by MCNP5 and can be obtain from the output file. The $w_f$ is the energy produced per fission, which is about 198 MeV/fission for U$^{235}$. The $k_{\text{eff}}$ is multiplication factor which is standard output for KCODE calculation. The F4 tally of cell flux in unit cm$^{-2}$ based on track-length estimate. The F4 tally is normally used for cells already defined in the input file. For undefined cells of arbitrary volume, one can use FMESH4 tally which can produce any desired mesh sizes. Using FMESH, the user can define the geometrical domain and energy range where the flux will be tallied.

On the other hand, for calculating fission energy deposition in a cell, F7 tally can be applied. The F7 tally result is in unit MeV/g, therefore the following formula then can be employed to obtain the real energy fission deposited in the cell:

$$P = F_7 \times S_s \times \left( \frac{1}{k_{\text{eff}}} \right) \times 1.6022 \times 10^{-13}$$  \hspace{1cm} (2)

Where $P$ is fission energy deposition in the tallied cell in unit watt/g, hence it has to be multiplied with the cell mass. The $S_s$ is the source strength, defined as:

$$S_s = \frac{P_{\text{core}} \times \nu \times 10^{-13} \times w_f}{1.6022}$$  \hspace{1cm} (3)

4. Results and discussions

As the current burn-up level of the Kartini core is very low, the calculations were assumed to have been loaded with fresh fuels. The reactor core consists of 79 standard fuel elements and three control rods. The configuration produces the neutron multiplication factor of 1.01562 with an estimated standard deviation of 0.00003.
Fig. 4 shows the 3D and 2D plot of the maximum thermal neutron flux of Kartini reactor that operates at nominal power of 100 kW. The flux tallies were taken at the mid-plane of the core. The figure exhibits four thermal neutron peaks that come from three withdrawn control rods in C-5, C-9 and E-1; and central thimble located in the centre of the core. Due to being fully filled with water, the four positions produce maximum moderation effect resulting in peak thermal fluxes. The maximum thermal neutron flux (< 1.0 eV) in central thimble exhibits $3.9 \times 10^{12}$ n/cm²s.

As most of the fast neutrons produced from fission reactions have been thermalized in the aforementioned positions, the fast neutron fluxes in those four positions exhibit low fast fluxes. This is shown in Fig. 5. The maximum fast neutron flux (>$1.0$ eV) is located in ring B of $5.1 \times 10^{12}$ n/cm²s.

Fig. 6 shows the axially maximum thermal neutron flux in SAMOP test facility. The flux is tallied in the mid-plane which is the same level as the beam port centre. In general within the SAMOP core, high thermal fluxes exist in water without fuel solution. The water receives fast flux from the fuel, and the neutrons are thermalized in their journey. In term of radial direction, the highest peak of thermal flux is located in the water surrounding central fuel solution. Other six peaks appear in between 6 fuel solution tubes, where light water exist moderating the fast neutrons. The maximum thermal neutron flux surrounding central tube is in the order of $2.0 \times 10^{10}$ n/cm²s.
Unlike thermal neutron flux, the fast fluxes are concentrated on the fuel solution where fast fission neutrons are born. The maximum fast flux is located in the central fuel solution in the order of $3.0 \times 10^{10}$ n/cm²s. From Fig. 7, the neutrons produced from six fuel solutions that travel to the right and left sides are moderated by water and end up as thermal neutrons, producing six line peaks of thermal fluxes, as shown in Fig. 6.

As for calculating the fission power in the SAMOP test facility, Eqs. (2) and (3) are used. It produces the source strength of $7.48 \times 10^{15}$, which is in line with the one calculated by Sutondo T. and Syarip of $7.42 \times 10^{15}$[9]. The calculated fission energy deposition $F_7$ and fission power of each uranium solution are tabulated in Table 1. The calculated power is based on reactor nominal power of 100 kW. The six holes in the peripheral region are loaded with the same uranyl nitrate solutions.
Table 1. Distribution of fission power in each fuel solution

| Fuel tube    | Tally F7 (Mev/g) | Mass (g) | Specific power (watt/g) | Power (watt) |
|--------------|------------------|----------|-------------------------|-------------|
| Annular tube | $1.30178 \times 10^{-5}$ | $3.24581 \times 10^{4}$ | $1.57547 \times 10^{-2}$ | 511.367     |
| Central tube | $2.41975 \times 10^{-5}$ | $3.33746 \times 10^{2}$ | $2.92848 \times 10^{-2}$ | 9.774       |
| Tube 1       | $1.21927 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.47561 \times 10^{-2}$ | 6.945       |
| Tube 2       | $1.21949 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.47558 \times 10^{-2}$ | 6.946       |
| Tube 3       | $1.24415 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.50572 \times 10^{-2}$ | 7.086       |
| Tube 4       | $1.23784 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.49809 \times 10^{-2}$ | 7.051       |
| Tube 5       | $1.22637 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.48420 \times 10^{-2}$ | 6.985       |
| Tube 6       | $1.24320 \times 10^{-5}$ | $4.70634 \times 10^{2}$ | $1.50457 \times 10^{-2}$ | 7.081       |

The table reveals that the total SAMOP power when the reactor operates at 100 kW is 563.2 watt, where the six holes are filled with uranyl nitrate solutions. When the reactor operates at the maximum limit of 110% (or 110 kW), it will generate SAMOP power of 613.0 watt.

Table 2. Distribution of fission power in fuel solution and TRIGA fuels

| Fuel           | Tally F7 (Mev/g) | Mass (g) | Specific power (watt/g) | Power (watt) |
|----------------|------------------|----------|-------------------------|-------------|
| Annular tube   | $1.78920 \times 10^{-5}$ | $3.24581 \times 10^{4}$ | $2.1676 \times 10^{-2}$ | 703.56      |
| Central tube   | $3.32072 \times 10^{-5}$ | $3.33746 \times 10^{2}$ | $4.0230 \times 10^{-2}$ | 13.43       |
| TRIGA Fuel 1   | $4.06844 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9289 \times 10^{-3}$ | 11.02       |
| TRIGA Fuel 2   | $4.06270 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9219 \times 10^{-3}$ | 11.00       |
| TRIGA Fuel 3   | $4.08610 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9503 \times 10^{-3}$ | 11.07       |
| TRIGA Fuel 4   | $4.09870 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9655 \times 10^{-3}$ | 11.10       |
| TRIGA Fuel 5   | $4.09404 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9599 \times 10^{-3}$ | 11.09       |
| TRIGA Fuel 6   | $4.06690 \times 10^{-6}$ | $2.23530 \times 10^{3}$ | $4.9270 \times 10^{-3}$ | 11.01       |

On the other hand, if the six peripheral holes are loaded with standard TRIGA fuel elements, it will generate 783.2 watt for Kartini core nominal power of 100 kW, shown in Table 2. For 110 kW Kartini reactor power, it will produce 860.8 watt of SAMOP power.

Both tables indicate that the highest specific powers are generated in the central movable solution followed by annular tube. As consequence, the central tube will produce the maximum specific activity of Mo99.

There are some uncertainties that have not been taken into account in these calculations, such as the accuracy of geometry data, input data, physical model, etc. Taking these into account, it is recommended to conduct thermal hydraulic calculations on SAMOP test facility based on minimum total power of 1000 W. Syarip et al. have conducted burnup calculation on SAMOP of Thorium nitrate solution fuel based on the total power of 1 kW [10].

5. Conclusions
Calculations on fission power distribution in SAMOP test facility have been conducted using MCNP5 code. In the case that six peripheral holes are loaded with uranyl solutions, for 100 kW and 110 kW of Kartini core power, the results show that the total SAMOP powers exhibit 563.2 and 613.0 watt, respectively. For the insertion of six TRIGA fuels in the peripheral holes, the SAMOP generates 783.2 and 860.8 watt, respectively. Taking uncertainties into account, it is recommended to conduct thermal
hydraulic calculations on SAMOP test facility based on minimum total power of 1000 W. The calculations also unveil that the central movable fuel solution produces the highest specific power.

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7. References
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