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The Assessment of the Safety Operation of RSG-GAS Reactor for Radioisotope Target Irradiation

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ABSTRACT

The RSG-GAS multipurpose reactor is operated to serve the utilization in the field of radioisotope production, neutron activation analysis (NAA), and material research. The reactor actually has the power of 30 MW thermal, but upon considerations of efficiency and of most user's requirements, the reactor is mostly operated at the power of 15 MW thermal, 5 days a week to produce a primary radioisotope from the target of 2 grams U-235. To ensure safe operation and optimum utilization, a safety procedure was established. The paper is intended to assess the operation safety in serving radioisotope target irradiation at its cycle operation. The assessment was carried out for core numbers 102 – 105. The result shows that excess reactivity and shutdown margin reactivity are safe to provide the target irradiation in the core for each cycle operation.

1. INTRODUCTION

The RSG-GAS reactor is a Multi-Purpose Reactor using Low Enriched Uranium (LEU) fuels (19.75% enrichment) [1-3]. Although the reactor is actually designed for producing a thermal power of 30 MW, based on requests of most users and reactor operation efficiency, the reactor is mostly operated at the power of about 15 MW. At the beginning of the cycle (BOC), a fuel refreshing and reshuffling should be conducted according to the loading pattern 5/1 which means five standard fuel elements and one control element must be replaced.

Come along with the reactor design specification, the reactor is mainly aimed for experiments, radioisotope production, and material research. To support all activities related to R&D in the field of reactor technology, the reactor was firstly employed for neutronic and thermal-hydraulic experiments. To assure all reactor physics parameters are fulfilled, those experiments are mostly carried out at the beginning of the core.

As mentioned earlier, the reactor is also put to use for radioisotope production, namely, Molybdenum-99 (Mo-99), Iridium-192 (Ir-192), Iodine-125 (I-125), etc. To produce a main radioisotope Mo-99, a target of highly enriched uranium (HEU) containing 2 grams of U-235 is irradiated for 5 days in the reactor core. The production of I-192 is also achieved from irradiating Ir-191 in the reactor core. In addition, by using a Xenon loop attached in the beam tube S-2, I-125 can be contrived from Xenon-124 enriched [4-6].

The RSG-GAS reactor is also completed with 4 radial and 2 tangential beam tubes. The beam tubes S-1 and S-2 are respectively dedicated to a xenon loop to produce I-125 and a neutron radiography facility. Meanwhile, beam tubes S-4 and S-5 completed with a guide tube are both applied for investigating the structure of crystals. Finally, beam tube S-6 completed with a neutron

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diffractometer is applied for investigating types of crystals.

One of the research reactor purposes is to irradiate targets to produce radioisotopes. To irradiate sorts of targets in the reactor core takes into account the complexity of safety aspects. Therefore, in the RSG-GAS facility, there is a safety procedure on how to irradiate new targets in the reactor core. One of the safety procedures that should be taken into account is to prepare a safety analysis report (SAR) document containing neutronic and thermal-hydraulics of the target to be irradiated and contemplate the interaction between the target and the reactor core. Other than that, the documents should also conceive other important things such as the possibility of fission gas released from the target and that of the target melting. Finally, the documents should also cover analysis deliberating possibilities of a nuclear and non-nuclear accident during the irradiation of the target in the core. Only the most severe accident during the target irradiation in the reactor core is explicitly analyzed.

This SAR has been available and implemented since the beginning period of the reactor operation until core number 101. So, irradiation of the radioisotope target in the core numbers 102 - 105 shall meet the result of this SAR. The reactor operation performance for target irradiation is then compared to the safety constraint.

2. REACTOR OPERATION AND UTILIZATION

2.1. Reactor Operation

A typical working core (TWC) configuration consists of 40 fuel elements, 8 control elements and 24 beryllium reflector elements [11-13]. The calculated thermal neutron flux is 2.4 x 10^{14} n.cm^{-2}s^{-1} in the central irradiation position, 1.4 x 10^{14} n.cm^{-2}s^{-1} in the active core irradiation position and 1.1 x 10^{14} n.cm^{-2}.s^{-1} in the beryllium reflector irradiation position. The in-core and out-of-core irradiation positions are arranged to support research, and development activities [14-16] is illustrated in Figure 1.

Since the year 1998, a new loading pattern 5/1 was imposed on the RSG-GAS reactor [17-20]. According to this pattern, a reactor is operated for a duration of 625 MWD each cycle. Upon optimization of fuel availability, user requirements, and efficiency, an annual reactor operation program was set up. The reactor is operated at a power level of 15 MW for 4 cycles a year. Each cycle is divided into three phases of operation. Each operation runs for 12 days and the shutdown time between two operations is 16 days. By taking into account a couple of weeks to prepare core experiments and preventive maintenance, one cycle lasts about three months commencing from BOC and ending at EOC [21-23].

Prior to the BOC of the reactor core, there are some experiments to estimate and analyze safety parameters, such as the reactivity worth of each control rod and excess reactivity of the core. Once all of the safety parameters are obtained and do not exceed the design limits, the RSG-GAS can go to cycle operation safely.

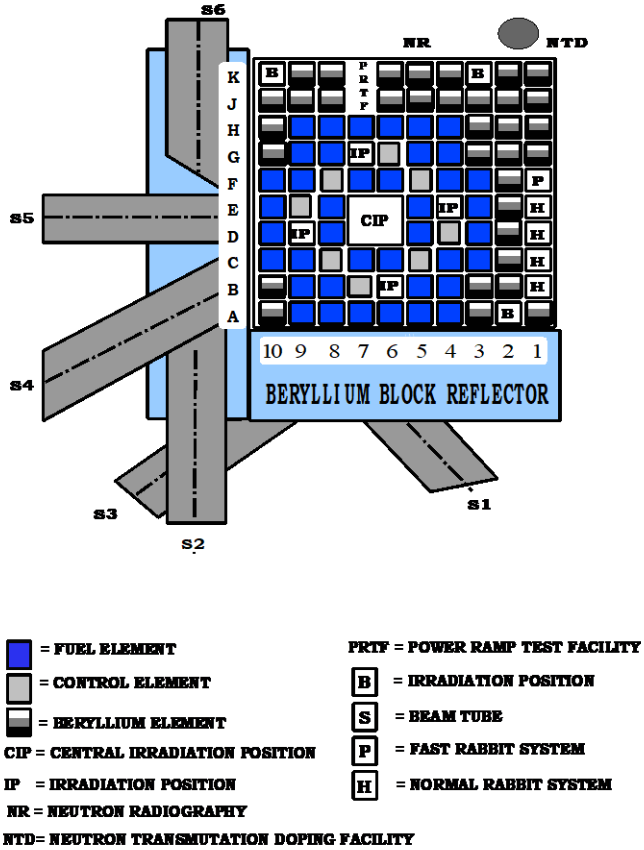

Fig.1. The RSG-GAS core configuration [24]

The conduct of reactor operation and implementation of the loading pattern of 5/1, shows that the in-core fuel management successfully provided the equilibrium core. The results support the conduct of operation in a safe manner for optimal utilization with stable parameters and under stable nuclear safety conditions.

2.2. Utilization of RSG-GAS Reactor

Based on the design specification of the RSG-GAS reactor, the reactor is mainly for irradiation services and material research activities.

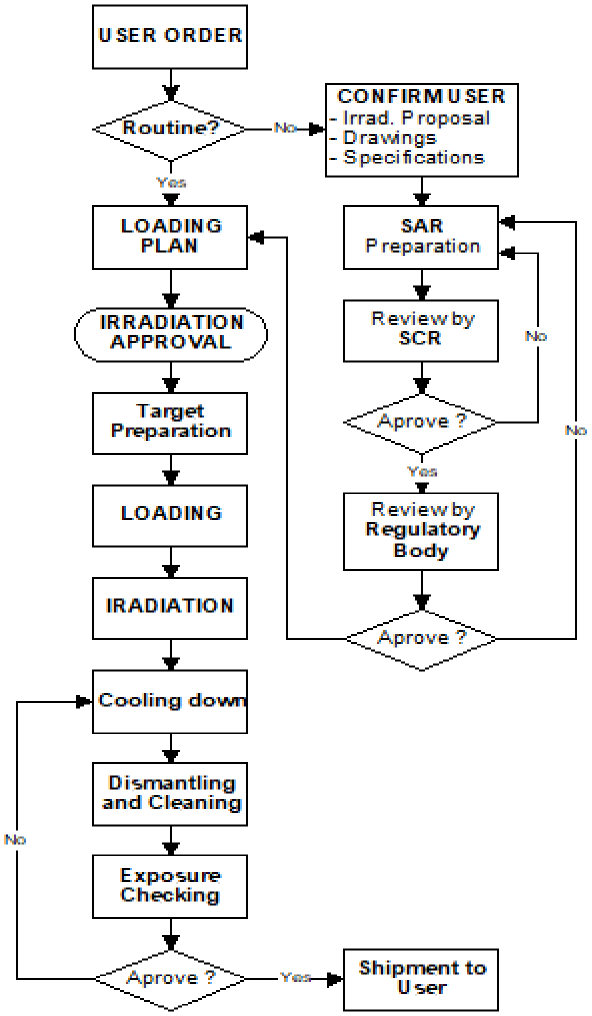

Fig. 2. Flow diagram of irradiation procedure [25]

Generally, the RSG-GAS is equipped with many facilities, such as central irradiation and irradiation positions (CIP and IP), beam tubes etc. The followings are current activities carried out in the RSG-GAS.

a. The RSG-GAS is completed by 4 irradiation positions and a Central Irradiation Position classified to be the highest thermal neutron flux in the core. The CIP is usually applied for U-235 irradiation to produce Molybdenum-99 (Fission Product Molybdenum = FPM). Meanwhile, IP's are used for other target irradiation, such as, iridium-191, sulfur-32 etc. For current status, U-235 is irradiated once a week for 5-day irradiation, while other targets are irradiated at least once a month.

b. The reactor power of 15 MW is sufficient for science and material research activities. There are a neutron radiography, a neutron guide tube, a neutron diffraction facility to investigate types of crystals and a small angle neutron scattering facility (SANS) to explore the quality of crystals. For those purposes, beam tubes S-2, S-4, S-5 and S-6 are applied.

c. The beam tubes S-1, is dedicated for a xenon loop. The loop is intended to produce iodium-125 from xenon-124 enriched. The gas tube contains around 500 cc of the iodium-124 gas and the separation of iodium-125 is processed in another facility called Radioisotope Production Center.

d. Other than mentioned above, there are facilities respectively called a Power Ramp Test Facility (PRTF), a Neutron Transmutation Doping Facility. The former can be utilized to probe the quality of PWR fuel pins while attempting a power ramp. The latter is dedicated to produce germanium (Ge) by irradiating silicon in the core. Actually, there is a facility called an In-Pile Loop applied to analyze the quality of fuel bundle and this facility can be assembled in CIP of the core. However, this facility will not be assembled and employed for research activities in the near future.

e. Come along with the limitation of HEU to produce Mo-99 by the international community, the use of LEU to produce Mo-99 in the future will be preferred. Indonesian Nuclear Energy Agency (BATAN) has made joint research with ANL

f. to realize the production of Mo-99 from LEU since 1992.

3. SAFETY ASSESSMENT

3.1. Safety Procedure to Irradiate Targets in the RSG-GAS.

Based on national and international nuclear safety rules applied, if one intends to do experiments and irradiate new targets in a reactor core, he should firstly prepare a safety analysis report taking into account neutronic and thermal-hydraulic analysis, the influence of the targets/experiments with the core as well as, if available, radiation hazards released by the existence of those.

In the Center for Multipurpose Reactor, a safety procedure has been established [8]. Someone submits a SAR to the director of the center. The director then asks the Safety Review Committee of the RSG-GAS Reactor to review it. In the process of reviewing the report, the author of the report should present it in the Safety Review Committee formal meeting previously scheduled. Upon approval from the Committee, the center responsible for the experiments/new target irradiation in the reactor core proposes the report to the Indonesian Nuclear Regulatory Body (BAPETEN). The Regulatory Body will review the report and make comments on it. After reviewing SAR, they will release a license for doing experiments and or irradiating new targets in the core. The detailed procedure to do experiments and irradiate new targets in the RSG-GAS reactor core can be followed in Figure 2 [9, 15, 17, 24].

3.2 Safety Constraints

Operational limitations for experiments in the reactor contained in chapter 16 of the RSG-GAS Safety Analysis Report represents the safety constraints that should be taken into account, once a target irradiated in the reactor core. Those safety constraints are [26-27]:

- total reactivity of the target irradiated in the core : 2 % dk/k
- max. activity of single or moveable target: 0.5 % dk/k
- min. of flow instability criterion: 1.48
- min. flow in the grid of the target: 10 kg/sec.

These constraints will be imposed on any new irradiation target or experiment in assessing the safety aspects.

3.2. Safety Analysis

As mentioned earlier, one shall prepare a safety analysis report (SAR) to do an experiment as well as to irradiate targets in the RSG-GAS core. The safety analysis report should cover the following items:

a. Estimate of target activity and interaction between target and core

Each target in the RSG-GAS core is bombarded by neutrons during reactor operation. Interaction between the neutron and the target in the core will result in the activity of the target. Moreover, to analyze the perturbed core reactivity of the target in the reactor core, a calculation of target reactivity taking into account perturbation theory is carried out.

b. Analysis of minimum flow to assure the sufficiency of core cooling

This is part of thermal-hydraulic analysis taking into account assurance of core cooling sufficiency. Once minimum core cooling is achieved, it is assured to maintain the temperature of the target, hence neglecting the melting point of the target. To calculate the temperature of the target and onset of flow instability, computer codes GAMSET/GENGTC and PARET/ANL can be utilized.

c. Accident analysis.

Accident analysis should take into account fission gas release of melting target. The analysis should be based on the worse target accident that might occur during irradiation of the target in the reactor core. An example of the safety analysis report is for the FPM target, $Gd2O3$, and $SnO2$.

4. RESULTS AND DISCUSSION

An example of safety assessment on reactor utilization at RSG-GAS reactor is the production of Mo-99that has been licensed by BAPETEN. Although in the reality, the production is routinely conducted at reactor power of 15 MW and the target weight of around 2 grams uranium, the safety analysis was done under the following assumptions:

Targets U-235: 6 grams
Loading positions: CIP (D-6 and E-7)
Reactor Power: 30 MW

The main results of the safety analysis are as follows [28-30]:

a. The highest perturbed reactivity in the core, % dk/k is + 0.35 %
b. Onset of Flow Instability: 1.97
c. Highest temperature of the U-235 target, C: 145.7
d. Accident analysis in the case of broken target has been carried out by conservatives assumptions. The radiological consequences are minor compared to the melting of a fuel element and still meet the safety constraint. An operator receives radiation exposure of not more than 0.5 mrem.

The analysis shows that the insertion of the Mo-99 production system meets the safety constraints.

Assessment of operation safety was done for the reactor operation of the 4 cycles namely Core numbers 102, 103, 104, and 105 covering the period of the year 2021 and the beginning of 2022. At each core, control rod calibration was carried out to evaluate nuclear safety namely adequacy of excess reactivity and shutdown margin reactivity. The results are presented in Tables 3 and 4.

Table 3. Result of the control rod reactivity (ρ) measurement of 8 control rods at core 102-105

Core No.	ρ JDA 01	ρ JDA 02	ρ JDA 03	ρ JDA 04	ρ JDA 05	ρ JDA 06	ρ JDA 07	ρ JDA 08	ρ Total
102	-1.5764	-1.5153	-1.7490	-1.6789	-1.6950	-1.2403	-1.2888	-1.7580	- 12.50
103	-1.5710	-1.5045	-1.7705	-1.6843	-1.6267	-1.2439	-1.2816	-1.7777	-12.46
104	-1.5980	-1.5369	-1.7723	-1.7616	-1.7382	-1.2726	-1.3535	-1.8352	- 12.87
105	-1.5512	-1.5099	-1.7238	-1.6789	-1.7094	-1.1899	-1.3284	-1.7849	- 12.48

Table 4. Reactivity balance of the RSG-GAS Reactor

Core number	CR pos BOC (cold, clean)	Fuel loading (FE/CE)	ρ CR Total (%)	ρ Core excess (%)	ρ Shut down (%)	ρ CR max (%)	ρ Shut down margin (%)
102	287/287	5/1	- 12.50	+ 6.77	- 5.73	- 1.76	- 3.98
103	288/288	5/1	-12.46	+ 6.58	- 5.89	- 1.78	- 4.11
104	290/289	5/1	- 12.87	+ 6.75	- 6.12	- 1.84	- 4.29
105	284/284	5/1	- 12.48	+ 6.82	- 5.66	- 1.78	- 3.87

Reactivity values of the individual control rod of core number 102-105 are presented in Table 3. Based on the result control rods bank at BOC, a reactivity balance is generated as shown in Table 4. It shows that the reactivity values of the control rod of each core perform no significant change. It means that by implementing a 5/1 pattern of in-core fuel management the RSG-GAS is stable.

The excess reactivity provide sufficient reactivity to the reactor to be operated until the end of the cycle. And, each core cycle provide also very big shut down margin reactivity to shut down the reactor whenever needed upon disturbance of operation. From nuclear safety of view, the operation of the core no. 102 – 105 are very safe.

Reactor utilization, that is radioisotope target irradiation at core no. 102 – 105 are summarized in Table 5. Those targets are to be used for radioisotope production. This is a continuation utilization program from the previous cores [14, 19, 26, 30]. The mass of the targets is mostly lower than the mass values in their safety analysis report. Hence it can be said that the safety of the target is safe because meets the safety constraint of the target.

Tabel 5. Data of target irradiation at operation of Core No. 102 – 105

No	User	Target	Mass (gram)	Time From	Time finished	Position in core	Dose rate (µSv/h)
1	PTRR	Sm2O3 Lu2O3 MoO3	0.01 0.0003 4	19-02-2021 08:35	23-02-2021 13:30	E-7	40
2	PT INUKI	TeO2	83	19-02-2021 08:35	23-02-2021 13:30	D-6	2.3
3	PTRR	Gd2O3 MoO3	0.0003 4	05-03-2021 08:10 16-03-2021 11:55	15-03-2021 05:29 17-03-2021 05:14	D-6	80
4	PTRR	Lu2O3	0.0003	05-03-2021 08:10 18-03-2021 00:00	15-03-2021 05:29 19-03-2021 00:00	. E-7	330
5	PTRR	Sm2O3 Gd2O3 TeO2	0.01 0.5 50	12-03-2021 07:21 16-03-2021 11:55	15-03-2021 05:29 17-03-2021 05:14	D-6	90
6	PT INUKI	TeO2	83	12-03-2021 14:45	15-03-2021 05:29	E-7	0.58
7	PTRR	Sm2O3 MoO3 TeO2	0,01 4 50	26-03-2021 09:15	30-03-2021 15:00	D-6	90
8	PT INUKI	TeO2	85	26-03-2021 09:15	28-03-2021 07:11	E-7	2.3
9	PTRR	Sm2O3 Lu2O3 MoO3 Sc2O3	0.01 0.00026 1 0.023	23-04-2021 08:39	27-04-2021 13:30	D-6	120
10	PTRR	Sm2O3 MoO3 TeO2	0.01 4 50	28-05-2021 09:14	01-06-2021 13:40	D-6	120
11	PRSG	Au-198	0.25	27-05-2021 13:01	27-05-2021 13:21	D-6	250
12	PTRR	Sm2O3 MoO3 Lu2O3 Sulfur	0.01 4 0.00026 10	18-06-2021 08:23	22-06-2021 13:00	D-6	210
13	PTRR	TeO2	100	18-06-2021 08:23	22-06-2021 13:00	E-7	27
14	PTRR	Sm2O3	0.01	02-07-2021 08:37	06-07-2021 13:04	D-6	210

5. CONCLUSION

Safety procedure for reactor utilization at the RSG-GAS reactor has been implemented to reactor operation and utilization at core numbers 102 to 105 for radioisotopes targets. The reactor operation were safe and reliable to serve the radioisotope target irradiation.

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AUTHOR CONTRIBUTION

Iman Kuntoro, Lily Suparlina and Purwadi are equally contributed as the main contributors of this paper. All other authors read and approved the final version of the paper.

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