Fuel Burn-up and Radioactivity Inventory Analysis for New In-core Fuel Management of the RSG-GAS Research Reactor

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Abstract. A new fuel management pattern has been applied to the RSG-GAS Research reactor operation. The new fuel management pattern is done so that the replacement of fuel in every operating cycle is more efficient. The new fuel replacement pattern required various safety analyzes, among others related to the fuel fraction and radioactivity inventory of the RSG-GAS. Both of those are the main elements in dose acceptance analysis for workers and communities around the reactor when the reactor operates both in normal or in abnormal conditions. Fuel burn-up and inventory analysis was performed using ORIGEN2 computer program. Inputs for ORIGEN2 are the fuel mass, the time required for one operating cycle as well as the peak power factor in each fuel in the specified fuel management pattern. The result for the 97th Core configuration (T97) are the fuel mass, the time required for one operating cycle as well as the peak power factor in each fuel in the specified fuel management pattern. The result for the 97th Core configuration (T97) is that the average burn-up fraction of each cycle is 6.79%, and the maximus fuel fraction is 52.36% for Fuel Elemet and 56.52% for Control Elemet. It is also obtained that the largest and dangerous human inventory activity at the end of cycle (EOC) for Iodine radionuclide group is I-131 for 5.18E+04 Ci, and for the alkali metal radionuclide group Cs-137 of 7.65E+03 Ci.

1. Introduction
The RSG-GAS reactor has been operating since 1987. RSG-GAS is a pool reactor consisting of uranium silicide ($\text{U}_3\text{Si}_2$-Al) plate-type fuel with low uranium enrichment level (19.75%). The reactor also has a light water coolant ($\text{H}_2\text{O}$) and beryllium reflector. Various activities have been undertaken at the reactor, among others, for materials research, fuel burn-up (BU) research, production of silicon doping and radioisotopes. The operation of the reactor required the management pattern of the preparation and replacement of fuel in the reactor core in such a way as to obtain high flux neutron and maximum operating cycle.

The RSG-GAS equilibrium core consists of 40 Fuel Elements (FEs) and 8 Control Elements (CEs), arranged in 6 burn-up classes with each BU class representing the burn-up fraction of 8%. Minimum burn-up fraction on the reactor core is 0% and maximum is 48%. The arranged management pattern is generated from calculations using the IAFUEL computer code. The resulting pattern is that each cycle will be retracted 6 FEs and 1 CE (6/1) with the largest fuel fraction (56%) and will be inserted 6 FEs and 1 CE fresh. This pattern is carried out until the 6th cycle and started from 7th cycle to pattern has changed to 6 FEs and 2 CEs (6/2). This in core fuel management was carried out until the 26th (Teras 26/T26) core configuration. After the these study, it seems that the fuel management pattern is not in its maximum condition, because in the seventh cycle it will be taken 2 FEs with fuel fraction that has not been maximally used (which is about 48% BU). Therefore, some reviews are undertaken to obtain a better pattern of new fuel management. Liem PH
et al [1] has done so, obtained a new fuel management pattern using the BATAN-EQUIL-2D computer program [2]. The resulting pattern is that each operating cycle will be issued 5 FEs and 1 CE (5/1) with the largest burning fraction of 52.00%, and replaced with 5 fresh FEs and 1 fresh CE. This pattern takes place continuously. In this fuel management pattern, fuel retracted is a fuel that already has a maximum burn-up fraction in the reactor core.

The new fuel management pattern requires a variety of safety analyze. One of them is the analysis of radionuclide dispersion which results in the study of doses received by workers and communities around the reactor neighbourhood. Radionuclide analysis requires input of a sourceterm based on the inventory present in the reactor. The reactor inventory calculations have been carried out for various types of reactors, among others, for HTGR reactors by S. Kuntjoro et al [3], H Jeong et al [4], on MOX's Fuel Reactor LWR by S. Fehéra [5], for CANDU reactor by Z. Yasin [6], on the Syrian miniature neutron source by K. Khattab et al [7], for Reactor core heterogeneity by K. Obaidurrahman et al [8], on the VVER-1000 reactor First Core condition by M. Rahgoshay et al [9], also at the RBMK reactor reactor by Smaizys [10] and for the MNSRs reactor by the researcher S. Waqar [11]. Various computer codes were used for reactor inventory calculations, such as ALEPH-2 and SCALE 6.2 used by researchers L. Fiorito et al [12], GETERA by S. Dewahra et al. [13].

Research on the RSG-GAS inventory for new fuel management pattern has never been performed. The purpose of the current research is to determine the RSG-GAS inventory in the new in core fuel management. The research was done through calculations performed using the ORIGEN2 computer program [14]. The ORIGEN2 computer code is a computer program to calculate the depletion of uranium as an interaction with neutrons. As input for this program are the mass of uranium, the reactor power or the neutron flux of uranium, and the time of neutron irradiation of uranium.

The output expected are uranium mass, parent and daughter nuclides mass from the fission products. The activity of radionuclides of fission products are obtained as well. The observed nuclides were divided into 8 groups: tritium and noble gas group, halogen group, alkali metal group, tellurium group, strontium and barium group, noble metal group, lanthanid group and cerium group [15]. The RSG-GAS core conditions observed were the 97th core [16]. The subsequently obtained radionuclide inventory will be used to determine the sourceterm of the RSG-GAS reactor, which is part of RSG-GAS reactor safety report. The Reactor Safety Analysis Report is intended to meet the licensing requirements of BAPETEN regulatory bodies.

2. Reactor Core Geometry

The RSG-GAS reactor core is composed by 40 Fuel Element (FE) and 8 Control Element (CE). The FE material is U$_3$Si$_2$-Al and has cladding of AlMg$_3$. Fuel Element or Control Element is a plate type fuel and consists of 21 symmetric plates for standard fuel element and 15 plates for control elements, the FE and CE geometry are the same, the only difference is that on CE 3 the fuel plate on the left and right side is removed and replaced with a column for the entry of a fork-shaped neutron absorber. The absorbent material used is AgInCd. The geometry data of FE and CE materials can be seen in Table 1.

### Table 1. Fuel element and fuel control element data of plate-type fuel of the RSG-GAS Reactor [17]

| Parameter                        | Fuel Element | Fuel Control |
|----------------------------------|--------------|--------------|
| Fuel material                    | U$_3$Si$_2$Al| U$_3$Si$_2$Al|
| Absorber material                | -            | Ag-In-Cd     |
| Cladding material                | AlMg$_3$     | AlMg$_3$     |
| Channel width (mm)               | 2.55         | 2.55         |
| Number of plates                 | 21           | 15           |
| The number of U-235 per element of fuel (g) | 250          | -            |
| The number of U-235 for each control element (g) | -            | 178.6        |
| Fuel dimensions (mm)             | 0.54 x 62.75 x 600 | 0.54 x 62.75 x 600 |
| U-235 Enrichment (w/o)           | 19.75        | 19.75        |
| Uranium density in fuel (g/cm$^3$) | 2.96         | 2.96         |
The RSG-GAS reactor core has cooling water in the form of light water (H$_2$O) and a beryllium-based reflector. Beryllium is selected as a reflector because it has a large reflection factor to neutrons, so very few neutrons escaped from the reactor. In addition to cooling, H$_2$O acts as a moderator, which serves to moderate neutrons from high-energy to thermal energy. Thermal neutrons are required because U-235 has a large fission capture probability for thermal neutrons, so the resulting fission reactions are large, in order to obtain large reactor power.

The reactor core configuration observed for the study is 97$^{th}$ core. This core configuration is presented in Figure 1.

![Figure 1](image.jpg)

**Figure 1.** Configuration of the RSG-GAS reactor core in BOC with 40 fuel elements (FEs) and 8 control elements (CEs).

From Figure 1 it can be seen that in each box, the first line shows the type of fuel of FE or CE, the second line depicts the burn-up fraction in BOC (%) and the third line states the Power Peaking Factor (PPF) in FE or CE. RSG-GAS reactor has 4 Central Irradiation Position (CIPs) of and also 4 Irradiation Position (IPs). CIP and IP are intended for material irradiation for research purpose as well as for the radioisotope production.

3. Calculation Methodology

The inventory calculation of the RSG-GAS reactor is based on the reaction between neutrons and the fuel-material, uranium. Physical reaction results between neutron with uranium produces several neutrons with high energy as well as the fission products of parent nuclides and decayed nuclides resulting daughter nuclides. In addition, there are also alpha, beta and gamma radiations. Fission product nuclides as well as the decay results need to be monitored, as some nuclides are harmful to humans, because they emit large gamma energy, as well as their toxicity to humans. Therefore, the nuclides are part of the safety aspect calculated in the safety analysis of a reactor. The formed nuclides inside the reactor core is called reactor inventory.

Inventory calculations on the RSG-GAS reactor are carried out using the ORIGEN2 program. As input is the mass of each fuel, power of the reactor as well as the length of operation. The core configuration observed is 97$^{th}$ core, as shown in Figure 1, for beginning of cycle conditions (BOC). Inventory calculations are performed for each FE and CE. For BOC condition, the mass of each fuel
is required. In the one new fuel conditions, the mass of U-235 is 250 gram, while the mass U-235 in the control of the element is 15/21 of mass U-235 fresh fuel, which is equal to 178.57 grams. Furthermore the power affected in each fuel is determined, i.e the averaged power multiplied by the PPF. The average power for each fuel is the power of the reactor divided by the amount of fuel that is equal to 15 MW / (40+ (15/21 × 8), i.e 0.32812 MW, while for the element control of 0.23437 MW. i.e the time for a 630 MWD operating cycle, for 42 days.

After all of each input is obtained, calculations are made for the BOC condition and EOC condition. The results obtained are the mass of uranium and other fission products as a function of the fuel fraction. The inventory of the RSG-GAS reactor in the form of radionuclide functionality is also obtained. The observed radionuclide activity is divided into 8 radionuclide groups as performed in NUREG-1465 from the United States-Nuclear Regulatory Commission (US NRC).

4. Results and Discussions

The results obtained are the mass of U-235 in FE and CE as a function of burnup as seen in Figure 2. It is observed that the mass of U-235 in FE and CE decreases as a function of burnup. This is because U-235 will be burnt due to the fission between U-235 and thermal neutrons. The decline trends of U-235 mass in FE and CE are the same, since the uranium contained in both FE and CE is the same, i.e. uranium with 19.75% enrichment.

![Figure 2. Radionuclide mass function of burnup for FE and CE](image)

The difference is that the mass of U-235 in one fresh conditions in FE of 250 grams (21 fuel element plate), while in CE of is only 178.6 grams. Another difference is the number of U-235 burnt in each cycle is different, where U-235 mass in CE is burnt more, due to the location of CE in the center of the core, so the averaged PPF in CE is greater than in FE. Thus with the same irradiation time, the amount of U-235 burnt in CE is greater than in FE. Other results are the amount of U-234, U-235, U-236, U-238, Pu-238 and Pu-239 mass as seen in Table 2.

| Radionuclide | Mass in BOC (gram) | Mass in EOC (gram) |
|--------------|--------------------|--------------------|
| U-234        | 2.30               | 2.27               |
| U-235        | 8693.43            | 7930.26            |
| U-236        | 397.08             | 507.68             |
| U-238        | 46448.90           | 46431.40           |
| Pu-239       | 40.75              | 51.44              |
| Pu-240       | 3.43               | 5.08               |

Table 2 shows that U-235 mass in the reactor core during 1 cycle decreases dramatically, this is because U-235 has large macroscopic fission cross-section for thermal energy, so that during 1 cycle operation of U-235 is burnt in big amount. For U-238 and U-234 the masses are decreased, but not
significantly, this is because U-238 and U-234 have low macroscopic fission cross-section on thermal energy, so it is not burnable due to fission reaction.

The U-236, Pu-239 and Pu-240 masses are rising at the End of the Cycle (EOC), since the three nuclides are the nuclide of the fissile product which has increased in number due to fission reactions. The decrease in the mass of U-235 at the end of the cycle requires fresh fuel, therefore at the beginning of each cycle 5 FEs and 1 CE are replaced. For new fuel management the amount of replaced fuel is 5 FE and 1 CE. Which have the largest burn-up fraction and replaced with fresh FE or CE. It is also obtained results of mass U-234, U-235, U-236, and U-238 as a function of burn-up. Results can be observed in Figure 3 and Figure 4.

![Figure 3. Mass of uranium function of fuel burnup in one fuel element](image)

![Figure 4. Mass of Plutonium as function of fuel burnup in one fuel element](image)

Figure 3 shows the amount of U-235 is sharply reduced as the function of the fuel fraction, because U-235 burns rapidly by thermal fission reaction, whereas U-234 and U-238 are very small react with thermal neutrons, since both have small probability features. As Figure 4 shows the amount of plutonium Pu-239 and Pu-240 formed is greater, since both these Pu nuclides are the result of the fissions that will increase in number each time a physical reaction between neutrons with U-235.

The result of radionuclide inventory calculations in the RSG-GAS reactor core under BOC and EOC conditions is seen in Table 3.
Table 3. Activity (in Ci) of nuclide inventory at BOC and EOC of the RSG-GAS reactor

| Group   | Radionuclide Group | Nuclide | Activity (Ci) | Group   | Radionuclide Group | Activity (Ci) |
|---------|--------------------|---------|---------------|---------|--------------------|---------------|
| 1       | Tritium and Noble Gas | H-3     | 2.58E+01      | 2       | Halogen            | I-131         |
|         |                    | Kr-85   | 7.26E+02      | 3       | Alkali Metal       | Cs-137        |
|         |                    | Kr-88   | 0.00E+00      | 4       | Tellurium          | Te-132        |
|         |                    | Xe-133  | 1.31E+04      | 5       | Strontium dan Barium | Sr-89        |
|         |                    | Xe-135m | 0.00E+00      |         |                    |               |
|         |                    | Xe-138  | 0.00E+00      | 6       | Noble Metal        | Sr-90         |
|         |                    |         |               |         |                    | Ba-140        |
|         |                    |         |               | 7       | Lantanida          | Cs-134        |
|         |                    |         |               |         |                    | Sr-90         |
|         |                    |         |               |         |                    | Ba-140        |
|         |                    |         |               |         |                    | Sr-90         |
|         |                    |         |               |         |                    | Ba-140        |
|         |                    |         |               |         |                    | Sr-90         |

Table 3 shows that the radionuclide inventory of the EOC condition is greater than that of the BOC, this is because the existing radionuclide is a radionuclide of direct fission and its derivative. Thus with increasing irradiation time on FE or CE, the number of radionuclide activities also increases.

Also seen in Table 3 that the largest radionuclide activity is Nb-95 from the Lanthanide radionuclide group of 3.65E+05 Ci, but because it has a low toxicity level, it requires no special attention. Radionuclides that have high toxicity and have a specificity are from the Halogen group, namely I-131 nuclides and from the Alkaline metal group, the Cs-135 nuclides. Nuclide I-135 is dangerous, because it has precipitated properties in the thyroid, so that when entering the human body will give a harmful effect. While Cs-137 is a high-energy gamma transmitter, so exposure to radiation emitted is harmful to humans. The activity for I-131 nuclides is 5.18E+04 Ci, while for Cs-137 is 7.65E+03 Ci. For other groups like noble gas no special attention is needed, because noble gas does not interact with the material.

5. Conclusion

Determining of fuel burn-up fraction and inventory for the new material management pattern of RSG-GAS reactor have been performed using the ORIGEN2 computer code. The results obtained are the amount of U-234, U-235, U-236, U-238, Pu-239 and Pu-240 as a function of fraction with EOC condition of 2.27 gram, 7930.29 gram, 507.68 gram, 46431.40 grams, 51.44 grams and 5.08 grams. The largest inventory of radionuclide activity is Nb-95 of 3.65E + 05 Ci. The amount of mass and activity present in the reactor (inventory) is dangerous to humans when released from fuel. By thereby the integrity of the fuel must be maintained through a safe operating procedure. The next generated radionuclide inventory activity will be used to obtain the reactor sourceterm under normal and abnormal conditions. Sourceterm will be used as a basis for calculating dose acceptance of workers and communities around the reactor.

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