Analysis of Safety Reactivity Factor on RSG-GAS Core using New Fuel

T Surbakti¹, Surian P¹, Farisy Y¹, Imron M²

¹Center for Nuclear Reactor Technology and Safety, BATAN, Kawasan PUSPIPTEK Gd. No. 80 Serpong, Tangerang Selatan, 15310 Indonesia
²Centre for Multipurpose Reactor, BATAN Center for Nuclear Reactor Technology and Safety, BATAN, Kawasan PUSPIPTEK Gd. No. 31 Serpong, Tangerang Selatan, 15310 Indonesia

Email: tukiran@batan.go.id

Abstract. The RSG-GAS is using U3Si2-Al dispersion fuels with a uranium density of 2.96 gU/cc. The silicide uranium fuels are not used anymore for the future. To anticipate the usage of other fuels in the RSG-GAS core, UMo-Al fuels were chosen. The UMo-Al fuel has many advantages some of them, it can be used at a higher density in the reactor core. There are high uranium densities in UMo-Al dispersion fuels up to 16 gU/cm³ with numerous contents of Mo. In this analysis, the RSG-GAS core is used with a high density of UMo-Al fuel. The neutronic parameter is such as reactivity balances, keff, and power peaking factor and safety reactivity factor of UMo-Al fuel with higher density. The UMo-Al core criticality data are achieved by calculation using the Batan-FUEL code. The UMo-Al fuel macroscopic cross-section data as the output of cell calculation WIMSD-B5 (ENDFVII.0) were used for the calculation. The core calculations were performed using a 2 and 3 dimension diffusion code. The calculation results show that the good fuel for RSG-GAS is U7Mo-Al with maximum radial and axial power peaking factor of U7Mo-Al with high density at 20 cm control rod depth is 1.32 and 1.73 respectively and safety reactivity factor more than 1.5. The results show that all neutronic parameters are met the safety criteria. Hence U7Mo with higher density could be applied for RSG-GAS core and operated for 1500 MWD cycle length

1. Introduction

One of the research activities with high priority in the PTKRN-BATAN is to upgrade the utilization of RSG-GAS reactor using an U7Mo/Al fuel. The high density of ⁴⁰⁰^{235}U loading as fissile material in the U7Mo/Al fuel is expected to increase the reactor operating time; thereby, increasing reactor utilization and fuel efficiency while the fuel cost can be reduced[1]. At present, an international discussion forum is considering the use of U7Mo/Al fuel in research reactors based on their results of research. U7Mo-Al fuel has been approved for use as a more attractive fuel for research reactors than uranium silicide fuel. The U7Mo/Al fuel that can be fabricated with high density are taken into consideration for reactor designers and also operators of research reactors to use U7Mo/Al fuel. International organizations no longer want to reprocess for uranium silicide fuels so for countries that are not allowed to reprocess the used silicide fuels, the reactor operator must move to U7Mo/Al fuel. After decades of research, the UMo fuel has the prospect, in terms of the stability of the fuel U8Mo/Al and U7Mo/Al are more stable in the radiation field than other fuels. Batan will research on the fabrication...
of U7Mo/Al fuel and its use in the RGS-GAS core, to find out its characteristics under irradiated. Batan is also interested in U7Mo-Al fuel and will conduct the research by making mini-fuel elements and will include them into the devices such as the RSG-GAS fuel assembly. Only three plates are loaded with high-density U7Mo/Al will then be irradiated the core of the RSG-GAS reacon[3].

In a reactor, the higher the fuel densities the less amount of fuel used in the core at the same core power and volume. This will also affect the length of the reactor operating cycle so that the longer the fuel in the core will be more effective and efficient as long as the safety factor is maintained.

Because of the many advantages of using UMo fuels, the RSG-GAS reactor also conducts the conversion of silicide to U7Mo/Al fuels. This conversion program determines how many U7Mo fuel assemblies can be used on the optimal high-density RSG-GAS core. As well as a strategy to reach the equilibrium core of RSG-GAS reactor. Since the program began, the study of fuel conversion has been carried out for various types of core configuration have been proposed[4].

In this study, the silicide fuel management procedure was adopted to study the optimal high-density U7Mo/Al fuel in RSG-GAS equilibrium core. Compared to the present silicide fuel with 2.96 gU/cm³ density which can operate 25 core cycle length under nominal power of 30 MW, the new silicide equilibrium core with 3.55 gU/cm³ density can give significant extension of the core cycle length, that is to about 32.5 days, it is the same with U6Mo-Al fuel, while saving one fuel element per cycle. This achievement increases the reactor utilization and reduction of fuel costs. But according to bad irradiation results, this type of fuel is rejected. Then the study only focuses on high-density fuel from which the U-Mo alloys with a Mo content of 7-9 w%[5].

In this research, the parameter of safety reactivity factor (SRF) analyzed on RSG-GAS core using new fuel, namely high-density molybdenum. This parameter is very related to the safety of the reactor operation. The analysis will be done for the new core configuration of RSG-GAS using a high density of molybdenum fuel. The in-core fuel management will adopt refueling/shuffling strategy which is called 5/1 scheme where 5 fresh fuel elements (FEs) and 1 control element (CE) must be loaded in the core at BOC (Beginning of Cycle).

This paper presents the results of RSG-GAS core configuration neutronic parameters calculation for the RSG-GAS multipurpose reactor having adopted the new 5/1 scheme of fuels. The calculation used WIMSD-5B and Batan-FUEL codes. The WIMSD-5B code was used for generating the cross-section and the Batan-FUEL code was used for core calculation. The neutronic parameter is analyzed based on the safety reactivity factor. The safety reactivity factor for the equilibrium core must be ≥1.5. If it is less then 1.5 the core configuration will be rearranged because the safety limit is violated.

2. RSG-GAS core description

RSG-GAS is the first MTR (Material Testing Reactor) research reactor in the world that is operated directly using the LEU (Low Enriched Uranium). The first time the RSG-GAS was designed with LEU oxide (U₃O₈-Al) fuel elements. RSG-GAS uses an oxide fuel with a density of Uranium in the meat of 2.96 gU/cm³ with 235U enrichment of 19.75%. The reactor uses light water as a core cooler and also as a moderator. The core components of the reactor are arranged on a grid consisting of 10 x 10 positions. The grid is surrounded by a core-sheath to direct the flow of cooling to pass through the components of the core. Outside the core-sheath, L-shaped reflector blocks made of Beryllium are placed side by side with the reactor core. The lattice consists of 100 identical holes to hold the fuel element, the control fuel element, the Beryllium reflector element, and the irradiation position. The ends of these elements fit right into the lattice hole. Smaller additional holes are available between the main grating holes to cool the element's outer surface. The available space on the 10 x 10 lattice with a pitch of 81 mm x 77.1 mm is filled with a reflector element made from Beryllium material and an irradiation position for the rabbit system. This reflector arrangement closes the two sides of the reactor core. Beryllium reflector blocks and experimental positions, especially the bundled tube cover the other two side edges. The Beryllium block is separated from the reactor core by the core housing. The core configuration of the RSG-GAS reactor is shown in figure 1.
The fuel element is based on MTR technology. Each standard fuel element consists of an end section at the bottom, and a holding device at the top, two side plates and 21 fuel element plates. Each fuel element plate consists of an AlMg2 frame and two cover sheets of the same material, which wrap the fuel meat dispersion plate.

The control fuel element is designed to be forked type. The part that contains the fuel element in the control rod element is identical to the part that contains the fuel element in the fuel element. A total of 15 internal fuel element plates are held by two side plates. A total of 3 (three) fuel element plates are taken at each end of the area containing the fuel element to make room to insert the absorber blade. Aluminum plates replace two of the three plates taken from the fuel element. Each fuel element consists of:

a. The lower end of the right fitting enters into the grating plate hole to place the fuel elements.
b. Two side plates (side plates) with fastening grooves and retaining elements of the fuel element.
c. The handle at the top as handling equipment that fits the handling tool.
d. Twenty-one fuel element plates of the same width and thickness each consist of an AlMg2 frame and two cover sheets of the same material which encapsulate a $U_3Si_2Al$ dispersed meat plate.
e. One comb spacer with a width of 3 mm at the top end of the fuel element plate to ensure that the distance between the fuel element plates does not change.

The lower end of the fitting is designed in a cylindrical shape with an outer diameter of 61 mm, a height of 171.5 mm and a wall thickness of 6.6 mm. The upper end of the lower end of the fitting is widened to the transition section which holds the two side plates 4.5 mm thick. All structural parts are made of Aluminium alloy. The side plates are extended to the top end of the fuel element which is equipped with a handle. The handle has a diameter of 13 mm arranged so that it can accept the handling tool holder’s tip.

The length of all the fuel elements is 868.5 mm. A total of 21 fuel element plates, each having a thickness of 1.30 mm, are an important part of the fuel element. 0.54 mm thick meat covered by two cover plates with a thickness of 0.38 mm. The length of the meat area is 600 mm while the width is 62.75 mm. Meat is put into the frame by using the picture frame technique (picture frame technique). The frame and cover plate have nominal dimensions of 625 mm x 70.75 mm for 19 inner plates and 693.5 mm x 70.75 mm for 2 outer plates. The fuel element plate is connected to the two side plates by a special rolling procedure. Meat on a fuel element plate consists of $U_3Si_2Al$ dispersion in Aluminium. Uranium density in meat 2.96 g/cm$^3$.

The RSG-GAS control fuel element is designed to accept fork absorbent types. Of all the existing and proven absorbent designs for the MTR fuel element core reactor, this absorber design provides the highest effectiveness for the control of the reactor. The part containing the fuel element in the control fuel element is identical to that contained in the standard fuel element. A total of 15 internal fuel element plates are held on both sides by two side plates. While the 3 fuel element plates are taken at each end of the zone containing the fuel element to make room for the absorbent plate to enter into it.
### Table 1. Main data of RSG-GAS core[12]

| Parameter                        | Size /material/type |
|----------------------------------|---------------------|
| Reactor type                     | Tank in open pool   |
| Fuel element                     | silicide MTR        |
| Moderator/coolant                | H₂O                 |
| Reflector                        | Be and H₂O          |
| Power at first core (MWt)        | 30                  |
| No. of a fuel element            | 40                  |
| No. of a control element         | 8                   |
| No. of fork type absorber        | 8                   |
| Fuel/control element             | 77.1x8.1x60         |
| Fuel plate thickness (mm)        | 1.3                 |
| Coolant channel width (mm)       | 2.55                |
| No. of plate per fuel element    | 21                  |
| No. of plate per control element | 15                  |
| Fuel plate cladding material     | AlMg2               |
| Fuel plate cladding thickness (mm)| 0.38               |
| Fuel meat dimension (mm)         | 0.54x62.75x600      |
| Fuel meat material               | U₃Si₂Al             |
| ²³⁵U enrichment (w/o)             | 19.75               |
| Uranium density in meat (g/cm³)  | 2.96                |
| ²³⁵U loading per fuel element (g)| 250                 |
| ²³⁵U loading per control element (g)| 178.6          |
| Absorber meat material           | Ag-In-Cd            |
| Absorber thickness (mm)          | 3.38                |
| Absorber cladding material       | SS-321              |
| Absorber cladding thickness      | 0.85                |
3. Methodology

Perform macroscopic constant calculations of U7Mo/Al mass of 400, 500, 600, and 700 g of the fuel fraction function using WIMSD-5B. The configuration of the RSG-GAS core design of the uranium silicide-fuelled plate type chosen in this study is a TWC core with the same fuel and control rod size as shown in Figure 1 and Figure 2. The reactor core consists of 40 fuel elements which each fuel consists of 21 plates and 8 control elements which each control element consists of 15 plates which means that in one core consists of 960 fuel plates. The fuel element used is uranium silicide with a load of 400, 500, 600 g and 700 g of uranium enrichment of 19.75% and a fuel density of 2.96%. Figure 3 presents the WIMSD-5B input model of the RSG-GAS fuel assembly and Table 1 shows the nuclear parameters used in this calculation. In this research activity, the WIMSD-5B program package is used in generating macroscopic cross-sections of a fuel assembly.

The cross-sectional generation calculations are performed with a computer using the neutron transport method that is available in the WIMSD-5B program in cold conditions and Xenon and Samarium free, cold and Xenon free Samarium equilibrium, hot and Xenon free Samarium equilibrium, hot Xenon and Samarium equilibrium. All calculations use the latest ENDF-BVII.0 microscopic constant. The WIMSD-5B program package is a program package that is used at the cell count calculation for core materials such as fuel. This program functions to process input from the reactor core to produce an output in the form of macroscopic cross-sectional constants of the reactor core material. In this program, the core elements of the RSG-GAS reactor are modeled as a collection of plates composed of meat, cladding, moderator, and the extra region as shown in Figure 3. The input prepared for the WIMSD-5B program package is the composition of the fuel element.

In the first part, neutron spectrum is calculated in a certain geometry and groups corresponding to the program library (69 neutron energy groups), and used to summarize the amount of power into only 4 groups (few groups), namely: Fast neutrons, groups 1-5 with an energy of 0.82 MeV < $E \leq 10$ MeV. Resonance neutron, group 6-15 with energy 5,531 eV < $E \leq 0.821$ MeV. Epithermal neutron, group 16-45 with the energy of 0.625 eV < $E \leq 5.531$ KeV. Thermal neutron, group 46-69 with energy < 0.615 eV[13]. In the RSG-GAS core conversion neutronic design, core parameters calculated include reactivity equilibrium parameters, radial and axial peak power factors, S-curve control rods, kinetic parameters and neutron flux distribution in irradiation facilities. The reactivity equilibrium parameter is calculated to determine the adequacy of the more core reactivity during the reactor operating in one cycle at a nominal power of 30 MW.

Besides that, the ability of 8 control rods on the core must be enough to cover the core excess reactivity. Determination of the peak axial power factor and the S-curve of the control rod are carried out with a program package of the 3-dimensional Batan-3DIFF neutron diffusion method. This is done because these parameters depend on the position of the entry/ withdrawal of the control rod. Whereas the other core parameters are calculated by the 2-dimensional Batan-FUEL neutron diffusion method.

The calculation of the balance of silicide balance with a density of 2.96 gU cm$^3$ with pattern 5/1 was carried out with the Batan-FUEL program package. The optimum length of one cycle of core operation is determined based on more core reactivity when BOC, cold and without Xenon, core excess reactivity when EOC, hot and Xenon are equilibrium and maximum discharged burn up. If the core parameters exceed the design limits such as safety reactivity factor $\geq 1.5$, a core configuration and fuel loading strategy are rearranged. Cross-section and Core calculations for RSG-GAS are shown in Table 2.

| Items                    | Code for RSG-GAS reactor core          |
|--------------------------|----------------------------------------|
| Nuclear Data File        | ENDFVII.0 (for WIMSD-5B code)          |
| Cell Calculation Code    | WIMSD-5BSN method                      |
| Theory Model             | 1-D with multi-plate model             |
| Core Calculation Code    | Batan-FUEL                             |
| Theory Model             | Diffusion2-D, X-Y geometry             |
| No. of groups (Fast + Thermal) | 4(3+1)                                |
3.1 Calculation of criticality and reactivity of the core.

In neutronic calculations, a balanced reactivity core is modeled in 2-dimensional X-Y geometry, 4 groups of neutron energy with Batan-EQUIL-2D 2-dimensional neutron diffusion program. One of the most important inputs in the Batan-EQUIL-2D program is the fuel element shift pattern in which 24 fuel elements and 8 control elements are grouped into 4 classes of fuel fractions with a mean burn-up fraction of 0, 11, 22 and 33%, respectively for fuel burn up classes 1, 2, 3 and 4. The core configuration and division of the fuel class are shown in f
Figure 3. As a result, at the beginning of the cycle, there are 6 fuel elements and 2 control elements are loaded according to the number of spent fuel elements with the maximum burn-up released from the core.

3.2 Safety factor and acceptance criteria
The RSG-GAS has operating limits and safety factors as well as the acceptance criteria in its design. The length of the operating cycle at 30 MWth power is 25 days (750 MWD) with the excess reactivity of 9.2 % k/k and the shutdown margin reactivity of -2.2% k/k. The safety factor and acceptance criteria applied in the design are as follows.

a. The minimum shutdown margin reactivity is -0.5 % k/k.

b. The maximum radial power peaking factor is 1.4.

c. The maximum discharged burn-up of the design core at EOC is 70 % loss of $^{235}$U).

d. The number, as well as the performance of irradiation positions and facilities, should be maintained.

e. Safety Reactivity Factor (SRF) on the design core is $\geq 1.5$. SRF = total control rods reactivity worth/ core excess reactivity.

Furthermore, the burn-up classes and distribution as shown in figure 1. Figure 1 for 40 fuels and 8 control rods. The RSG-GAS core with molybdenum fuel design (U7Mo/Al) using 24 fuels and 8 control rods. The refueling scheme for both core configurations is different and considered as the strategy of in-core fuel management in generating all equilibrium cores.

4. Results and calculation
4.1 Silicide equilibrium core
Table 3 shows the result of the core reactivity balance for silicide fuel. For the density fuel 2.96 and 3.55 g/cm$^3$ the core configuration using 40 fuel elements and 8 control elements. The refueling and reshuffling strategy finally adopted in the existing core. The 40 FEs and 8 CEs are grouped into 8 burn-up classes (0, 7, 14, 21, 28, 35, 42, 49 and 56%). Consequently, at the end of the core (EOC) 5 FEs and 1 CE taken out from the core after the maximum burn-up is reached. Consequently, at the end of the core (EOC) 5 FEs and 1 CE taken out from the core after the maximum burn-up is reached. To choose the optimal cycle length it will be limited to the core excess reactivity of 1 % at the end of the cycle (EOC). For a shorter cycle length, the reserve EOC excess reactivity becomes larger but the safety reactivity margin for one stuck rod condition decreases. Thus, for the present silicide fuel 2.96 g/cm$^3$ meat density, the feasible range of core cycle lengths are roughly from 18.5 to 22.5 days. Comparing these values to the design core cycle length of 25 days, the adoption of the 5/1 fueling scheme significantly shortens the extension of the cycle length. It is shown in Table 3. that the cycle length of 20.0 days results in 8.78 % BOC excess reactivity (at cold and xenon free condition).

Therefore, for the rest of the discussion, we will concentrate on the results for 20.0 days cycle length. The safety reactivity factor for this core is more than 1.5. For the density of 3.55 g/cm$^3$ the same core configuration is achieved 30 days of operation cycle length safety reactivity factor is also more than 1.5. But for a density of 4.8 and 5.2 g/cm$^3$ using a core configuration of 24 fuel elements and 8 control elements. The search for 5.2 g/cm$^3$ silicide core reactivity with a mass of 439 g of uranium carried out using the Batan-EQUIL-2D program package began with all the standard fuel elements and control elements in fresh conditions. From the results of these calculations, the values of the shutdown margin, safety reactivity factor, maximum discharged burn up and radial PPF meet the safety criteria are obtained. The higher fuel density makes the cycle of length also higher. Higher cycle length of reactor operation becomes the fuel longer in the core. The utilization of the RSG-GAS will improve when the fuel higher density was used.

The values of neutron flux on the core in the irradiation position is presented in Table 4. From Table 4 it can be seen that the regions that have high thermal fluxes are in the middle core position, namely D6, D7, E7, and E8, while the value of thermal flux on the outer core is smaller. That is why the fuel with high fuel burn up is placed on the central core, in addition to compensating the reactivity
of the core as well as to keep the neutron flux high. The thermal neutron flux in the CIP and IP are enough for irradiation to produce a radioisotope production.

4.2 Molybdenum equilibrium core

The result for the equilibrium core using UMo-Al fuel can be seen in Table 5. In this table, the UMo/Al fuel is used with a density of 3.55 g/cm³ and the content of Mo in the fuel is variable such as 9wt%, 8wt%, 7wt%, and 6wt%. The neutronic parameter such as reactivity parameter, k-eff, neutron fluxes, shutdown margin, safety reactivity factor, and power peaking factor of UMo-Al fuel with a density of 3.55 g/cm³ for the typical working core calculation has been carried out. The UMo-Al core criticality data achieved by calculation using the Batan-FUEL code. The UMo-Al fuel macroscopic cross-section data were generated from the cell calculation of the WIMS-D-B5 code.

The core calculations to get the neutronic parameter using a 2 and 3 dimension diffusion code. The calculation results show that the good fuel for RSG-GAS is U7Mo-Al. The maximum radial and axial power peaking factor of U7Mo-Al with a density of 3.55 g/cm³ at 30 cm control rod depth is 1.23 and 1.73 respectively and met the safety criteria. Hence U7Mo-Al with 3.55 g/cm³ could be applied for RSG-GAS core and operated for 900 MWD cycle length without any part of core configuration changes. The burn-up values for RSG-GAS core using U7Mo-Al fuel at BOC and EOC are shown in figure 6. It can be seen from the results that the FE/CE burn-up values at EOC obtained below the safety limits. The results prove that the proposed searching procedure and the code worked satisfactorily. From figure 6, it can be observed that the maximum FE and CE discharged burn-up was found to be 56 % and 60 %, respectively.

![Figure 6.Burn-up of RSG GAS using U7Mo/Al fuel](image)

![Figure 7.PPF of the RSG GAS using U7Mo-Al fuel](image)

The radial PPF values of RSG-GAS core at BOC with molybdenum fuel can be seen in figure 7. From this figure, there are no safety limits that exceed all values below the safety limit of 1.4. The highest value is 1.24 which is the C-8 position of the control rod. This is by the design stated in the safety analysis report that the highest radial PPF is in the position of control rod or fuel but near the control rod. From the results of calculation, the loading strategy and higher number of burn-up classes were effective in minimizing the radial PPF values. The complete of ppf distribution for U7Mo-Al with a density of 3.55g/cm³ can be seen in figure 7.

Table 5 shows the comparison of the reactivity between the RSG-GAS core using UMo/Al fuel with the same density namely 3.55 g/cm³. Increasing the core cycle length it depends on the content of material Mo in the fuel. The one stuck rod subcritical analysis is tabulated also in Table 5. All cores are fulfilled the stuck rod criteria and taken for the one stuck rod subcritical analysis as a safety factor. For the safety reactivity factor (SRF) all cores are also ≥1.5 only for the RSG-GAS core that...
using U6Mo/Al the SRF less than 1.5, so the proposed core design will be rejected. Otherwise, it does not have to be reconfigured.

### Table 3. Neutronic parameter of RSG-GAS core using silicide fuels

| Parameter                     | Beginning of cycle | U3Si2-Al | U3Si2-Al | U3Si2-Al | U3Si2-Al |
|-------------------------------|--------------------|---------|---------|---------|---------|
| Uranium density (gram/cm³)    | 2.96               | 3.55    | 4.80    | 5.20    |
| Number of fuel elements       | 40                 | 40      | 24      | 24      |
| Number of control elements    | 8                  | 8       | 8       | 8       |
| Power (WM), Length of Cycle (days) | 30/20.5         | 50/30   | 30/33   | 30/40   |
| Average Burn-up at BOC, % Loss of U-235 | 23.71          | 28.60   | 14.44   | 15.39   |
| Average Burn-up at EOC, % Loss of U-235 | 30.17          | 39.14   | 24.71   | 26.27   |
| Max. FE burn-up (% loss of ²³⁵U) | 55.62           | 59.30   | 43.26   | 46.96   |
| Max. CE burn-up (% loss of ²³⁵U) | 56.90           | 63.45   | 47.21   | 51.97   |
| Max. radial fuel element channel factor | 1.24            | 1.27    | 1.23    | 1.23    |

#### Reactivity balances

- Δρ hot to cold: 0.46, 0.47, 0.45, 0.45
- Δρ equilibrium xenon poisoning: 3.51, 3.55, 3.60, 3.57
- Δρ burn up: 3.01, 3.20, 3.23, 3.41
- Δρ for exp., partial Xe override, etc.: 2.0, 2.0, 2.0, 1.50
- Core excess reactivity: 8.78, 9.01, 9.92, 10.35
- Total shutdown reactivity: -16.41, -15.13, -16.08, -16.94
- One stuck rod shutdown reactivity margin: -1.12, -1.30, -2.07, -1.71

### Table 4. Neutron fluxes in the RSG-GAS core for 5.2 gram/cm³ of U₃Si₂-Al fuel.

| Neutron fluxes | Position in the core (x 10¹⁴ n.cm⁻².s⁻¹) |
|----------------|------------------------------------------|
|                | D3            | D6            | D7            | D10           | E3            | E6            | E7            | E10           |
| Fast           | 0.2172        | 0.4586        | 0.4708        | 0.2395        | 0.2244        | 0.4632        | 0.4824        | 0.2372        |
| Epithermal     | 0.5846        | 1.0381        | 1.0642        | 0.6254        | 0.5977        | 1.0508        | 1.0890        | 0.6259        |
| Thermal        | 1.1023        | 1.7614        | 1.7855        | 1.1477        | 1.0894        | 1.7878        | 1.8108        | 1.1849        |

### Table 5. Neutronic parameter of RSG-GAS core using molybdenum fuels with density of 3.55 gU/cm³

| Parameter                     | Beginning of cycle | U9Mo/Al | U8Mo/Al | U7Mo/Al | U6Mo/Al |
|-------------------------------|--------------------|---------|---------|---------|---------|
| Uranium density (gram/cm³)    | 3.55               | 3.55    | 3.55    | 3.55    |
| Number of fuel elements       | 40                 | 40      | 40      | 40      |
| Number of control elements    | 8                  | 8       | 8       | 8       |
| Power (WM), Length of Cycle (days) | 30/30.0          | 30/31.0 | 30/32.0 | 30/32.5 |
| Average Burn-up at BOC, % Loss of U-235 | 30.20           | 31.60   | 29.46   | 32.10   |
| Average Burn-up at EOC, % Loss of U-235 | 38.10           | 39.30   | 37.21   | 39.90   |
| Max. FE burn-up (% loss of ²³⁵U) | 61.50           | 61.90   | 63.10   | 66.90   |
| Max. CE burn-up (% loss of ²³⁵U) | 64.80           | 65.10   | 66.50   | 69.70   |
| Max. radial fuel element channel factor | 1.24            | 1.25    | 1.26    | 1.27    |

#### Reactivity balances
Δρ hot to cold 0.39 0.39 0.49 0.49
Δρ equilibrium xenon poisoning 4.19 4.19 3.78 3.77
Δρ burn up 3.42 3.41 3.40 3.49
Δρ for exp., partial Xe override, etc. 1.80 1.63 1.45 1.08
Core excess reactivity 9.72 9.54 9.43 9.24
Total shutdown reactivity -14.91 -14.51 -14.21 -13.62
One stuck rod shutdown reactivity margin -1.91 -1.82 -1.73 -1.18

Table 6. Neutronic parameter of RSG-GAS core using molybdenum fuels with higher density

| Parameter | U7Mo/Al | U7Mo/Al | U7Mo/Al | U7Mo/Al |
|-----------|---------|---------|---------|---------|
| Uranium density (gram/cm³) | 5.34 | 6.50 | 7.80 | 8.30 |
| Number of fuel elements | 24 | 24 | 24 | 24 |
| Number of control elements | 8 | 8 | 8 | 8 |
| Power (WM), Length of Cycle (days) | 30/41 | 30/45 | 30/47 | 30/50 |
| Average Burn-up at BOC, % Loss of U-235 | 28.34 | 30.84 | 33.67 | 34.23 |
| Average Burn-up at EOC, % Loss of U-235 | 39.45 | 40.39 | 43.58 | 44.07 |
| Max. FE burn-up (% loss of 235U) | 53.45 | 54.56 | 55.34 | 56.96 |
| Max. CE burn-up (% loss of 235U) | 55.68 | 56.78 | 57.12 | 58.97 |
| Max. radial fuel element channel factor | 1.24 | 1.27 | 1.30 | 1.32 |
| Reactivity balances | | | | |
| Δρ hot to cold | 0.45 | 0.45 | 0.46 | 0.46 |
| Δρ equilibrium xenon poisoning | 3.58 | 3.59 | 3.58 | 3.68 |
| Δρ burn up | 3.44 | 3.51 | 3.64 | 3.78 |
| Δρ for exp., partial Xe override, etc. | 1.9 | 2.0 | 2.1 | 2.20 |
| Core excess reactivity | 9.45 | 9.98 | 10.01 | 10.35 |
| Total shutdown reactivity | -15.34 | -15.78 | -16.43 | -16.54 |
| One stuck rod shutdown reactivity margin | -2.10 | -2.20 | -2.02 | -2.01 |

Table 7. Neutron fluxes in the RSG-GAS core for 5.2 gram/cm³ of U₇Si₇-Al fuel.

| Neutron fluxes | Position in the core (x 10¹⁴ n.cm⁻².s⁻¹) | D3 | D6 | D7 | D10 | E3 | E6 | E7 | E10 |
|---------------|---------------------------------|----|----|----|-----|----|----|----|-----|
| Fast          | 0.2172                          | 0.4586 | 0.4708 | 0.2395 | 0.2244 | 0.4632 | 0.4824 | 0.2372 |
| Epithermal    | 0.5846                          | 1.0381 | 1.0642 | 0.6254 | 0.5977 | 1.0508 | 1.0890 | 0.6259 |
| Thermal       | 1.1023                          | 1.7614 | 1.7855 | 1.1477 | 1.0894 | 1.7878 | 1.8108 | 1.1849 |

Table 8. Neutron fluxes in the RSG-GAS core for 5.34 gram/cm³ of U₇Mo/Al fuel.

| Neutron fluxes | Position in the core (x 10¹⁴ n.cm⁻².s⁻¹) | D3 | D6 | D7 | D10 | E3 | E6 | E7 | E10 |
|---------------|---------------------------------|----|----|----|-----|----|----|----|-----|
| Fast          | 0.5174                          | 0.5587 | 0.6708 | 0.5396 | 0.5244 | 0.6634 | 0.6823 | 0.5371 |
| Epithermal    | 0.7846                          | 1.1381 | 1.1642 | 0.7254 | 0.7977 | 1.1502 | 1.1891 | 0.7253 |
From the results of core calculation, the value of the initial and end of the core burn-up is divided into 4 burn-up classes. The magnitude of the fuel burn-up of the core is a function of the length of the operating cycle. Determination of the optimal core is done by observing the calculation results obtained, namely the distribution of the equilibrium core and neutron flux in the irradiation facility for the beginning of the cycle as shown in Table 6. From this table can be seen that for all core with higher density the safety reactivity factor is more than 1.5. The maximum discharged burn up must be less than 70% as required in the initial calculation. For molybdenum equilibrium core with a higher density is divided into four burn up classes, with a maximum discharged fuel burn up at the end of the cycle of 58.97% for 1500 MWD.

The fuel burn-up distribution data is used in the calculation of the core with the Batan-2DIFF program package to obtain the values of neutronic parameters such as excess reactivity, shutdown margins, radial PPF and neutron fluxes, and safety reactivity factor. Other neutron parameters such as xenon generation, change in reactivity from cold to hot conditions. The calculation results in the form of reactivity balance are presented in Table 6. From some 2-dimensional core calculation results in the
form of reactivity balance, the optimal U7Mo core configuration can be determined. Table 6 presents the neutron parameter values of the core of the research reactor fuelled by U7Mo. In this table, the U7Mo core configuration is chosen with a 1500 MWD cycle length with 30 MW of operating power for 30 days. For core with a density of 8.30 gU / cm³ the average fuel burn-up at the beginning of the cycle is 28.60% and the end of the cycle is 39.14% and the others can be seen in Table 6, thus the average combustion that occurs every cycle is around 10.54%. The availability of more reactivity at the beginning of the cycle with xenon free cold conditions of 9.74% and the final reactivity of the equilibrium xenon condition cycle of 5.15% as well as a minimum outage and maximum radial peak power factor of less than 1.4 i.e 1.38.

The core configuration is chosen, then the neutron flux value is seen in the irradiation facility whether it is the desired one. It turns out that the neutron flux on the core is insufficient and by the designer. When compared with other core, the core with a molybdenum density of 8.40 gU / cm³ is the most optimum because the highest neutron flux is $3.717 \times 10^{14}$ n / cm²s. This is higher than that of a silicide core. But fuel with the same density but different material (silicide and molybdenum) which differs only slightly. Because the silicide core is almost the same as the molybdenum core, then on the molybdenum core is also certain with increasing density, the cycle length is also increased, in this case, the parameters of the cycle length are only 30 days. Tables 7, 8, 9, 10 and 11 show the U7Mo core neutron flux on the most optimum core at a density of 5.45, 6.52, 7.00 and 8.30 gU / cm³ respectively. At the center of the core, the thermal neutron flux is about $3.7174 \times 10^{14}$ n / cm²s. In the irradiation position, a fast neutron flux is obtained around $1.1 \times 10^{14}$ n / cm²s.

This neutron flux is by the design and no safety margin parameters are exceeded. From the calculation results between the silicide core and the molybdenum core with the same density that is 3.55 gU / cm³ is not much different both from the neutron parameters and the thermal neutron flux values so that for the other core no longer need to be compared.

5. Conclusion
Based on core calculation using Batan-FUEL code, the RSG-GAS core design proposed using new fuel uranium molybdenum (U7Mo-Al) with higher density can increase the operating cycle length and maximum thermal neutron flux at the IP and CIP. The safety reactivity factor and other parameters meet the design requirement. There is no safety parameter in terms of the neutronic aspect which is violated.

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