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The Feasibility Study to use UMo-AL Fuel at RSG-GAS core

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***Abstract*- THE FEASIBILITY STUDY to USE UMo-Al FUEL AT RSG-GAS CORE. At present, The RSG-GAS is using U3Si2-Al dispersion fuels with uranium density of 2.96 gU/cc and the . silicide uranium fuels will not be 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, such as, it can be used at higher density in the reactor core. There are high uranium densities in UMo-Al dispersion fuels up to 15 gU/cc with numerous contents of Mo. In this analysis, the UMo fuel is used with density of 3.55 gU/cc and the contents consists of UMo9wt%-Al, Mo8wt%-Al, Mo7wt%-A and Mo6wt%-Al, called U9Mo, U8Mo, U7Mo and U6Mo respectively. The neutronic parameters, such as, reactivity balances, k-eff and power peaking factors of UMo-Al fuel with higher density (3.55 g U/cc) for the existing typical working core calculation have been carried out. The UMo-Al core criticality data were calculated using 2 dimension diffusion code Batan-EQUIL. The UMo-Al fuel macroscopic crossection data as the output of cell calculation WIMSD-B5 (ENDFVII.8) had been used for the calculation. The core calculations were performed using 2 and 3 dimension diffusion codes. The good fuel for RSG-GAS can be U7Mo-Al with the density of 3.55 g U/cc. The maximum radial, axial power peaking factor of the fuel at 31 cm is 1.28 and 1.30 when all control rods down and up respectively. Those are also met with the safety criteria. Indeed, the fuel of U7Mo with 3.55 gU/cc could be applied for the RSG-GAS core and operated for 960 MWD cycle length without any part of core configuration changes.**

Keywords : UMo-AL Fuel, Reactivity Core , Neutronic Parameter, RSG-GAS Core

I.INTRODUCTION

Currently, there is an international effort underway to develop UMo-Al fuel as the next generation of LEU fuel for research reactors. The high uranium densities achievable with UMo fuel become make attractive not only for designers of advanced research reactors but also for reactor operators who need higher uranium loadings than currently qualified with silicide fuel. Also, given that no commercial organization currently offers reprocessing services for silicide fuel, reactor operators who do not have access to local spent fuel storage or disposal solutions find UMo fuel as an attractive option because it offers an opportunity to close the fuel cycle via commercial spent fuel reprocessing. UMo fuel is under research in the world and after 15 years there some results to follow. In term of stability, composition of UMo fuel 7 to 8 % wt Mo indicates that more stable than others. Fuel composition of 7 wt. Mo (U7%wt.Mo-Al) is the best for fabrication [1]. In Batan, it has also been studied the UMo fuel from neutronic and fabrication aspect point of view, such as, U9Mo-Al and U6Mo-Al but for composition of U9Mo-Al there is a change in phase cause of heat in temperature around 600oC [2]. The fuel U6Mo-Al is not good based on fabrication and irradiation. Batan has interested and already fabricated mini fuel with U7Mo-Al composition irradiated in RSG-GAS reactor to examine the fuel characteristic [3]. It is important to analyze the possibility of the U7Mo-Al fuel in RSG-GAS core.

In RSG-GAS reactors, higher density fuels will also decrease the number of fuel assemblies required to operate the reactors in the same power level or extend the operating cycle, and hence reducing the total of fuel cycle cost. Back end fuel cost could also be reduced since the number of spent fuel assemblies decreased. It is therefore very possible to use UMo-Al fuel in the RSG-GAS core.

Due to many advantages offered by UMo fuel, it has been studied core conversion program from silicide to molybdenum fuel [4], such as, determining the optimal molybdenum equilibrium core design as well as the strategy to achieve the equilibrium core. The program just commenced and several design studies have been carried out. Among other studies, the work is the most noteworthy and it was proposed refueling/reshuffling strategy now adopted for RSG GAS molybdenum core [5].

In that work, the design procedure and fuel management strategy were proposed for converting the silicide core of RSG GAS to the new equilibrium molybdenum core using higher uranium loading. A procedure to directly search the equilibrium core is implemented in an in-core fuel management code developed for RSG GAS. Compared to the present silicide fuel with 2.96 gU/cm3 meat density which can only provide 25 core cycle length under nominal power, the new molybdenum equilibrium core with 3.55 gU/cm3 meat density can give significant extension of the core cycle length, increasing to about 32.5 days, for U6Mo-Al, while saving one fuel element per cycle[6]. This achievement increases the reactor availability and utilization, as well as reduction of fuel cost. However, according to poor irradiation, a number of high-density uranium compounds from which the U-Mo alloys with a Mo content of 7-10 w% were chosen as the best candidates. [7]

The practical strategy to achieve the molybdenum equilibrium core which enable the operator to operate at the present nominal power is through several numbers of molybdenum cores which use both the present (probably partly burnt) silicide fuel elements and higher loading molybdenum fuel elements. In the beginning, the present silicide core of 2.96 gU/cm3 meat density will adopt refueling/reshuffling strategy which is called 5/1 scheme where 5 fresh fuel elements (FEs) and 1 control element (CE) to be loaded in the core at BOC.

This document presents the calculation results of core configuration parameters for the RSG-GAS by adopting the new 5/1 refueling strategy. The calculation was done using WIMSD-5B [8] and Batan-FUEL codes [9]. While the WIMSD-5B code was used for generating the cross section, the Batan-FUEL code was applied for core calculation.

A. Description of RSG GAS

RSG-GAS, a Multipurpose reactor, is a reactor with a light water cooled and moderator, open pool reactor with thermal power of 30 MW and constructed for the use of low enriched 19.75 %) uranium. The core has 10 x 10-grid plate with 100 identical bore holes suitable for fuel elements, control elements, beryllium reflector elements and irradiation inserts. A typical working core configuration with maximum power level of 30 MW consists of 40 fuel elements and 8 control elements, one large central irradiation position (CIP) comprising 2 x 2 grid positions and 4 small in-core irradiation positions (IP).

RSG-GAS started commissioning operation in July 1987 and to reach the typical working core, RSG-GAS was operated at several core configurations. The first core configuration consisted of 12 fresh fuel elements and 6 control elements with maximum power level of 10.7 MW thermal and step by step ran into transition cores, by adding the fuel elements until six core (full core). The reactor was finally achieved 30 MW power level in 1992 [10].

The standard fuel element contains 21 standard U_3O_8-Al alloy MTR type fuel plates, with 19.75 % low enriched uranium. One control rod element has a same size with fuel element and contains 15 fuel plates and an absorber assembly composed of two stainless-steel (SS321) clad AgInCd blades.

Beryllium is used as material for reflector and the reflector consists of two types, such as, beryllium reflector element with the dimension of 75 mm x 79 mm x 683 mm, and beryllium block reflector, positioned in L-shaped surrounded the two legs sized 1215 mm/ 865 mm and 1255mm/ 905 mm, 800 mm high, and 350 mm wide. The core is provided with 4 irradiation positions and the irradiation position is filled with dummy element if not used by experimental insert. The open grid plate positioned out side the active core will then be converted with plug element.

The core is also provided with other facilities, such as, four Hydraulic Rabbit System (HYRA), one Pneumatic Rabbit System (PNRA) and Power Ramp Test Facility (PRTF). The grid plate and block reflector are surrounded by a shroud to guide the coolant flow through the core components.

The reactor core contains demineralized light water as moderator. The heat removal is taken place by a light water cooling system of primary and secondary loops. Insides the pool, the water streams down-wards through the cooling channels between the fuel plates. For the reactor core at 30 MW, the mass flow minimum amounts to 800 kg/s. The respective velocity in the cooling channels results to 3.8 m/s. For the control and shutdown of the reactor operation, a fork type absorber is used by replacing the outer fuel plate of the standard fuel element. The core reflector configuration and the reactor main data are shown in Fig. 1 and Table 1, respectively. Presently, the reactor uses MTR-type LEU (19.75 w/o) oxide fuel elements (FEs). On the 10 x 10 core grid positions there are 40 standard FEs (each consists of 21 fuel plates as depicted in Fig. 2), 8 control elements (CEs, each consists of 15 fuel plates as depicted in Fig. 3) initially loaded with 250 and 178.6 g 235U respectively, and Be reflector elements and other irradiation facilities. This fuel loading corresponds to uranium meat density of 2.96 gU/cm3. With the original nominal core cycle of 25 days, 7 burn-up classes with an average burn-up step of approximately 8 % loss of 235U the core produces energy of 750 MWD per cycle [11].

The typical working core (TWC) stated in the RSG-GAS Safety Analysis Report (SAR) was considered by the vendor to be the equilibrium core in contrast to the transition cores during the commissioning phase. As stated in the SAR, for each TWC nominal cycle, 6 fresh fuel elements (FE) and 1 control element (CE) must be loaded into the core at BOC. However, after this 6/1 fueling scheme repeats for six times then the seventh core cycle the fueling scheme switches to 4/2, i.e. 4 new FEs and 2 CEs must be loaded into the core. But since 1998, equilibrium core at nominal power, 5 fresh fuel elements and 1 control element has been loaded into the core.

II.CALCULATION PROCEDURE

The fuel unit cell in this reactor consist of three different regions: fuel, cladding and water. The WIMSD-5B code with ENDF-BVII microscopic cross section is first used to calculate the group constants for homogenized fuel unit cell. The fuel element for this reactor core has 21 fuel plates and two aluminum side plates which hold the fuel plates as one unit fuel element. The fuel element has an extra amount of water with 0.5 mm thick surrounding it. The fuel element is divided into 21 similar slabs (called multi slab model) homogenized plate type fuel cells. The model can be looked at Fig. 4. The dimension and density numbers of each region of the multi slabs cell are introduced in the WIMSD-5B code to calculate the group constants using four neutron energy groups. The upper energy group limits are chosen a follows; (10 MeV,< E < 8.21 MeV), (8.21 MeV < E < 5.531 keV), (5.531 Kev,< E < 0.625 eV) and < 0.625 eV[13]. The control fuel element is modeled as a slab type unit cell. The control rod group constants are generated using the WIMSD-5B code as well. The group constants for other reactor components, such as beryllium and water, are calculated using the slab type option in the WIMSD-5B code. Table 1 shows the nuclear parameters that are used in the RSG-GAS core.

The neutronic design procedure is shown in the schematic diagram of Fig. 5. First, the cross section library for fissile and non-fissile materials is prepared with the WIMSD-5B cell calculation code. The library is prepared to accommodate wide ranges of design parameters, such as, fuel burn-up level, fuel meat density, fuel operational temperature, and existence of important neutron poisons (xenon and samarium). The general reactor data, refueling and fuel reshuffling strategy, and the core cycle length are fed into a dedicated in-core fuel management code module, Batan-EQUIL-2D.

The main function of Batan-EQUIL-2D code is to directly search for the equilibrium core without simulating the transition cores. Since the code uses 2-D diffusion theory, an accurate axial buckling must be provided through rigorous 3-D diffusion calculations by the Batan-3DIFF module. The equilibrium core with the prescribed core cycle length is obtained, and a check is then done to determine whether the excess reactivity at the end of cycle (EOC) under the hot and xenon equilibrium condition is sufficient. If the initially specified core cycle length is not appropriate, it must be adjusted to provide a sufficient EOC excess reactivity.

Calculations in 2-D diffusion theory with the Batan-2DIFF module are then conducted to check the one-stuck-rod sub-criticality condition. If this safety requirement is not satisfied, some modification of the FEs' arrangement across the core or even the refueling and reshuffling strategy must be made. Similar adjustments may also be needed to obtain a flat power distribution across the core.

During design the RSG-GAS core using new fuel, the following constrains will be applied [9]:

- Minimum shutdown margin available – 0.5 %Δk/k at BOC, cold and xenon and samarium free.
- Maximum radial peaking power factor (PPF) 1.4.
- Maximum discharge fuel burn up at EOC specified up to to 70 %.

The constrains are also applied to optimize core configuration and the operation length of the equilibrium core for new UMo-Al fuel at RSG-GAS core. If one of the calculated parameter violates the design constrains, the core configuration and in-core fuel management will be changed until fulfill the constrains[14].

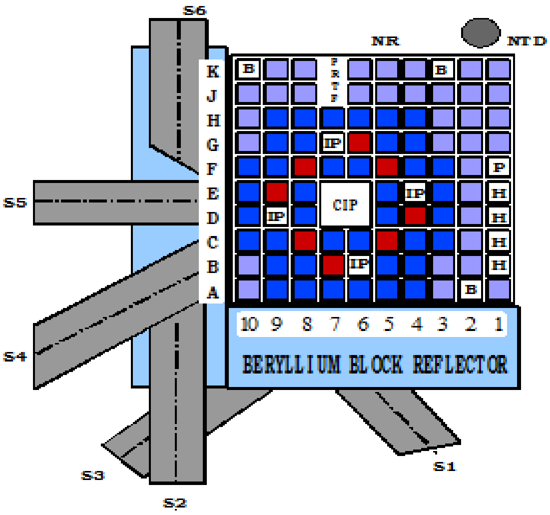


Fig 1. RSG-GAS core and reflector

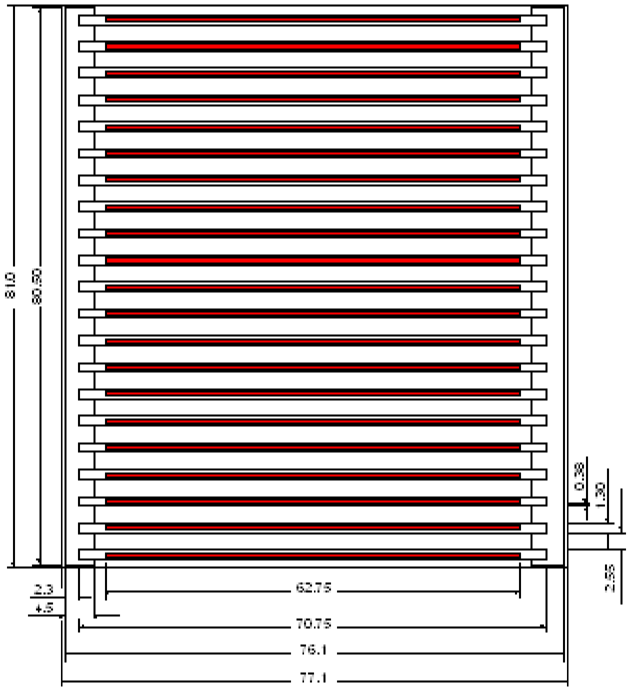


Fig 2. Standard Fuel element of RSG-GAS

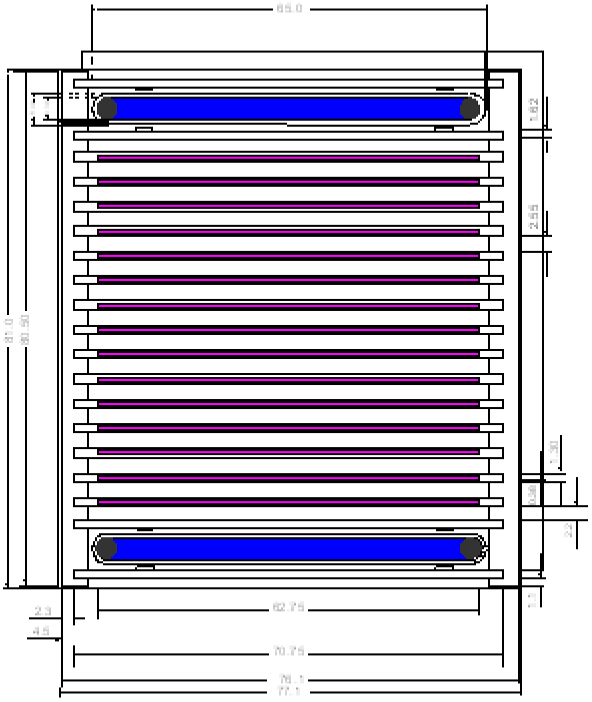


Fig 3. Standard control element of RSG-GAS

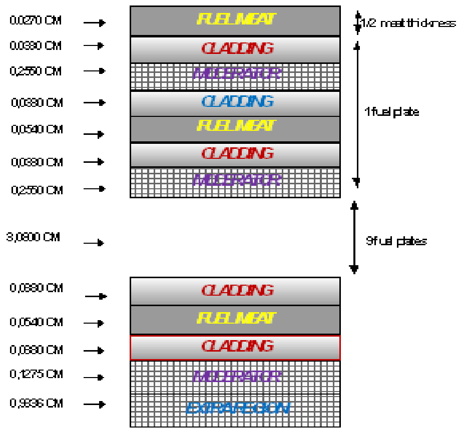


Fig 4. Fuel slab model for input WIMSD-5B code

TABLE 1. REACTOR MAIN DESIGN DATA OF RSG GAS [9]

Nuclear Design Parameters	Values
Number of Fuel Elements	40
Number of Control Elements	8
Number of Absorbers	8
Cycle length, full power days (fpd)	25
Average Burn-up at BOC, % Loss of U-235	23.3
Average Burn-up at EOC, % Loss of U-235	31.3
Average Discharge Burn-up at EOC, % Loss of U-235	53.7
Core Reactivity	
Excess Reactivity at BOC, cold, without Xenon, %	9.2
Reactivity Reserve for Movable Experiments, %	2.0
Reactivity Worth of Control Rod System (8 Control Rods), %	-14.5
Shut-down Reactivity at BOC, Cold, without Xenon, (8 Control Rods Inserted), %	- 5.3
Shut-down Reactivity at BOC, Cold, without Xenon, Stuck Rod (7 Control Rods Inserted), %	- 2.2
Maximum Controlled Reactivity Insertion Rate (including 15 % Safety Addition), Δρ/s	2.8×10^4
Kinetic Parameter	
Kinetic Characteristics (BOC)	
Fuel Temperature Coefficient, Δρ/k	-1.6×10^{-5}
Moderator Temperature Coefficient, Δρ/k	-1.1×10^{-4}
Moderator Void Coefficient, Δρ/%	-1.2×10^{-3}
Delayed Neutron Fraction	0.0071
Lifetime for Prompt Fission Neutrons, μs	61.3

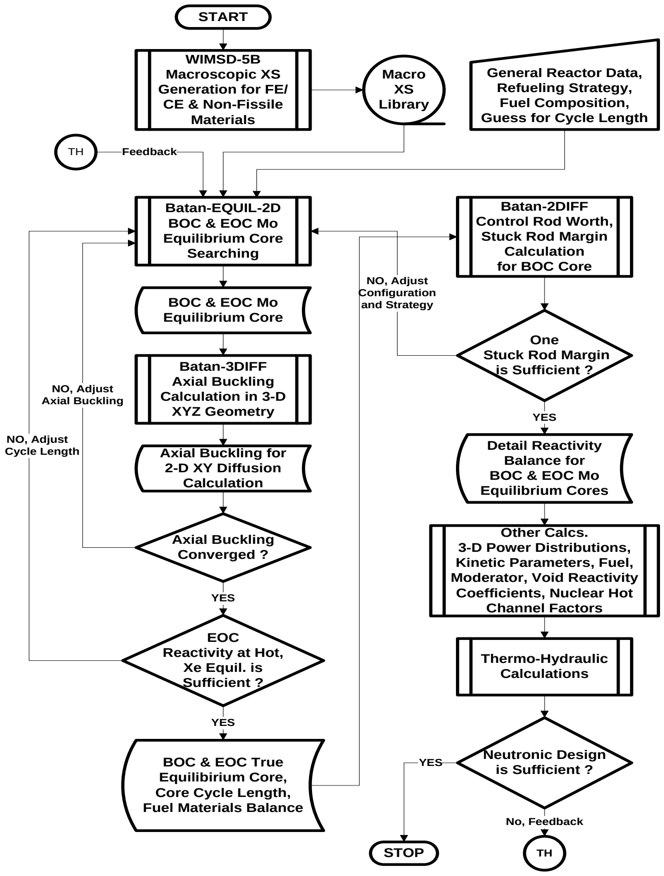


Fig 5. Design procedure for the molybdenum equilibrium core of RSG GAS [9]

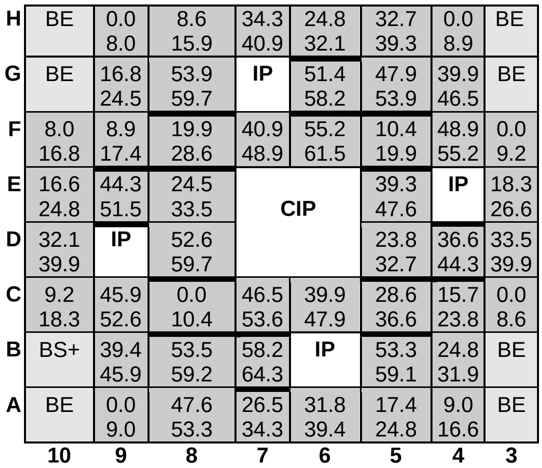
III.RESULTS AND DISCUSSION

The methodology and the computer codes used to perform the neutronic calculations for UMo-Al fuels in RSG-GAS core have already been validated in our previous works. The group constants and infinite multiplication factor were calculated for different content of Mo in uranium loading with using standard code WIMSD-5B. It was assumed that the core A fuel loading is 300 gram of uranium, and content of Mo 6 %; Core B, content of Mo 7 %; Core C, content of Mo 8 % and core D, content of Mo 9 %. The mass of uranium loading per standard fuel element 300 gram in 21 fuel plates, the water channel width is 0.255 cm and the values of group constants were calculated. Buckling is different when the content of Mo in uranium is different in the fuel. But k-inf is the same when the loading of uranium the same and also the same in the same step burn up. That also increases with increase mass of uranium in the fuel and decreases when step burn up increase. The values of k-inf were calculated as function of burn up step using WIMSD-5B for each core with the same configuration of core base on 960 fuel plate in the core. Table 2 presents the result of the macroscopic X-sections from WIMSD-5B for UMo-Al fuels for L Be-reflector materials besides the core. It contains three most important group constants required as input parameters in the Batan-2DIFF code, such as, the diffusion coefficient (D) of the region, the absorption cross section (∑a) and the nu-fission cross section but nu-fission cross section is zero for reflector.

TABLE 2. MACROSCOPIC X-SECTIONS FROM WIMSD-5B FOR UMO-AL FUELS

U6Mo-Al	Neutron Energy			
	Group 1	Group 2	Group 3	Group 4
D_1	2.398276E+00	1.291296E+00	8.254741E-01	2.932551E-01
D_2	2.398276E+00	1.291296E+00	8.254741E-01	2.932551E-01
Σ_a	9.779684E-04	7.290409E-04	1.544896E-02	9.788596E-02
Σ_{tr}	7.402122E-02	8.881499E-02	8.083568E-02	4.654601E-04
δ-fission	1.613431E-03	8.256208E-04	1.269903E-02	1.734729E-01
U7Mo-Al	Neutron Energy			
	Group 1	Group 2	Group 3	Group 4
D_1	2.400139E+00	1.292254E+00	8.257828E-01	2.932767E-01
D_2	2.400139E+00	1.292254E+00	8.257828E-01	2.932767E-01
Σ_a	9.776070E-04	7.278497E-04	1.542630E-02	9.787044E-02
Σ_{tr}	7.399188E-02	8.881373E-02	8.084373E-02	4.651248E-04
δ-fission	1.613537E-03	8.256116E-04	1.269990E-02	1.734821E-01
U8Mo-Al	Neutron Energy			
	Group 1	Group 2	Group 3	Group 4
D_1	2.399624E+00	1.291733E+00	8.252574E-01	2.932588E-01
D_2	2.399624E+00	1.291733E+00	8.252574E-01	2.932588E-01
Σ_a	9.780965E-04	7.311667E-04	1.549757E-02	9.790222E-02
Σ_{tr}	7.401275E-02	8.881265E-02	8.081756E-02	4.655868E-04
δ-fission	1.613511E-03	8.256145E-04	1.269708E-02	1.734628E-01
U9Mo-Al	Neutron Energy			
	Group 1	Group 2	Group 3	Group 4
D_1	2.394467E+00	1.288482E+00	8.233822E-01	2.939632E-01
D_2	2.394467E+00	1.288482E+00	8.233822E-01	2.939632E-01
Σ_a	9.799910E-04	7.415281E-04	1.571464E-02	1.014813E-01
Σ_{tr}	7.412297E-02	8.881155E-02	8.073897E-02	4.834309E-04
δ-fission	1.613137E-03	8.256185E-04	1.268847E-02	1.716058E-01

To calculate the core parameter, firstly, the refueling and reshuffling strategy adopted in the design is discussed. The 40 FEs and 8 CEs are grouped into 8 burn-up classes (batches or zoning). Consequently, at the Beginning of Cycle (BOC) 5 FEs and 1 CE are loaded after discharging the same number of old FEs and CE with highest burn-up level from the core. As already stated above, the refuelling scheme proposed can be categorized as scatter loading. The detail information on the FE and CE movement during reshuffling is indicated in Fig 5. The zoning was indicated by the burn-up class number in the second rows and yielded a flat power peaking factor (PPF) distribution. The number of burn-up classes is 8 for all the molybdenum core resulted in excess reactivity at BOC in the Table 3. Increased Mo content in the fuel can be lower in the fuel cycle eventhough it is not too much and an increase of fuel discharge burn-up on the other hand.



	10	9	8	7	6	5	4	3
H	BE	0.0 8.0	8.6 15.9	34.3 40.9	24.8 32.1	32.7 39.3	0.0 8.9	BE
G	BE	16.8 24.5	53.9 59.7	IP	51.4 58.2	47.9 53.9	39.9 46.5	BE
F	8.0 16.8	8.9 17.4	19.9 28.6	40.9 48.9	55.2 61.5	10.4 19.9	48.9 55.2	0.0 9.2
E	16.6 24.8	44.3 51.5	24.5 33.5	CIP		39.3 47.6	IP	18.3 26.6
D	32.1 39.9	IP	52.6 59.7			23.8 32.7	36.6 44.3	33.5 39.9
C	9.2 18.3	45.9 52.6	0.0 10.4	46.5 53.6	39.9 47.9	28.6 36.6	15.7 23.8	0.0 8.6
B	BS+	39.4 45.9	53.5 59.2	58.2 64.3	IP	53.3 59.1	24.8 31.9	BE
A	BE	0.0 9.0	47.6 53.3	26.5 34.3	31.8 39.4	17.4 24.8	9.0 16.6	BE

Fig 6. U7Mo-Al Core configuration of RSG GAS with BOC burn-up class in the first row and EOC in the second rows (FE: fuel element, CE: control element, BE: Be reflector element, BS+: Be reflector element with plug, IP: irradiation position, CIP: central irradiation position, PNRS: pneumatic rabbit system, HYRS: hydraulic rabbit system).

Secondly, the results of the parametric survey on the cycle length are discussed. Fig. 6 shows some important parameters of the equilibrium core as function of the core cycle length (or energy generation per cycle), i.e. the BOC excess reactivity (at cold and xenon free condition), the EOC excess reactivity (at hot and xenon equilibrium condition), and the maximum discharge burn-up of FE or CE. The EOC excess reactivity is limited by the subcriticality constraint but it is a common practice to provide a sufficient excess reactivity allowance at EOC for effective reactor power manuevering, compensating irradiation targets, and partial xenon overide. On the other hand, the BOC excess reactivity is limited by the one stuck rod subcriticality condition, while the maximum discharge burn-up has been set to be around 70 %.

To select the optimal core cycle length, some trade-off must be made. 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 molybdenum fuel 3.55 gU/cm3 meat density, the feasible range of core cycle lengths are roughly from 30.0 to 32.5 days. Comparing these values to the present core cycle length of 25 days, the adoption of 5/1 fueling scheme significantly shorten extension the cycle length. In the SAR RSG-GAS, it is shown that the cycle length of 25.0 days results in 9.2 % BOC excess reactivity (at cold and xenon free condition).

The equilibrium core the fuel burn-up distributions at BOC and EOC is shown in Fig. 5. It can be observed from the figure that the FE/CE burn-up values at EOC obtained with Batan-EQUIL-2D code coincided within the convergence criteria to the FE/CE burn-up values at BOC of the next core cycle. The result proved that the proposed searching procedure and the code worked satisfactorily.

Table 3 summarizes the fuel burn-up characteristics of the molybdenum equilibrium core. The fuel burn-up characteristics of the previous silicide core are same when the density of fuel the same namely 3.55 gU/cc.. But it is not yet been inserted to the RSG-GAS core. However, RSG-GAS core until now uses silicide fuel with 2.96 gU/cc of density. The result of silicide equilibrium core with 3.55 gU/cc of density is already published. They claimed that the average burn-up step per cycle is also around 8 %.

The average burn-up step for each cycle of the molybdenum fuel core was found to be 8 % and the same as that in the design core. Hence, with an increased number of burn-up class (8 classes), the EOC discharge burn-up of the oldest fuel element roughly will approximate 70 %. From the table, it can be concluded that the maximum FE and CE discharge burn-up were found to be 61.5 % and 64.3 %, respectively

The radial PPF distribution at BOC is shown in Fig. 7. The scatter loading strategy and higher number of burn-up classes were effective in minimizing the radial PPF so that there was no need for modification of the primary cooling system. From the figure or from Table 3, it can be seen that the maximum radial FE channel factor was found to be 1.24 which is lower than that of the previous silicide core and is still much lower than the permissible value derived from safety analysis report SAR(1.4).

TABLE 3. COMPARISON OF THE FUEL BURN-UP CHARACTERISTICS BETWEEN UMo-AL FUELS.

Parameter	Beginning of cycle			
	UMo9-Al[15]	UMo8-Al	UMo7-Al	UMo6-Al[15]
Uranium density (gram/cc)	3.55	3.55	3.55	3.55
Power (WM), Length of Cycle (days)	30/30.0	30/31.0	30/32	30/32.5
Average Burn-up at BOC, % Loss of U-235	30.2	31.6	29.46	32.1
Average Burn-up at EOC, % Loss of U-235	38.1	39.3	37.31	39.9
Max. FE burn-up (% loss of ^{235}U)	58.9	60.9	61.5	61.9
Max. CE burn-up (% loss of ^{235}U)	62.5	63.1	64.3	65.0
Max. radial fuel element channel factor	1.24	1.25	1.26	1.27
Reactivity balances				
$\Delta\rho$ hot to cold	0.4	0.4	0.5	0.5
$\Delta\rho$ equilibrium xenon poisoning	4.2	4.2	3.8	3.7
$\Delta\rho$ burn up	3.3	3.4	3.3	3.4
$\Delta\rho$ for exp., partial Xe overide, etc.	1.81	1.62	1.44	1.07
Core excess reactivity	9.7	9.5	9.4	9.24
Total shutdown reactivity	-14.9	14.5	14.2	13.6
One stuck rod shutdown reactivity margin	-1.9	-1.8	-1.7	-1.07

TABLE 4. COMPARISON OF THE FUEL BURN-UP CHARACTERISTICS BETWEEN OXIDE, SILISICE AND U7MO-AL FUELS.

Parameter	Beginning of cycle			
	U_3O_8-Al [16]	U_3Si_2Al [17]	U_3Si_2Al [17]	U7Mo-Al
Uranium density (gram/cc)	2.96	2.96	3.55	3.55
Power (WM), Length of Cycle (days)	30/25.0	30/25.0	30/32.5	30/32
Average Burn-up at BOC, % Loss of U-235	24.8	23.8	32.2	29.46
Average Burn-up at EOC, % Loss of U-235	33.2	31.7	40.5	37.31
Max. FE burn-up (% loss of ^{235}U)	52.3	52.3	68.2	61.5
Max. CE burn-up (% loss of ^{235}U)	56.0	55.4	71.1	64.3
Max. radial fuel element channel factor	1.27	1.24	1.27	1.26
Reactivity balances				
$\Delta\rho$ hot to cold	0.3	0.4	0.6	0.5
$\Delta\rho$ equilibrium xenon poisoning	3.5	4.2	3.7	3.8
$\Delta\rho$ burn up	3.0	3.4	3.8	3.3
$\Delta\rho$ for exp., partial Xe override, etc.	2.0	1.62	1.07	1.44
Core excess reactivity	9.2	9.5	9.24	9.4
Total shutdown reactivity	-14.5	13.6	13.05	14.2
One stuck rod shutdown reactivity margin	-2.2	-1.1	-1.5	-1.7

Table 4 shows the comparison of the reactivity between the previous oxide typical working core and the present silicide equilibrium core and also silicide and molybdenum cores with the same densities (3.55 gU/cc). Increasing the burn-up class to 8 for the present molybdenum core can reduce the BOC excess reactivity to a value comparable with the existing core. On top of that, it can be observed that the present silicide equilibrium core is suffered from smaller excess reactivity at EOC. The one stuck rod sub-criticality analysis is tabulated in Table 5. The control rod in the C-5 core grid position was found to induce the smallest sub-criticality margin and taken for the one stuck rod sub-criticality analysis. All sub-criticalities for stuck rod criteria are fulfilled for U7Mo-Al, and in the safety analysis report, that amounts to -0.5 %.

TABLE 5. CORE REACTIVITY AS FUNCTION OF CONTROL ROD POSITIONS FOR U7Mo-AL FUEL

Control rod position	Core reactivity (%)
All control rods fully up	9.42
All control rods fully down	-3.75
CR G-6 fully up, others fully down	-1.54
CR F-8 fully up, others fully down	-1.67
CR F-5 fully up, others fully down	-1.65
CR E-9 fully up, others fully down	-1.88
CR D-4 fully up, others fully down	-1.42
CR C-8 fully up, others fully down	-1.84
CR C-5 fully up, others fully down	-1.27
CR B-7 fully up, others fully down	-1.62

H	BE	1.24 1.27	1.08 1.14	0.89 0.91	0.94 0.95	0.82 0.83	1.12 1.12	BE
G	BE	1.17 1.22	0.78 0.78	IP	0.83 0.85	0.73 0.84	0.82 0.87	BE
F	1.23 1.24	1.20 1.23	1.21 1.26	1.02 1.00	0.76 0.73	1.22 1.26	0.79 0.78	1.19 1.21
E	1.19 1.19	0.98 0.96	1.19 1.19	CIP		1.04 1.02	IP	1.09 1.26
D	1.05 0.99	IP	0.88 0.82			1.17 1.19	1.05 1.07	0.89 0.93
C	1.17 1.12	0.82 0.78	1.28 1.28	0.86 0.85	0.99 0.97	1.08 1.11	1.13 1.20	1.25 1.30
B	BS+	0.81 0.77	0.66 0.63	0.72 0.67	IP	0.77 0.76	1.02 1.06	BE
A	BE	1.09 1.02	0.67 0.63	0.95 0.92	0.96 0.93	1.01 1.03	1.10 1.11	BE
	10	9	8	7	6	5	4	3

Fig 7. Radial power peaking factor distributions of the RSG GAS using UM7o-Al fuel having adopted 5/1 refueling/reshuffling strategy and core cycle length of 32 days (first and second rows represent all control rods up and down conditions, respectively. BE: Be reflector element, BS+: Be reflector element with plug, IP: irradiation position, CIP: central irradiation position)

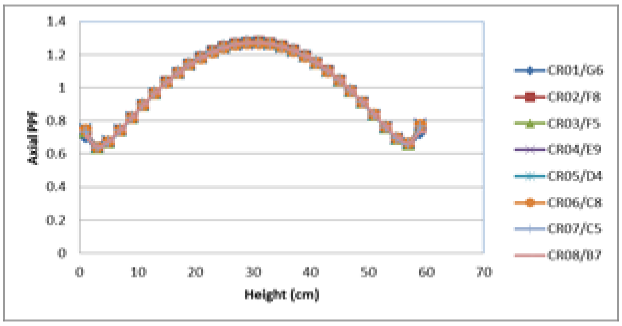


Fig 8. Axial PPF for all control rods down

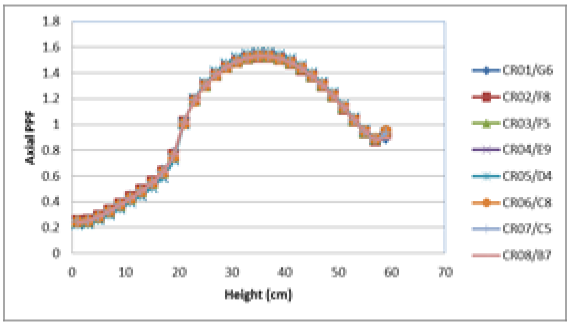


Fig 9. Axial PPF for all control rods at 20 cm

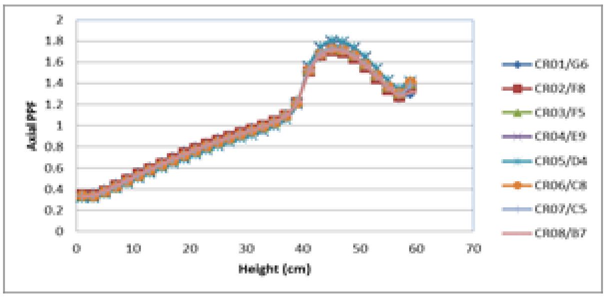


Fig 10. Axial PPF for all control rods at 40 cm

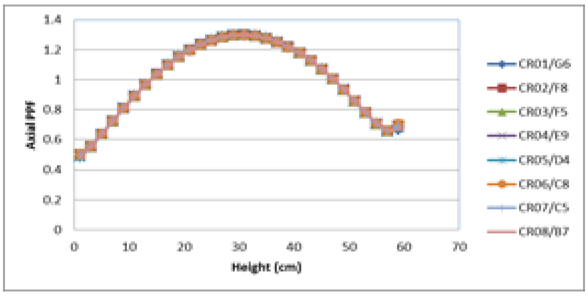


Fig 11. Axial PPF for all control rods up

Figure 7 shows the distribution of power factor due to changes in the U7Mo-Al fuel using in the RSG-GAS equilibrium core with density 3.55 gU / cc. It is shown, at the first row, the radial power peaking factor (PPF) is as control rods down. While the second row shows the distribution of radial power peaking factor values as control rods up. The maximum radial power peaking factors at control rod down and up are respectively 1.28 and 1.30, far below the acceptance criteria 1.40.

Rise and fall of the values of the power peaking factor does not take place specifically in a particular position, but occur randomly in the entire fuel. It is caused by the homogeneity of the material fuel and control element in the core. The values still fulfil the PPF below the maximum value listed in SAR.

Figure 8 shows the axial power peaking factor as control rod down. The maximum value of it is 1.28 at 31 cm of height from the bottom. Figure 9, 10 and 11 show the distribution of axial power factor due to changes in the insertion of control rods in the RSG-GAS core with U7Mo-Al fuel. Figure 9, 10 and 11 also show the profile axial power peaking factor when the control rod inserted 20 cm, 40 cm, 60 cm of height. The peak value changes or moves higher due to the depth of insertion of the control rods in the core. Changes resulted from the increase in the value of the PPF reduction in fission reactions in areas where there is insertion of control rods absorbent material, so that the fission reaction shifted towards the edge of the core. Additionally, the insertion of control rods into the core also leads to changes in the distribution of power peaking factor. Fuel close to the absorbent material decreases power peaking factor while the power factor of the fuel away from the control rod position has increased the power factor. This is because the number of thermal neutrons that react with fuels to generate more heat automatically will also be absorbed by the control rods.

IV.CONCLUSION

The core configuration parameters for the RSG-GAS multipurpose reactor having adopted 5/1 fueling scheme have been calculated for the possibility of using UMo fuel. The adoption of the scheme shortens the core cycle length significantly. The analyses showed that the adoption of existing refueling/reshuffling strategy can be done successfully and the obtained equilibrium molybdenum core met the safety requirements. For RSG-GAS core, the U7Mo-Al fuel can be used with density of 3.55 gU/cc and there are no violation safety criteria. The core can obtain 32 days of cycle length, more than 7 days compared to the design core. The equilibrium core with no other change configuration of the core can also be reached. It is, however, needed to further analyze thermal-hydraulic characteristic of the core to make sure the safety margin of the core achieved.

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REFERENCES

[1] Fabio Branco Vas de Oliveiraand Delvonee Alves de Andrade, Stability of γ-UMo nuclear fuel alloys by thermal analysis, Current research in nuclear reactor technology in Brazil and worldwide, book chapter 5 edited by Amir Zacarias Mesnuita. ISBN 978-953-51-0967-9 (2013)

[2] Aslina Ginting, Suparjo, Agoeng Kadarjono and Dian Anggraini., The effect of Mo content with changes in phase and heat capacity of UMo alloys., Urania Journal,Vol. 17 No.2 Juni 2011 (76-86)

[3] Tukiran S. and Tagor MS, Nuetronic analisys of U7Mo-Al mini fuel in RSG-GAS reactor, Journal TDM Volume 18, Nomor 1, Februari 2016

[4] S. Van Den Berghe and L. Lemoine, Review of 15 years of high density low enriched UMo dispersion fuel development for research reactors in Europe, Nuclear Engineering and Technology, Vol 46 no. 2, April (2014) 125-146.

[5] Seo, C.G., Cho, N.Z. A core design concept for multi-purpose research reactor. Nucl. Eng. Des. (2012); 252: 34-41

[6] Tukiran S, Surian Pinem, Tagor MS, Lily S, Jati Susilo, Conceptual design of innovative research reactor core using U-Mo fuel from neutronic point of view, Journal Technology of Nuclear Reactor, TDM. October. (2012) ;Vol 14; No 3: 178 – 191.

[7] Lily Suparlina, Tukiran Surbakti, "Analisys of fuel management of the innovative research reactor core MTR type. Journal Technology of nuclear Reactor, TDM October (2014) Vol 16; No.2; 89-99

[8] IAEA. WIMS-D Library Update. IAEA, Vienna, (2007).

[9] Liem, P.H., Batan-FUEL: A general in-core fuel management code. Atom Indonesia (1996), 22, No. 2

[10] Raina, V.K., Sasidhaöran, K., Sengupta, S., Singh, T. Multi purpose research reactor. Nucl. Eng. Des. (2006) ;236: 770–783

[11] Teruel, F.E, Rizwan-uddin. An innovative research reactor design. Nucl. Eng. Des. (2009); 239: 395-407

[12] B. Dionne, AP Olson, JG Stevens, S. Kalcheva, G Van den Branden, E. Koomen" Steady state safety basis and performance evaluation of the BR2 core using UMo dispersion fuel" RERTR 2012-34th International meeting on reduced Enrichment for research and test reactor, Warsaw Poland. Oct 14-17, (2012), 1-9.

[13] HJ. Ryu, JM. Park, YJ. Jeong, KH. Lee, YS. Lee, CK. Kim and YS. Kim, Post irradiation analyses of U-Mo dispersion fuel rods of komo tests at Hanaro, Nuclear Engineering and Technology, Vol. 45. No. 7, Dec 2013 (847-858)

[14] Douglas E. Burkes, Andrew M. Casella, Amanda J. Casella, Edgar C. Buck, Karl N. Pool, Paul J.Mac Farland, Matthew K. Edward, Frances N. Smith, Journal of Nuclear Material, Elsevier vol. 464 April 2015 (331-341)

[15] Tagor MS., Iman K., Core Conversion study for silicide to Molibdenum fuel in the indonesian 30 MW Multipurpose reactor-RAS (RSG-GAS), Transactions of 9th international topical meeting of RRFM, Budapest, Hungary, April 10-13, 2005.

[16] Batan, SafetyAnalysis Report 1987

[17] Tukiran S., Surian P.,Tagor MS., Analysis of Silicide fuel densities impact on kinetic parameter for RSG-GAS reactor. Journal of JPFA (2013) 3 No.1.