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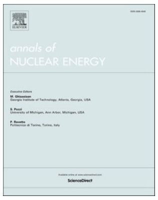

Review on the fuel management strategy of the RSG-GAS equilibrium core☆

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ABSTRACT

The RSG-GAS reactor has reached a typical working core (TWC) after the 6th core configuration, consisting of 40 standard fuel elements (FE) and 8 control fuel elements (CE) and it can be operated at a nominal power of 30 MWth. At TWC, the number of fuel elements discharged or added was not fixed when forming the core configuration for the next cycle. In addition, to increase the operation duration of the reactor core, the RSG-GAS fuel that initially uses oxide fuel (U_3O_8-Al) can be converted to silicide fuel (U_3Si_2-Al) with a higher fuel density. The reactor core was converted to silicide fuel with the same density in the initial stage through a mixed oxide and silicide core. At the same time as the core conversion, a new fuel management strategy was also implemented to achieve an equilibrium core. Hence the process of forming the core configuration in each fuel cycle could be simplified for the RSG-GAS personnel. This new fuel management strategy was developed using an in-house 2D neutron diffusion program that also solves fuel depletion, Batan-FUEL. The calculated mixed oxide-silicide conversion core was implemented safely so that the RSG-GAS core with silicide fuel can be fully operated until today. During the conversion process, there was no significant change in core neutronic parameters, especially when compared to the oxide core. This also shows that the reactor utilization was not affected during the core conversion. After the silicide-fueled RSG-GAS core reached equilibrium, validation of the new fuel management strategy was carried out by measuring the burnup fraction and control rod worth. The measured burnup fraction was then compared with the calculated burnup fraction from the BATAN-FUEL which showed consistency in the burnup fraction and did not exceed the safety limit. The measured control rod reactivity was also used to validate the core model developed using the Monte Carlo Serpent2 program. The Serpent2 model for RSG-GAS showed that the calculated control rod reactivity was not significantly different from the measurement. The measured burnup distribution and the control rod worth confirmed that the silicide equilibrium core formed as planned with the new fuel management strategy.

1. Introduction

Multipurpose Reactor – G.A. Siwabessy (RSG-GAS) achieved its first criticality on 1987 July 29, using 12 fuel elements (FE) and 6 control elements (CE) with low enriched uranium (LEU) oxide fuel (U_3O_8-Al). RSG-GAS is located in the Science and Technology Area (KST) B.J. Habibie, Puspiptek Complex, South Tangerang, Indonesia. RSG-GAS is an open pool reactor that uses light water as a coolant-moderator, and beryllium reflector. The MTR (Material Testing Reactor) type plate fuel was used, which later changed to silicide fuel (U_3Si_2-Al) with the same uranium density, 2.96 gU/cc. The RSG-GAS reactor can operate up to 30 MWt with a thermal neutron flux within the order of 10^{14}n/cm2s in the in-core irradiation position and 10^{13}n/cm2s at the reflector region (Pinem and Sembiring, 2019). Currently, the RSG-GAS core consists of 40 FEs, each containing 21 fuel plates, and 8 CEs using only 15 fuel plates. The control element uses fewer fuel plates to facilitate the control

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blade movement AgInCd (18 % Ag, 15 % In, 5 % Cd) neutron absorber material with dimensions of 65 × 3.38 × 625 mm. The main data of the RSG-GAS reactor can be seen in Table 1 while the FE and CE dimensions are shown in Fig. 1.

The RSG-GAS has several neutron irradiation facilities, such as the central irradiation position (CIP) which occupies a 2 × 2 grid in the middle of the core, 4 irradiation positions (IP) which occupies one grid, a rabbit system facility, a capsule irradiation facility and 6 beam tubes (Erawati Fadli et al., 2019; Kuntoro, 2020; Luhur et al., 2013; Pinem et al., 2018). These facilities have been developed for material testing related to advanced material technology, material irradiation for industrial use, research institutions, and universities. Most of the irradiation activities are used for research, education, and training while other irradiation is intended for radioisotope production either for health and industry, as well as neutron activation analysis. In addition, as one of the research reactors in Indonesia with a fairly large power and has been in operation for more than 30 years, RSG-GAS is also an object for research related to aging management and safety evaluation.

Calculations related to the RSG-GAS fuel management were initially carried out using the IAFUEL program provided by the German reactor vendor, INTERATOM (Wickert, 1986). Since RSG-GAS's first core previously used 12 FE and 6 CE, to achieve a typical working core (TWC), 5 transition cores are used so that in the sixth core, the number of fuel is already 48, 40 FE, and 8 CE (Jujuratisbela et al., 1995). The fuel loading pattern of 6/1 or 6/2 was used as a fuel management strategy during the TWC (Susilo et al., 2018). This fuel loading pattern requires 6 FE and 1 CE to be discarded and added to the core, or 6 fresh FE and 2 CE to be added to the core in the 6/2 fuel loading pattern. During the use of 6/1 and 6/2 fuel loading patterns, the operators are required to plan (calculate) the new core configuration (including the shuffling method), and reactivity calculations every time a new core to be formed for the next cycle. The RSG-GAS core configuration with 48 fuels can be seen in Fig. 2.

With this fuel management strategy, the fuel in the RSG-GAS core can be grouped into 8 burnup classes with each burnup fraction increasing 7 % on average. A slight drawback of the 6/1 and 6/2 fuel loading patterns is that some fuel that has not reached 56 % burnup fraction must be discharged from the core. In addition, neutronic parameters such as core reactivity, shut-down margin, and control rod worth can also vary in each core configuration and this brings some challenges to the RSG-GAS operation.

To increase the reactor cycle length, a study was conducted to convert oxide fuel which can only reach a maximum heavy metal density of 3.2 gU/cc to silicide fuel, which can reach a higher density, such as 4.8 gU/cc (Surbakti et al., 2022; Gan et al., 2011; Yang et al., 2021). However, for the use of silicide fuel in the RSG-GAS core, previous research emphasizes the maximum density of 3.55 gU/cc can be applied to RSG-GAS without the modification in core configuration and safety criteria. With a density of 3.55 gU/cc, the cycle length can be increased from 25 days to 32 days at an average power of 30 MWth. From these studies, to achieve the RSG-GAS core using 3.55 gU/cc silicide fuel, two fuel conversion methods can be carried out, namely direct conversion from oxide fuel with a density of 2.96 gU/cc to 3.55 gU/cc silicide (Arbie et al., 2004) or the second method through indirect conversion. This indirect conversion provides a more promising safety aspect because the fuel conversion was carried out gradually through the conversion of oxide to silicide at the same density of 2.96 gU/cc (Liem et al., 1998). After the equilibrium silicide core of 2.96 gU/cc was achieved, then further conversion from 2.96 gU/cc to 3.55 gU/cc silicide fuel can be carried out. Based on the evaluation of both conversion methods, the indirect conversion method through conversion from oxide to silicide was chosen (Liem and Sembiring, 2010).

Table 1
RSG-GAS design parameters (RSG-Batan, 2011).

Type of fuel	U_3Si_2-Al
U-235 Enrichment, %	19.75
Uranium density in meat, g/cm^3	2.96
Cladding material	AlMg2
Type of absorber	Fork type
Material absorber	Ag-In-Cd
Absorber thickness, mm	3.38
Absorber cladding material	Steels
Active Length, cm	60
Number of standard fuel elements	40
Fuel plates per standard fuel element	21
Number of control fuel elements	8
Fuel plates per control fuel element	15
Core thermal power, MW	30
Effective flow rate for fuel cooling plates, kg/s	618
Surface area of fuel plates, m^2	72.29
Nominal inlet temperature, ℃	40.50
Average temperature increases in reactor core, ℃	10.07
Average outlet temperature in reactor core, ℃	50.57
Outlet maximum temperature of hot channel, ℃	75.30

Silicide fuel with a density of 2.96 gU/cc did not directly substitute all 48 oxide fuels in the RSG-GAS core, because this silicide fuel is still fresh and a transition core was needed for the conversion process. Basically, the conversion process can be carried out through a transition core, i.e. as the first oxide fuel core being used at the beginning of the RSG-GAS operation, or other options such as through a mixed oxide and silicide core. After going through several studies and considerations, it was determined that the conversion was carried out through a mixed oxide and silicide core so that the reactor could still be operated at a nominal power of up to 30 MW (Sembiring et al., 2000, 2001; Tukiran et al., 2003). With this approach, the remaining oxide fuel in the core can also be utilized as much as possible before finally being replaced by silicide fuel.

During the conversion stages from oxide to silicide fuel, proper calculation was needed to ensure the safety of reactor operation during the transition core. For that, the National Nuclear Energy Agency (BATAN) developed an in-house program for reactor core management calculations, Batan-FUEL (Liem, 2019; Liem, January 1996; Liem, 1994) and also Batan-3DIFF for calculating core neutronic parameters with its 3D neutron diffusion approach (Liem, 1999). Batan-3DIFF was used for some analyses where the BATAN-FUEL's 2-D calculation model may not produce accurate results, or the axial direction neutron flux and power profiles needed. For example, axial power peaking factors, partially inserted control rod worth, reactivity for irradiation targets, and determining axial buckling values that are needed by BATAN-FUEL. The Batan-FUEL and Batan-3DIFF have been verified using several benchmark scenarios, such as fuel conversion benchmarks for research reactors, IAEA-TECDOC-233 (1980) and IAEA-TECDOC-643 (1992) which showed consistency in several scenarios (Sembiring and Liem, 1997; Liem and Sembiring, 1997). In addition, this in-house program from also shown good performance when solving the Critical Assembly case from Kyoto University, KUCA (Zuhair and Liem, 1998).

This paper will give a glimpse of the conversion process being carried out for mixed oxide-silicide core in RSG-GAS. The new fuel management strategy and fuel loading pattern have been developed to achieve an equilibrium core and maintain it. In general, the design process was carried out using our in-house code BATAN-FUEL, while the neutronic aspect during the RSG-GAS operation was carried out using BATAN-3DIFF such as reactivity of target irradiation, its corresponding power peaking factor, and reactivity related aspect that need to follow the experiment's procedure. Some experiment data were shown to emphasize the RSG-GAS equilibrium core performance and some recent calculations showed the consistency between the calculation and experiment. This review paper could be beneficial for the designers and operators (practitioners) of research reactors regarding the development stages of an equilibrium core and maintaining it in a research reactor core, especially to improve the fuel discharge burnup for optimal fuel usage.

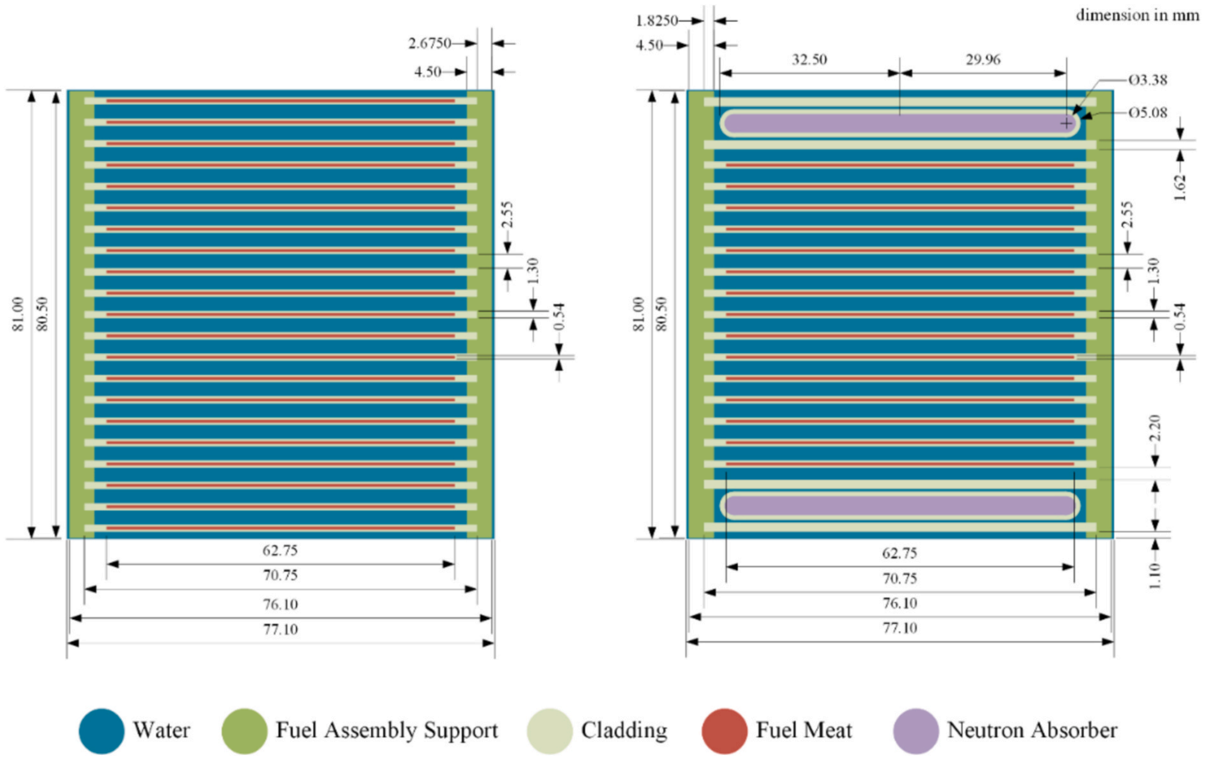

Fig. 1. RSG-GAS fuel element (left) and control fuel element (right) Br. Ginting A, Yanlinastuti, Boybul, Supardjo, Sungkono, Pinem S, et al. Burnup determination of Full-Scale, High-Density U3Si2-Al (Pinem et al., 2023).

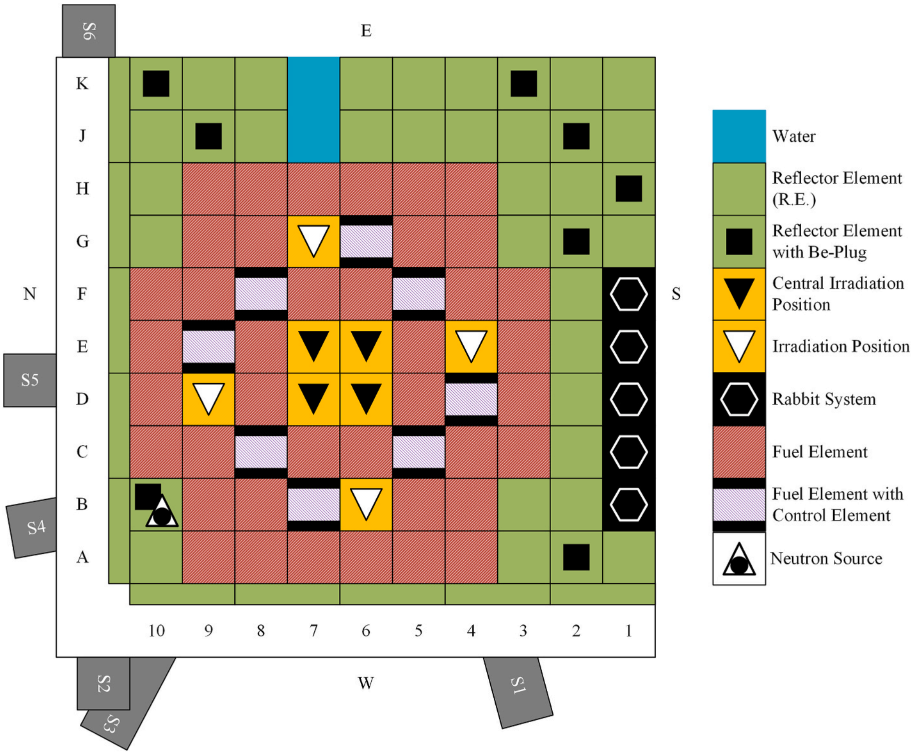

Fig. 2. RSG GAS core configuration.

2. Mixed oxide-silicide cores

While developing the mixed oxide and silicide fuel core, some safety requirements must be met, such as reactivity margin, stuck rod condition, and thermal–hydraulic safety. In addition, the maximum burnup at the end of the cycle (EOC) is 56 % burned U-235, while the number and performance of each irradiation facility must be similar to the existing core. The fuel management strategy used in the mixed core aims to obtain an equilibrium core in the full silicide core. All safety requirements in the mixed core and silicide equilibrium core must follow the RSG-GAS Safety Analysis Report (SAR) (RSG-Batan, 2011). From here, a 5/1 fuel loading pattern is used where only 5 fuel elements and one fresh control element are used at the beginning of cycle (BOC) since from the calculations that have been done, a full silicide core can be achieved with 10 mixed oxide silicide cores (TMIX). Details of silicide fuel being used on each mixed core TMIX-1 to TMIX-10 are shown in Table 2. For example, in TMIX-1, only 2 fresh fuel elements (FE) are added substituting 2 oxide FE in the core, while in TMIX-2, 5 fresh FE are used, and from TMIX-3 to 10, the 5/1 fuel loading pattern with 5 fresh FE and 1 CE being added on each cycle.

Each transition core of mixed oxide and silicide must meet the core safety parameters according to SAR RSG-GAS so that the reactor continues to operate safely. The neutronic parameters of the RSG-GAS from cycles 31 to 60 are shown in Table 3. The table shows the neutronic parameters of oxide fuel from 31 to 36 cores and the transition cores containing mixed oxide silicide cores at 37–45 cores. After that, the first 8 full silicide cores start from the last TMIX-10 at core number 46 to the core number 53, followed by the equilibrium core shown in cores 54–60. Some neutronic parameters from the recent cores are also shown in cores 95–98.

As previously mentioned, the indirect conversion through the conversion of oxide to silicide fuel at the same density of 2.96 gU/cc was used with the promise to achieve further conversion to use higher silicide fuel, 3.55 gU/cc. However, to this date, the RSG-GAS still uses the same 2.96 gU/cc silicide fuel, so the experiment results shown below were focused on the equilibrium core using the 2.96 gU/cc silicide fuel. Higher uranium density fuel post-irradiation examination (PIE) is undergoing, and after the regulatory body issues a license for this high-density silicide fuel, then we will be able to use the fuel.

The oxide-fueled RSG-GAS core as shown in core numbers 31–36 shows some differences in neutronic parameters in each operating cycle due to different fuel loading patterns being used. These behaviors are also shown at the beginning of the oxide and silicide mixed core (37-40) which shows neutronic parameters that are not yet stable because there are differences in loading patterns at the beginning of the transition core. But after 10 transition cores, from core number 46 which is already filled with all silicide fuel, the neutronic parameters begin to gradually become more stable as seen up to core number 53 even though there is still the influence of the previous mixed oxide-silicide transition core. After that, in core number 54–60 and the more recent equilibrium silicide core, 95–98, the neutronic parameters were shown to be lot consistent at each cycle which indicates that the equilibrium core has been achieved with a 5/1 fuel loading pattern while also simplifying the fuel management strategy for RSG-GAS.

3. RSG-GAS equilibrium core

In-core fuel management strategy is an important aspect of optimizing core operating parameters such as cycle length, burnup fraction, and shutdown margin. These parameters must be studied thoroughly to determine a fuel management strategy that can meet the economic aspects of nuclear reactor utilization (Keyvani et al., 2010; Tiyapun et al., 2019; Schlünz et al., 2014). In-core fuel management ensures efficient fuel utilization by increasing the fuel burnup fraction while still considering the safety of reactor operations. When converting oxide fuel to silicide using a 5/1 pattern to achieve an equilibrium core, this pattern was chosen so that 8 classes of burnup fractions can be maintained so that all discharge fuel burnup fractions can achieve 56 % (Pinem et al., 2023; Surbakti et al., 2022).

The 5/1 fuel loading pattern requires fuel at 5 positions (G-8, F-6, D-8, B-8, B-7, and B-5) to be removed at the end of cycle because it has reached the upper limit of the 8th burnup class, 56 %. Then, to form (create) a new fuel configuration for the next core cycle, the fuel elements are shuffled following the scheme as shown in Table 4 and visualized in Fig. 3. For example, the FE at A-9 is moved to A-4. It should be noted that positions B-7, C-8, C-5, D-4, E-9, F-8, F-5, and G-6 (dark purple) are the control element (CE) positions. Five fresh FEs and one CE are then inserted into positions A-9, C-3, C-8, F-3, H-4, and H-9 after the positions of other fuel shuffled to the fuel position in the core.

As shown previously in Table 3, the reactivity values from the RSG-GAS equilibrium core using 2.96 gU/cc silicide fuel are shown in the 54–60 cores and for the recent cores in 95–98 cores. This shows that there is no significant change in neutronic parameters after the core is in equilibrium core with the 5/1 fuel loading pattern. This indicates that the applied fuel management strategy can achieve the equilibrium core as planned. With this kind of fuel management strategy, new core formation for the next cycle could be implemented directly since RSG-GAS operators have clear and definite fuel loading guidelines. This also helps simplify the routine because the reactivity calculation for each cycle does not need to be done intensively and the new core can be formed directly more efficiently.

The reactivity value that can be maintained in each operating cycle is also proven, not only from calculations but also through neutronic parameters obtained from reactivity experiments, such as excess reactivity and control rod-worth experiments. However, when there is an indication of a change in core neutronic parameters, for example, the difference in highest or total control rod reactivity (worth), the initial critical position (bank) at the beginning of the cycle is not the same as the beginning of the previous cycle due to unintentional changes or due other reactor operations related such as sample or target being irradiated in the core, then the fuel burnup fraction and fuel position can be evaluated. Evaluation in each reactor core cycle must be carried out to ensure that there are no changes in core parameters and to anticipate some changes during reactor operations.

Table 2
Fuel loading schemes for mixed oxide-silicide transition core.

Mixed oxide-silicide core	Fresh silicide fuel		Silicide fuel in-core		
	FE	CE	FE	CE	Total
TMIX-1	2	0	2	0	2
TMIX-2	5	0	7	0	7
TMIX-3	5	1	12	1	13
TMIX-4	5	1	17	2	19
TMIX-5	5	1	22	3	25
TMIX-6	5	1	27	4	31
TMIX-7	5	1	32	5	37
TMIX-8	5	1	37	6	43
TMIX-9	5	1	40	7	47
TMIX-10	5	1	40	8	48

4. Burn-up measurement

After the equilibrium core using 2.96 gU/cc silicide fuel was achieved, the fuel management strategy that has been used needs to be validated such as by measuring the burnup fraction of the fuel elements that make up the core. The burnup fraction is one important neutronic aspect because this value must not exceed the reactor's operational safety limit. Various methods of measuring fuel burnup are available and widely known, for example, non-destructive and destructive methods that have been widely used in several reactors (Harp et al., 2014; IAEA, 2023; Iqbal et al., 2001; Suzaki et al., 1986). Similar methods have also been used in measuring the burnup fraction of RSG-GAS fuel, where for both methods, the fuel must be transferred to the hot cell for measurement (Kartaman Ajiriyanto et al., 2024; Liem et al., 2013; Ginting and Liem, 2015; Ginting et al., 2024). If the amount of fuel to be measured is large, for example, 40 FEs and 8 CEs as being used in the RSG-GAS equilibrium core, then the non-destructive and destructive methods become less practical.

The method of measuring the burnup fraction of fuel based on the reactivity value was much more practical because the fuel does not need

Table 3
Neutronic parameters for the RSG-GAS cores (Kuntoro et al., 2021; Tukiran, 2017).

Core number	Fuel loading (FE/CE)	Energy per cycle (MWD)	Total control rod worth (%)	Excess reactivity (%)	Reactivity shutdown margin (%)	Core BU BOC (%)	Core BU EOC (%)
Typical working core (TWC) with oxide fuel (1998–1999)							
31	6/1	556.91	−11.40	+7.40	−2.41	23.05	29.05
32	6/1	529.30	−11.10	+6.72	−2.65	23.01	28.77
33	6/1	526.44	−9.25	+6.07	−1.51	22.69	28.41
34	6/2	534.24	−14.61	+6.92	−2.05	22.23	29.75
35	6/1	500.14	−10.55	+7.46	−1.55	22.26	27.85
36	6/1	540.71	−9.80	+7.17	−1.22	21.82	29.14
Mixed oxide silicide core (1999–2003)							
37	2/0	500.38	−13.46	+9.65	−1.90	21.81	28.48
38	5/0	611.62	−12.93	+8.15	−2.80	22.50	28.91
39	5/1	601.44	−12.51	+7.54	−3.04	22.89	29.36
40	5/1	500.38	−11.64	+6.71	−3.24	23.36	28.79
41	5/1	512.38	−10.92	+6.73	−2.58	22.96	28.25
42	5/1	512.01	−13.34	+8.29	−3.10	22.96	28.35
43	5/1	623.29	−13.47	+8.71	−2.85	21.98	28.67
44	5/1	582.68	−13.15	+8.47	−2.91	22.55	28.92
45	5/1	636.32	−12.78	+8.13	−2.77	23.00	29.35
46	5/1	570.10	−13.25	+7.97	−3.41	23.39	29.41
Full silicide fuel core (2003–2005)							
47	5/1	618.82	−13.44	+8.14	−3.45	23.42	30.18
48	5/1	620.35	−12.63	+7.43	−3.34	23.95	30.63
49	5/1	632.34	−12.72	+7.63	−3.27	24.39	31.19
50	5/1	637.58	−11.59	+6.79	−3.05	24.76	31.73
51	5/1	629.27	−12.47	+7.15	−3.94	25.19	31.87
52	5/1	608.15	−12.70	+7.28	−3.56	25.43	31.69
53	5/1	644.83	−12.71	+7.55	−3.32	25.07	31.91
Equilibrium silicide core (2005–2007)							
54	5/1	712.51	−12.70	+7.67	−3.16	25.29	32.66
55	5/1	660.30	−12.91	+7.72	−3.27	25.43	32.24
56	5/1	641.14	−12.77	+7.52	−3.40	25.26	32.06
57	5/1	677.07	−12.67	+7.72	−3.15	24.83	32.04
58	5/1	691.14	−12.84	+7.78	−3.15	24.77	32.10
59	5/1	599.66	−12.61	+7.45	−3.30	24.94	31.30
60	5/1	621.26	−12.83	+7.67	−3.35	24.29	30.88
Recent equilibrium silicide core (2018–2019)							
95	5/1	625.64	−12.92	+7.04	– 4.02	24.06	30.52
96	5/1	625.01	−13.02	+7.21	– 3.96	24.01	30.47
97	5/1	625.00	−12.91	+7.10	– 3.97	23.97	30.43
98	5/1	625.01	−13.20	+7.00	– 4.35	23.94	30.39

Table 4
RSG-GAS fuel management strategy with 8 burnup classes (Pinem et al., 2023).

From	To	From	To	From	To
fresh	A-9	**fresh**	C-3	**fresh**	H-9
A-9	A-4	C-3	H-8	H-9	F-10
A-4	E-10	H-8	C-4	F-10	G-9
E-10	B-4	C-4	D-5	G-9	E-8
B-4	A-6	D-5	H-5	E-8	D-3
A-6	B-9	H-5	E-5	D-3	C-6
B-9	C-9	E-5	A-8	C-6	G-5
C-9	D-8	A-8	B-5	G-5	G-8
D-8	**out**	B-5	**out**	G-8	**out**
fresh	F-3	**fresh**	H-4	**fresh**	C-8
F-3	C-10	H-4	F-9	C-8	F-5
C-10	E-3	F-9	A-5	F-5	F-8
E-3	A-7	A-5	H-6	F-8	C-5
A-7	H-7	H-6	D-10	C-5	D-4
H-7	F-7	D-10	G-4	D-4	E-9
F-7	F-4	G-4	C-7	E-9	G-6
F-4	F-6	C-7	B-8	G-6	B-7
F-6	**out**	B-8	**out**	B-7	**out**

to be transferred to the hot cell. This method can be carried out with existing core conditions either in critical or even subcritical conditions. The method of measuring fuel burnup under subcritical conditions has been used by Binh et al. and this method has been used for measuring the burnup fraction in several research reactors (Binh et al., 1997; Do et al., 2018). This method was used in measuring the burnup fraction of RSG-GAS fuels, where the fuel burnup fractions were measured based on the linear relationship between reactivity and burnup.

Burnup measurements through reactivity experiments have been carried out at the RSG-GAS core number 88 at the BOC. Measurements were carried out using start-up channel fission counter detectors (JKT01 CX811 and JKT01 CX821). Because the measurements were carried out at the beginning of the cycle, 5 of the 40 FE fuels certainly had a burnup fraction of 0 % (fresh fuel) so their burnup fractions did not need to be measured. After considering the duration of the core shutdown time allowed for this experiment, only 22 out of 35 fuels were measured for their burnup fractions using the reactivity correlation.

A comparison between calculated and measured burnup fractions (C/E) using JKT01 CX811 and CX821 detectors for 22 fuel elements is shown in Table 5 (Liem and Pinem, 2017; Pinem et al., 2016). The table also shows the fuel name, grid position, and declared burnup fraction derived from calculations using the Batan-FUEL program. If the C/E

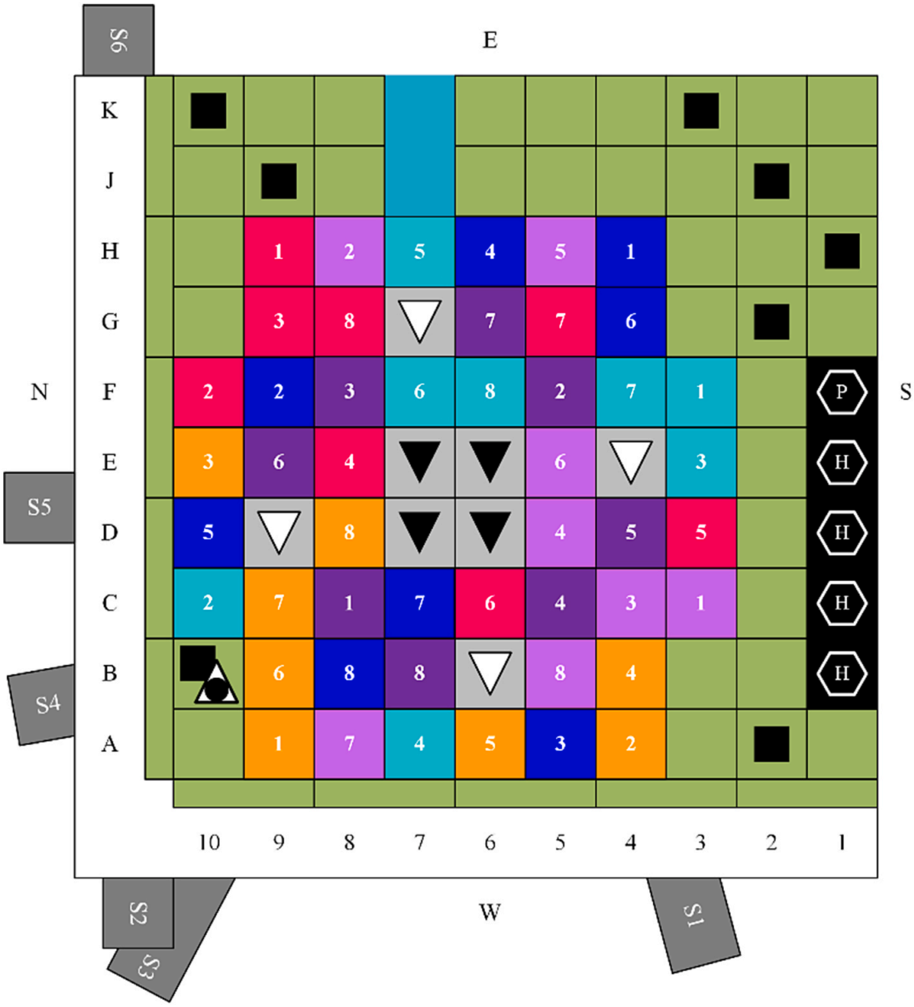

Fig. 3. RSG-GAS equilibrium core fuel management strategy with 5/1 fuel loading pattern.

value is close to 1, then the calculated burnup fraction is equal to the measured burnup fraction, with details of the measurement mechanism and determination of the burnup fraction explained in a previous study (Pinem et al., 2016). The calculation and measurement results show no significant difference between the two detectors, and no burnup fraction exceeds 56 % so the requirements in the RSG-GAS SAR are not exceeded even in core 88 which has been more than 30 cycles since the initial RSG-GAS equilibrium core was formed in core 54 (RSG-Batan, 2011). Therefore, the measured burnup fractions of these 22 fuel elements confirm that the distribution of the fuel burnup fractions in the equilibrium silicide core has been achieved under the new fuel management strategy with a 5/1 pattern.

5. Control Rod Worth of RSG-GAS

In addition to validating the fuel burnup distribution from the new fuel management strategy during the conversion of oxide to silicide fuel, the measured control rod reactivity was also compared. Determining the reactivity of each control rod is an important aspect of nuclear reactor operations because it is directly related to the control aspect of nuclear reactors (Kuntoro et al., 2022; Rahgoshay and Noori-Kalkhoran, 2013; Torabi et al., 2018). Evaluation of the control rod reactivity value was obtained from control rod reactivity measurement experiments that can be carried out using various methods as being used in research reactors around the globe (Liem et al., 2002; Luthfi et al., 2022; Surbakti et al., 2019).

In the reactivity experiment conducted at RSG-GAS, the positive-to-negative reactivity compensation method was used where one control rod was selected as a positive compensation rod whose initial position was completely inserted into the core (at 0 mm) while the other control rod was selected as a negative compensation rod whose initial position was above the core, fully withdrawn at 600 mm height. The other 6 control rods were placed at the same height (bank) so that the core was in critical condition at low power. Based on these results, the control rod integral curve will be obtained so that each control rod reactivity (worth) can be obtained from the control rod integral curve.

Experiments or measurements of control rod reactivity have been carried out on the 88th RSG-GAS core, the same equilibrium core as the burnup fraction measurement already mentioned. The results of control rod reactivity from the experiment were used to validate the RSG-GAS modeling that had been carried out with Serpent2, 3-dimensional (3-D) continuous-energy Monte Carlo code with the nuclear data libraries ENDF/B-VII.1 and ENDF/B-VIII.0 (Brown et al., 2018; Chadwick et al., 2006; Leppänen et al., 2015). The comparison between the calculated results and the measured control rod worth is shown in Table 6. The calculation results using ENDF/B-VII.1 nuclear data gave an average relative difference of 5.1 % to the measurement results, while a smaller difference was shown when using ENDF/B-VIII.0 with an average relative difference of 4.8 %. The maximum relative difference for the control rod worth was about 11.3 % for JDA-06 when using ENDF/B-VII.1 and about 13 % for JDA-08 by ENDF/B-VIII.0. This shows that the previously conducted core modeling still shows some consistency with the measurement results, which also indirectly shows that the RSG-GAS equilibrium core has been achieved with the new fuel management strategy

Table 5

Calculated to measured burnup fraction ratio by fission counter JKT01 CX811 and CX821 (Pinem et al., 2016).

No	Fuel Element	Grid Location	Declared Burnup (% loss of U-235)	JKT01 CX811	JKT01 CX821
1	RI-522	–	53.5	1.029 ± 0.176	1.016 ± 0.137
2	RI-523	B-8	45.7	0.984 ± 0.176	0.980 ± 0.139
3	RI-533	G-4	33.5	1.001 ± 0.210	1.009 ± 0.167
4	RI-542	D-10	27.2	0.972 ± 0.225	0.993 ± 0.182
5	RI-524	D-8	44.4	1.011 ± 0.146	1.013 ± 0.106
6	RI-528	C-7	39.3	0.985 ± 0.148	0.992 ± 0.107
7	RI-547	H-6	20.9	1.024 ± 0.216	1.009 ± 0.146
8	RI-525	B-5	46.6	0.946 ± 0.126	0.958 ± 0.122
9	RI-534	B-9	32.9	0.992 ± 0.159	0.986 ± 0.150
10	RI-529	C-9	38.6	1.018 ± 0.207	1.012 ± 0.173
11	RI-543	A-6	26.6	1.031 ± 0.260	1.048 ± 0.224
12	RI-544	H-5	29.0	0.987 ± 0.231	1.018 ± 0.203
13	RI-526	F-6	46.6	1.011 ± 0.204	1.049 ± 0.115
14	RI-535	E-5	34.4	0.992 ± 0.235	0.958 ± 0.112
15	RI-527	G-8	47.9	0.964 ± 0.180	0.975 ± 0.106
16	RI-530	A-8	41.8	1.023 ± 0.211	1.004 ± 0.115
17	RI-536	F-7	33.4	0.951 ± 0.212	0.918 ± 0.110
18	RI-531	F-4	40.6	0.954 ± 0.212	0.955 ± 0.214
19	RI-545	H-7	27.4	1.026 ± 0.284	1.018 ± 0.284
20	RI-532	G-5	42.3	0.998 ± 0.200	0.996 ± 0.195
21	RI-541	C-6	35.3	0.980 ± 0.213	0.964 ± 0.203
22	RI-546	D-3	29.4	0.986 ± 0.237	0.981 ± 0.231

being used.

6. Conclusion

The RSG-GAS core that initially used oxide fuel has been converted to silicide fuel through a mixed transition core and a new fuel management strategy with a 5/1 fuel loading pattern. This conversion process has been carried out properly and meets the safety aspects of reactor operations. Validation for this new RSG-GAS in-core fuel management strategy was carried out by comparing the neutronic parameters of the reactor core in various core cycles. The neutronic parameter of each core from the experimental results showed more consistent values in each core cycle after the conversion of silicide fuel with a new fuel loading pattern and the RSG-GAS equilibrium core can be obtained and maintained. In addition, the measured burnup fraction and control rod reactivity values in one of the RSG-GAS equilibrium cores, core number 88, were also compared with the calculation results from our in-house fuel management code, Batan-FUEL. The burnup measurement results showed agreement between the measurements and calculations, with the burnup fraction value not exceeding the RSG-GAS fuel burnup fraction limit that had been determined in the SAR. The control rod reactivity values also show some consistency with Monte Carlo calculations such as Serpent2 using ENDF/B-VII.1 and ENDF/B-VIII.0. Based on the core neutronic parameter values, measured burnup fraction and control rod reactivity, it can be concluded that the RSG-GAS equilibrium core with 2.96 gU/cc silicide fuel has been achieved as planned from the use of the new fuel management strategy with a 5/1 fuel loading pattern.

Table 6

Measured and calculated control rod worth for 88th core of RSG-GAS (PRSG, Batan. Report of the Operation of RSG-GAS Reactor - 88th Core. Serpong, Indonesia;, 2015; Sembiring et al., 2021).

Position of control rod in the core	Experiment (cent)	Calculation (Serpent2)	
		ENDF/B-VII.1 (cent)	ENDF/B-VIII.0 (cent)
JDA01/E-9	204.25 ± 12	222.79 ± 6.63 (9.1 %)*	221.16 ± 6.60 (3.4 %)
JDA02/G-6	224.75 ± 13	237.00 ± 6.98 (5.4 %)	239.57 ± 6.88 (6.6 %)
JDA03/F-8	243.75 ± 14	243.01 ± 6.86 (0.3 %)	240.68 ± 6.89 (1.3 %)
JDA04/F-5	241.10 ± 13	240.61 ± 6.89 (0.2 %)	254.84 ± 6.91 (5.7 %)
JDA05/C-5	234.50 ± 13	241.99 ± 6.91 (3.2 %)	233.07 ± 6.88 (0.6 %)
JDA06/C-8	182.75 ± 10	203.37 ± 6.13 (11.3 %)	195.51 ± 6.01 (7.0 %)
JDA07/D-4	242.95 ± 13	249.33 ± 6.86 (2.6 %)	244.73 ± 6.87 (0.7 %)
JDA08/B-7	181.30 ± 10	196.53 ± 6.06 (8.4 %)	205.16 ± 6.24 (13.2 %)

*(C/E −1) × 100 %.

CRediT authorship contribution statement

Surian Pinem: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Peng Hong Liem:** Conceptualization, Validation, Formal analysis, Writing – review & editing, Supervision. **Fitri Susanti:** Data curation. **Sukarno Sigit:** Data curation. **Bagus Dwi Nurtanto:** Data curation. **Syamsul Falah Akhmadi:** Data curation. **Wahid Luthfi:** Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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