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Analysis of the excess reactivity and control rod worth of RSG-GAS equilibrium silicide core using Continuous-Energy Monte Carlo Serpent2 code

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A R T I C L E   I N F O

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A B S T R A C T

This present work is a continuation of our previous work to verify the RSG-GAS equilibrium silicide core parameters. Earlier, the burnup of 22 fuel elements in the 88th equilibrium core has been measured, and it showed a good agreement between the experimental and calculation results. In this paper, several important neutronics parameters documented from the experiment at the same core, such as the excess reactivity, integral control rod worth, and total control rod worth, are confirmed using the full core calculation results of Monte Carlo Serpent2 code in conjunction with ENDF/B-VII.1 and the most recent ENDF/B-VIII.0 nuclear data libraries. The excess reactivity and integral control rod worth were measured by the positive and negative reactivity compensation method. It is worth mentioning that the measured integral control rod worth hasn't been verified because the in-core fuel management code of RSG-GAS (BATAN-FUEL) solves only for a 2-dimensional configuration. The fuel element burnup at the end of cycle calculated by BATAN-FUEL and Serpent2 is also compared and discussed. The 3-D Serpent2 model of RSG-GAS first core is modified, and several improvements in the models are proposed, including the explicit modeling of 6 neutron beam tubes in the beryllium block reflector. It is found that the calculated integral control rod worth has a good agreement with the experiment, while Serpent2 overestimates the excess reactivity by a maximum of 661 pcm. The impact of nuclear data is insignificant for the selected core parameters.

1. Introduction

RSG-GAS (Reaktor Serba Guna – G.A. Siwabessy) reactor, formerly named MPR-30, is an open pool material testing reactor with a nominal thermal power of 30 MW. It is located at the Puspiptek Complex, Setu, Tangerang Selatan, Indonesia. Since the first criticality in July 1987, the reactor has been operated through 5 transition cores and 95 full core configurations. The first full configuration was reached at the 6th core configuration using 40 standard fuel elements (FE) and 8 control fuel elements (CE). The FEs and CEs are arranged in the 10 × 10 core grid positions. There are 21 fuel plates in a FE with low enriched uranium fuel meat, and the total mass of U-235 is 250 g per element. The 15 fuel plates and 2 Ag-In-Cd blades (one on each side) are assembled in a CE, and the total mass of U-235 is 178.6 g. The detailed geometry and data specification of the FE and CE can be found in several references (BATAN, 1997; Liem et al., 1998; Pinem et al., 2016).

The reactor reached a typical working core that can be operated at the nominal power of 30 MWth at the 6th core configuration. For the typical working core, there is no fixed number of fresh and discharged FEs/CEs as well as the reshuffling pattern. The number of fresh FEs/CEs in the RSG-GAS' typical working core could be 6/1 or 6/2, and their locations in the core grid could be different between each typical working core. Later, during the core conversion from oxide fuel (U_3O_8-Al) to the silicide fuel (U_3Si_2-Al), a new in-core fuel management strategy was introduced to achieve the equilibrium core. The research on applying the new in-core fuel management strategy has been carried out for the mixed core of

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the oxide and silicide fuels to obtain an equilibrium silicide core by the neutron diffusion method code (Liem et al., 1998; Sembiring et al., 2001).

The equilibrium core means that all fresh, discharged, and reshuffled FEs and CEs have a predetermined loading, discharging, and reshuffling pattern (Liem et al., 1998). It is usually established in the core fuel management of a power reactor because the number of fuel assemblies being handled can be hundreds. A research reactor core is usually operated with a typical working core rather than under the equilibrium core condition because it operates at lower power and has fewer fuel elements than the power reactor. However, the in-core fuel management strategy for an equilibrium core minimizes the human errors in the loading, unloading, and shuffling of the FEs and CEs since the pattern is fixed. Moreover, the refueling time between each cycle is constant, and hence the beginning of the next cycle can be determined more precisely.

In this present work, the important core parameters measured in the equilibrium core of RSG-GAS, such as excess reactivity and control rod worth, are evaluated using the analytical tools. There is a strong motivation to perform this work because the measured core parameters of the equilibrium core haven't been verified adequately analytically. Previous researches focused on the neutronics parameters evaluation of RSG-GAS first-core which used only fresh fuels (Liem and Sembiring, 2012; Liem et al., 2018, 2019, 2020; 2020;; Hartanto et al., 2020). The RSG-GAS equilibrium core selected in this work is the 88th core in which the experiment for excess reactivity and each control rod worth was also performed. The fuel elements' burnup of the 88th core have been measured and compared with the analytical results using a linear relationship between reactivity and burnup (Pinem et al., 2016). The measurements were carried out for 22 irradiated FEs with a burnup level in the range of 20.85%-46.55% (loss of U-235). The evaluation showed a good agreement between the measurement and calculated burnup with the maximum error of 8%. Based on these results, the neutronic parameters of the 88th core of RSG-GAS are verified in the present work by the 3-dimension (3-D) continuous-energy Monte Carlo Method Serpent2 code (Leppänen et al., 2015).

This work also provides a meaningful discussion on a research reactor using beryllium (Be) as a reflector element. RSG-GAS has 37 beryllium reflector elements in addition to the L-shaped beryllium block reflectors at the two sides of the core periphery. The core also has 8 thermal neutron flux traps called irradiation position (IP): 4 IPs (2×2 grid) are located at the center of the core (central irradiation position, CIP), and the other 4 IPs (1×1 grid) are in among FEs and CEs. Therefore, the core has a high heterogeneity or various gradient of neutron flux. Hence, the Monte Carlo method code, such as Serpent2, is used for this work.

Additionally, the detailed geometry model of RSG-GAS core is revised in this work since the beam tubes were homogenized with the Be block reflector previously (Liem and Sembiring, 2012; Liem et al., 2018, 2019; 2020;; Hartanto et al., 2020). The effect of the impurity of Be reflector is also considered. The experimental core parameters, such as excess reactivity and control rod worth, are compared with the calculated Serpent2 code. The calculated burnup swing, BOC (beginning of cycle) to EOC (end of cycle), of each FE and CE is validated by the declared burnup. The effect of the recent ENDF/B nuclear data, ENDF/B-VIII.0, is also evaluated (Brown et al., 2018).

The rest of this paper is organized as follows: Section 2 discusses the description of the RSG-GAS 88th equilibrium core. Section 3 deals with the methodology adopted in the calculations. Section 4 discusses the results, and finally, Section 5 presents the conclusions and recommendations for future works.

2. Equilibrium core (Core 88th) of RSG-GAS reactor

Fig. 1 shows the 88th equilibrium core configuration of the RSG-GAS. Each FE and CE has a unique identification number, e.g., RI-570 is fresh FE at position H-9 of the core grid. Table 1 shows the detailed information of the declared burnup (% loss of U-235) for all FEs and CEs taken from the RSG-GAS in-core fuel management code's calculation results. Among them, there are 5 fresh FEs and 1 fresh CE. As mentioned previously, there are 4 locations (at grid D-6, D-7, E-6, and E-7) for CIP, as well as 4 locations (at grid B-6, D-9, E-4, and G-7) for the IPs (irradiation position). The CIP and IPs have been utilized for the radioisotope (RI) production which requires a high thermal neutron flux. At the nominal power of 30 MWth, the average thermal neutron flux at CIP and IPs are about 2×10^{14} neutron cm^{-2} s^{-1}.

The CEs are divided into 8 burnup classes at grid locations of B-7, C-5, C-8, D-4, E-9, F-5, F-8, and G-6. Therefore, the control rod worth depends on its burnup class and the burnup distribution of FEs around the CE. The control rod worth of each position by experiment and calculations is presented in this paper.

RSG-GAS core has two types of reflector element: the beryllium reflector elements (B, at 29 grid locations) and the beryllium reflector elements with stopper (BS, at 7 grid locations). The BS can be used for target irradiation since it has a hole with a diameter and length of 5 cm and 60 cm, respectively. The hole is plugged with a stopper if the BS is not utilized.

Fig. 2 shows the configuration of 6 neutron beam tubes (S-1, S-2, S-3, S-4, S-5, and S-6) installed at the beryllium block reflector, and Table 2 shows the important data of the beam tubes. The neutron flux in the core, especially near the beryllium block, is influenced by the condition of beam tubes, e.g., filled with water or air. This condition also affects the burnup of FEs next to the beryllium block. Therefore, all beam tubes are modeled in detail based on the design data (BATAN, 1997).

3. Methodology

3.1. RSG-GAS 3-D core model

The Serpent core model of RSG-GAS from the previous study (Hartanto and Liem, 2020) was modified to accommodate the fuel compositions at the BOC of the 88th core, calculated by the in-core fuel management code and documented in the operation report (PRSG-BATAN, 2015). The burnup of 22 FEs at BOC is also adjusted by considering the calculation to the measurement ratio reported in the previous work (Pinem et al., 2016).

It is found at the beginning of research work that the calculated excess reactivity at BOC is higher than experimental value using previous Serpent core Model (Hartanto and Liem, 2020). Therefore, to improve the calculation of Serpent2 code, several important refinements related to beryllium reflector element and beryllium block reflector are implemented into the core model, such as:

1. The six beam tubes, which are filled with water, are included in detail in the reflector block region to improve the calculation accuracy. In the previous work, the reflector block consisted of a mixture of homogenized water and beryllium. It is expected that the composition of the reflector block affects the multiplication factor and the neutron flux nearby the reflector block.

2. The chemical impurity is added to the material composition of the beryllium reflector. Based on the fabricant data, the maximum impurity of the beryllium reflector element and beryllium block reflector is around 10.113 ppm boron equivalent (BATAN, 1997).

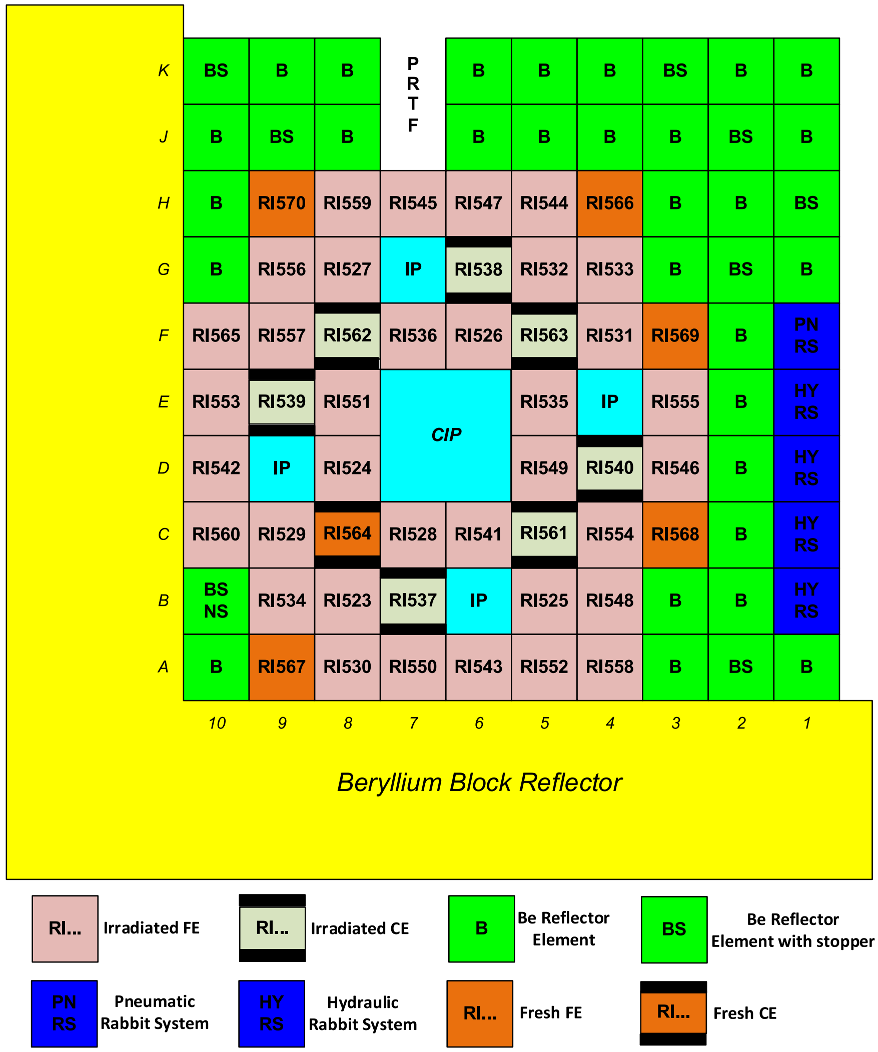

Fig. 1. The 88th core configuration of the RSG-GAS reactor.

Table 1
Declared burnup values of the irradiated FEs and CEs for the 88th equilibrium core of RSG-GAS reactor.

No	IdentificationNumber	Grid location	Declared burnup (% loss of U-235)	No	Identification Number	Grid location	Declared burnup (% loss of U-235)
1	RI-523	B-8	45.72	22	RI-544	H-5	28.97
2	RI-524	D-8	44.42	23	RI-545	H-7	27.36
3	RI-525	B-5	46.55	24	RI-546	D-3	29.38
4	RI-526	F-6	46.56	25	RI-547	H-6	20.85
5	RI-527	G-8	47.85	26	RI-548	B-4	20.01
6	RI-528	C-7	39.34	27	RI-549	D-5	21.18
7	RI-529	C-9	38.58	28	RI-550	A-7	21.00
8	RI-530	A-8	41.77	29	RI-551	E-8	21.49
9	RI-531	F-4	40.64	30	RI-552	A-5	14.43
10	RI-532	G-5	42.30	31	RI-553	E-10	12.84
11	RI-533	G-4	33.51	32	RI-554	C-4	13.78
12	RI-534	B-9	32.91	33	RI-555	E-3	13.98
13	RI-535	E-5	34.43	34	RI-556	G-9	14.37
14	RI-536	F-7	33.39	35	RI-557	F-9	6.70
15	RI-537	B-7	51.50	36	RI-558	A-4	6.42
16	RI-538	G-6	45.34	37	RI-559	H-8	7.38
17	RI-539	E-9	38.64	38	RI-560	C-10	7.15
18	RI-540	D-4	31.62	39	RI-561	C-5	24.21
19	RI-541	C-6	35.32	40	RI-562	F-8	16.21
20	RI-542	D-10	27.13	41	RI-563	F-5	8.31
21	RI-543	A-6	26.64	42	RI-565	F-10	6.92

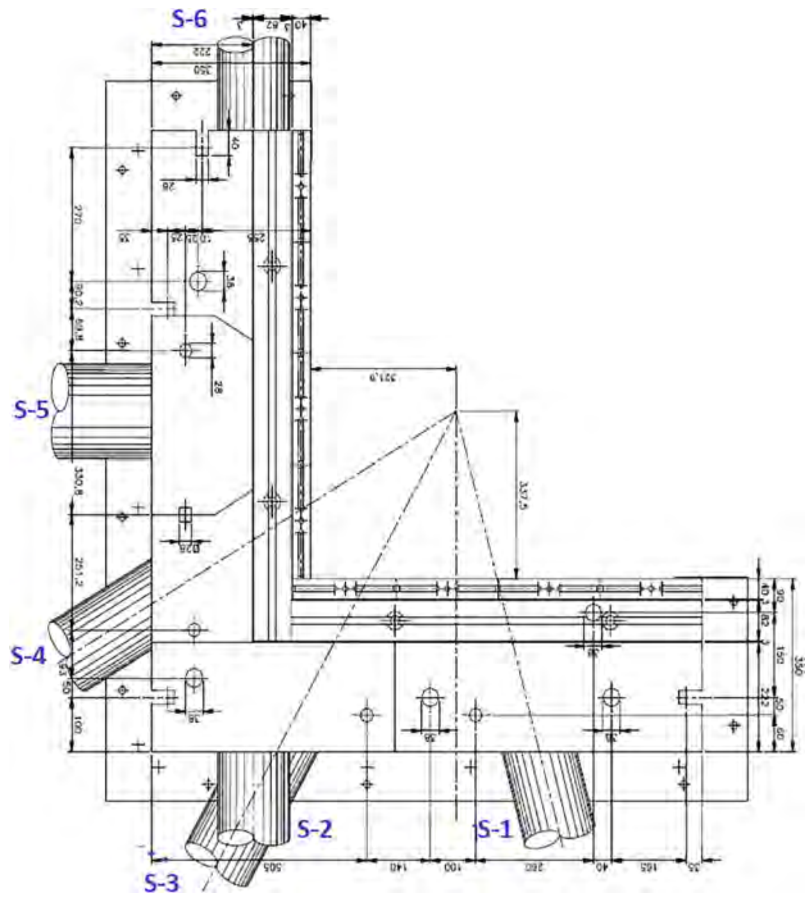

Fig. 2. The beam tubes configuration of RSG-GAS reactor (unit in mm).

Table 2
Utilization and position of the beam tubes.

Beam Tube	Utilization	Position, cm (from bottom of active core)	Inner diameter, cm
S-1	I-125 loop	20	16
S-2	Neutron radiography	40	16
S-3	–	20	16
S-4	Triple Axis Spectrometry (TAS)	20	16
S-5	- Four Cycle Diffractometer (FCD) - High Resolution Powder Diffractometer (HRPD) - Small Angle Neutron Spectrometer (SANS) - High Resolution Small Angle - Neutron Spectrometer (HRSANS)	20	16
S-6	Powder Diffractometer (PD)	40	16

3. The depletion of beryllium in the reflector is considered. The COUPLE/ORIGEN code in the SCALE6.2 package (Rearden and Jessee, 2018) is used for the calculation of the beryllium composition after operating for more than 30 years (from the 1st to the 87th core). In this calculation, 252 energy-group neutron spectra in the reflectors were tallied using Serpent2, and they were used in the depletion calculation.

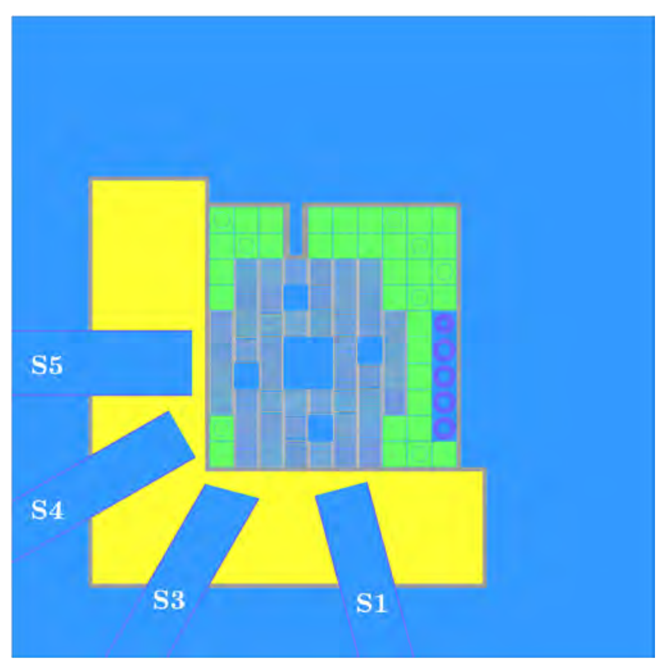

Fig. 3. Cross section view of the RSG-GAS Core at 20 cm from the bottom of active core.

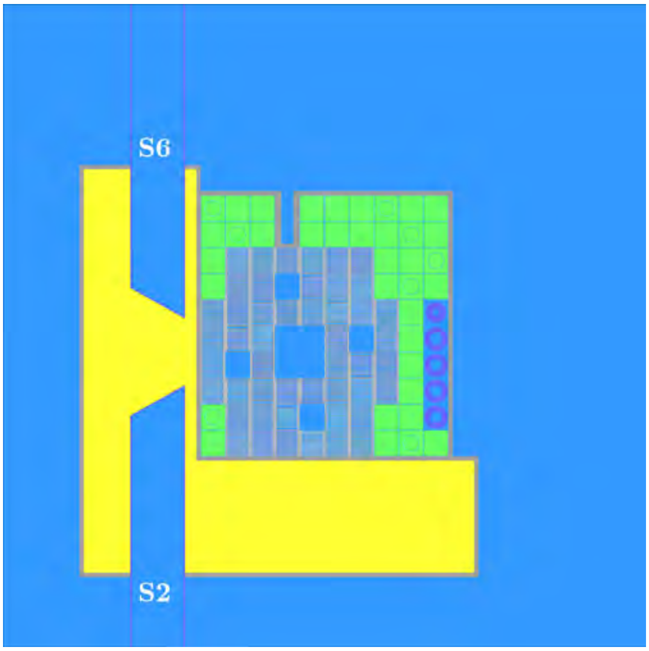

Fig. 4. Cross section view of the RSG-GAS Core at 40 cm from the bottom of active core.

Figs. 3 and 4 depict the RSG GAS 3-D geometry models plotted by Serpent2 in the present work at 2 elevations to clearly illustrate the addition of beam tubes into the model.

3.2. Control rod worth experiments and calculations

The control rod (CR) worth of the 88th core was measured by the control rod calibration using the positive to negative reactivity compensation method. In this method, one CR is chosen as a positive compensation rod, and its initial position is fully inserted into the core (at 0 mm). Another CR is selected as a negative compensation rod, and it is fully withdrawn from the core initially (at 600 mm). Meanwhile, the other 6 CRs are set at the bank position, so the core is in the critical condition at low power. In each experiment, the worth of two CRs can be measured. Table 3 shows the experimental condition for 4 cases of CR calibration in the 88th core. The CR is identified by the code number, for example, JDA-01 is the CR located at grid E-9. The detailed procedure of the positive to negative reactivity compensation method is explained by the steps below:

1. The core is set-up at low power with the criticality condition by adjusting one CR at 0 mm (fully down), one CR at 600 mm (fully up), and 6 CRs at bank position. The CRs at 0 mm and 600 mm are called positive and negative compensation CRs, respectively.
2. The compensated ionization chamber (CIC) detector (JKT04) is used to measure the positive and negative reactivities. The current of the JKT04 detector is 2.5×10^{-8} A or equal to 230 kW (low power). The JKT04 is connected to a reactivity meter.
3. The positive and negative compensation CRs are withdrawn and inserted, step by step. The maximum reactivity per step is ± 20 cents.
4. The positive compensation is carried out first, and then the negative compensation. This step is carried out continuously until the positive compensation CR at 600 mm (fully up) and the negative compensation CR at 0 mm (fully down).
5. The accumulation of all reactivity steps from each compensated CR is the control rod worth. Based on the reactivity meter, it is noted that the error of reactivity is ± 1 cent/step.

The control rod worth evaluation was carried for all step positions of experiments, as shown in Table 4. The experimental results, such as S-curve (integral rod worth curve) and the total worth of each control rod, are compared with the calculation results by Serpent2 with ENDF/B-VII.1 (Chadwick et al., 2011) and ENDF/B-VIII.0 nuclear data libraries. The ENDF/B-VIII.0 was demonstrated to have a better agreement with experimental results for the CR worth in the OPAL research reactor (Maul, 2018). In addition, the calculated total neutron flux distribution in the core at the initial and final positions of each calibration case is plotted to analyze its spatial effect on the CR worth.

The experimental excess reactivity can be determined by the S-curve of 8 CRs reactivity worth. Based on the criticality position of all CRs bank position, the total positive and negative reactivities can be determined from the S-curve. The experimental excess reactivity is the total positive reactivity which will be compared with the calculation results in this study.

3.3. Burnup calculation

The burnup calculation to reach the EOC of the 88th core has also been carried out in this work by following the one cycle operation history, such as control rod position, operation time, shutdown time, and reactor power. These data are collected from the log-book of the reactor operation. The reactor operation data shows 69 different positions of control rod while operating from BOC to EOC. The total energy produced in this cycle is about 630 MWd. In the burnup calculation by Serpent2, each FE and CE is divided into 5 axial regions (12 cm height for each region). The burnup of all axial regions in each FE/CE is later averaged and compared to the results calculated by the in-core fuel management code of RSG-GAS, BATAN-FUEL code (Liem, 1996). The calculations by Serpent2 are carried out using ENDF/B-VII.1 and the ENDF/B-VIII.0 nuclear data libraries.

4. Results and discussions

The first results discussed is the impact of the refined modification into the neutron multiplication factor *k* of the core, including the inclusion of the beam tubes into the Be block reflector, the addition of chemical impurity in the Be reflector, and the depletion of the Be reflector after operating for 87 cycles. In Serpent2 simulation, all materials are at room temperature. The thermal scattering libraries of Be and H_2O at room temperature are also used as well as the Doppler broadening rejection correction (DBRC)

Table 3
Control rod calibration cases in the 88th equilibrium core.

Case	Position of control rod, mm							
	JDA-01/ E-9	JDA-02/ G-6	JDA-03/ F-8	JDA-04/ F-5	JDA-05/ C-5	JDA-06/ C-8	JDA-07/ D-4	JDA-08/ B-7
1	0	262	262	262	600	262	262	262
2	274	0	274	274	274	600	274	274
3	260	260	600	260	260	260	0	260
4	277	277	277	0	277	277	277	600

Table 4
Step positions for the 4 CR worth experiment cases.

Case	Number of Step Position	
	Positive compensation	Negative compensation
1	13	14
2	14	11
3	14	14
4	14	10

Table 5
Effect of the refined modification to the core reactivity.

Modifications	ENDF/B-VII.1, pcm	ENDF/B-VIII.0, pcm
Inclusion of beam tubes	−155.04 ± 15.49	−146.61 ± 16.10
Addition of chemical impurity in Be	−465.23 ± 15.44	−459.33 ± 15.44
Depletion of Be reflector	−192.00 ± 15.55	−158.25 ± 15.54
Total	−812.27 ± 26.84	−764.19 ± 27.19

Table 6
Comparison of excess reactivity between experiment and Serpent2 calculation.

	Experiment	Calculation w/ ENDF/B-VII.1	Calculation w/ ENDF/B-VIII.0
Excess reactivity (%Δk/k)	7.305	7.937 ± 0.00011	7.966 ± 0.00011
(C-E)/E*		8.7%	9.0%

* C = calculation result and E = experimental result.

method. The number of neutron histories per cycle is 100,000, and the total number of cycles is 500 with 100 inactive cycles, resulting in a k value with a standard deviation of less than 13 pcm.

As shown in Table 5, the highest impact on the reactivity is due to the Be reflector's chemical impurity, which provided negative reactivity of 465.23 pcm. The explicit modeling of beam tubes reduces the reactivity by about 155.04 pcm. A similar impact is also noticed by taking into account the depletion of Be. Overall, these modifications decrease the total core reactivity by a maximum of 812.27 pcm, and hence it should be considered in the calculation. Meanwhile, it is shown that both ENDF/B-VII.1 and ENDF/B-VIII.0 have a similar trend in the reactivity decrement.

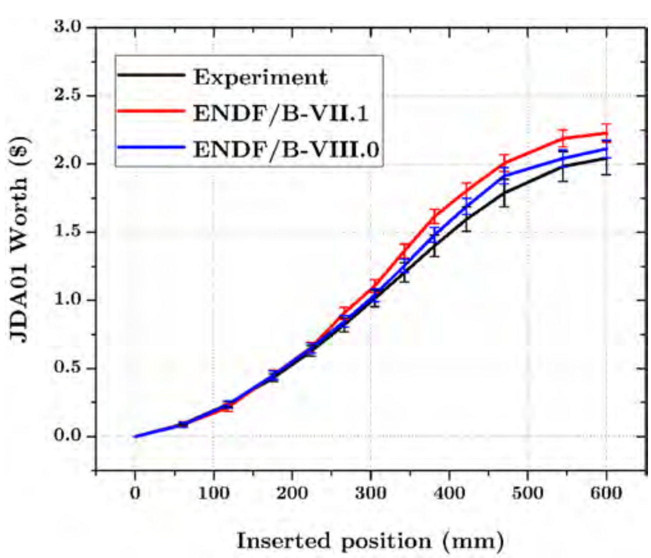

Fig. 5. Calculated and experimental integral CR worth of JDA-01.

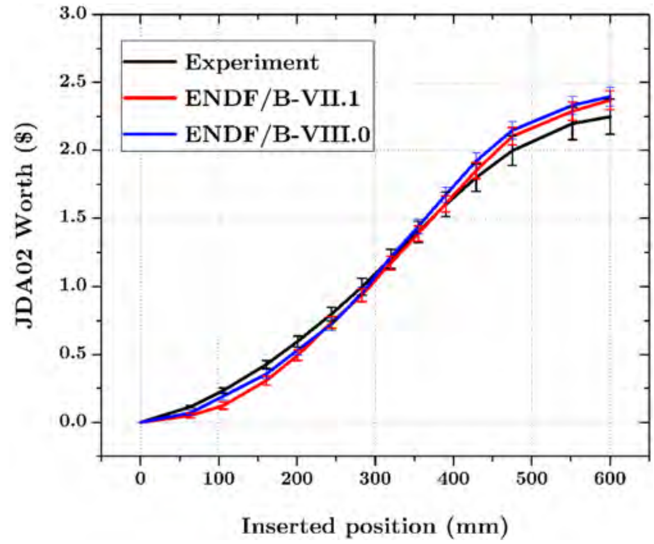

Fig. 6. Calculated and experimental integral CR worth of JDA-02.

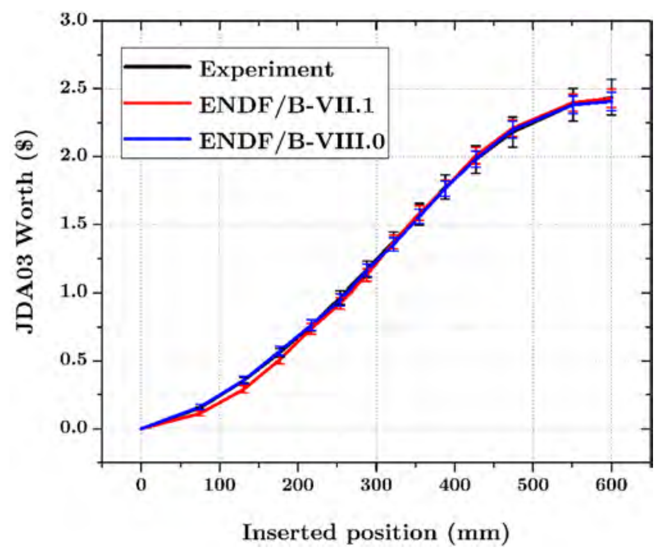

Fig. 7. Calculated and experimental integral CR worth of JDA-03.

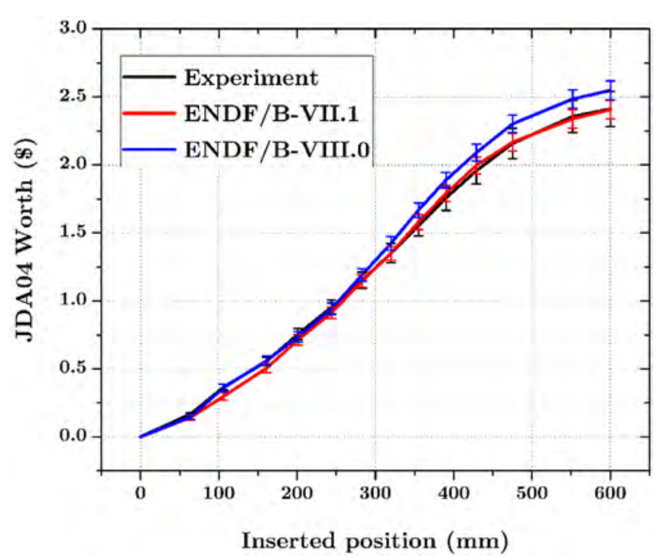

Fig. 8. Calculated and experimental integral CR worth of JDA-04.

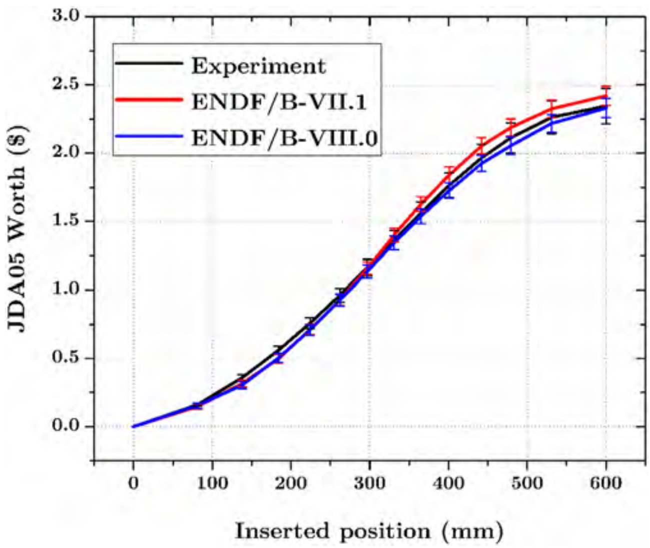

Fig. 9. Calculated and experimental integral CR worth of JDA-05.

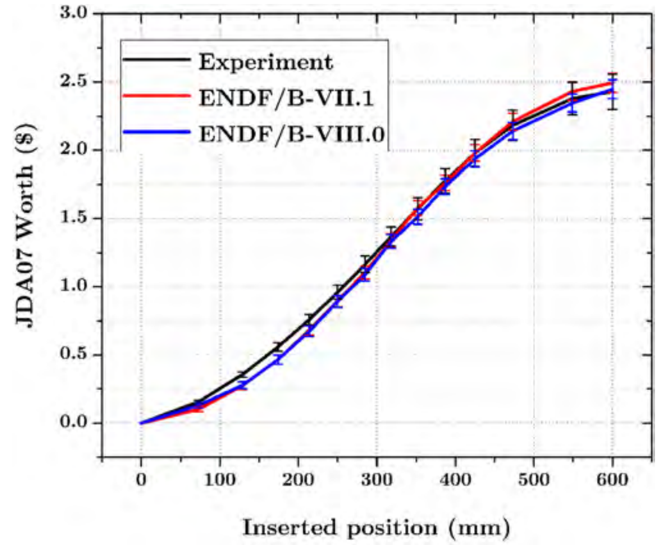

Fig. 11. Calculated and experimental integral CR worth of JDA-07.

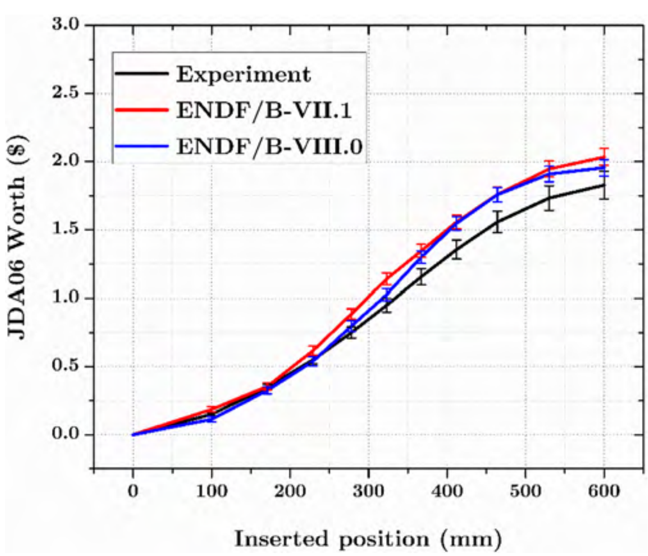

Fig. 10. Calculated and experimental integral CR worth of JDA-06.

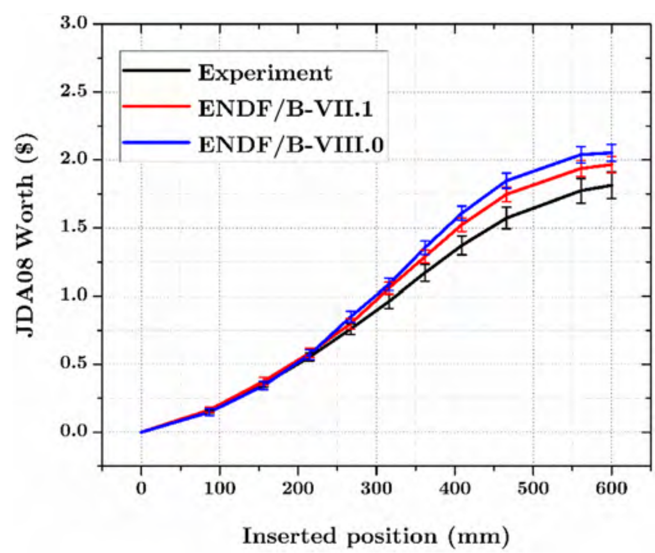

Fig. 12. Calculated and experimental integral CR worth of JDA-08.

Table 6 compares the excess reactivity between the experimental and calculated results for the 88th core of RSG-GAS at BOC (cold and Xe free condition). The corrections from Table 5 and the burnup (Pinem et al., 2016) are included in the calculations. The relative difference of the ENDF/B-VII.1 and ENDF/B-VIII.0 with the experiment is about 8.7% and 9.0%, respectively. The differences are equal to 632 pcm and 661 pcm of reactivity. It is considered high compared to the maximum error of ½β, which is about 350 pcm. It is due to a lack of burnup distribution data at BOC of this core. Only 22 out of 35 irradiated fuel elements have the measured burnup fraction data, while the remaining fuel elements are using the burnup fraction data from the BATAN-FUEL code. It is expected that the burnup distribution may slightly differ depending on the operation history, including the control rod insertion position. Therefore, the multicycles core burnup analysis is required to get a more accurate burnup distribution.

The integral reactivity worth of each CR in the 88th core are shown in Figs. 5–12 and summarized in Table 7. For the control rod worth calculation, the number of neutron histories per cycle

Table 7
Experimental and calculated total CR worth.

Control Rod	Experiment (Cents)	ENDF/B-VII.1 (Cents)	ENDF/B-VIII.0 (Cents)
JDA01	204.25 ± 12	222.79 ± 6.63 (9.1%)*	211.16 ± 6.60 (3.4%)
JDA02	224.75 ± 13	237.00 ± 6.98 (5.4%)	239.57 ± 6.88 (6.6%)
JDA03	243.75 ± 14	243.01 ± 6.86 (0.3%)	240.68 ± 6.89 (1.3%)
JDA04	241.10 ± 13	240.61 ± 6.89 (0.2%)	254.84 ± 6.91 (5.7%)
JDA05	234.50 ± 13	241.99 ± 6.91 (3.2%)	233.07 ± 6.88 (0.6%)
JDA06	182.75 ± 10	203.37 ± 6.13 (11.3%)	195.51 ± 6.01 (7.0%)
JDA07	242.95 ± 13	249.33 ± 6.86 (2.6%)	244.73 ± 6.87 (0.7%)
JDA08	181.30 ± 10	196.53 ± 6.06 (8.4%)	205.16 ± 6.24 (13.2%)

*(C-E)/E*100%.

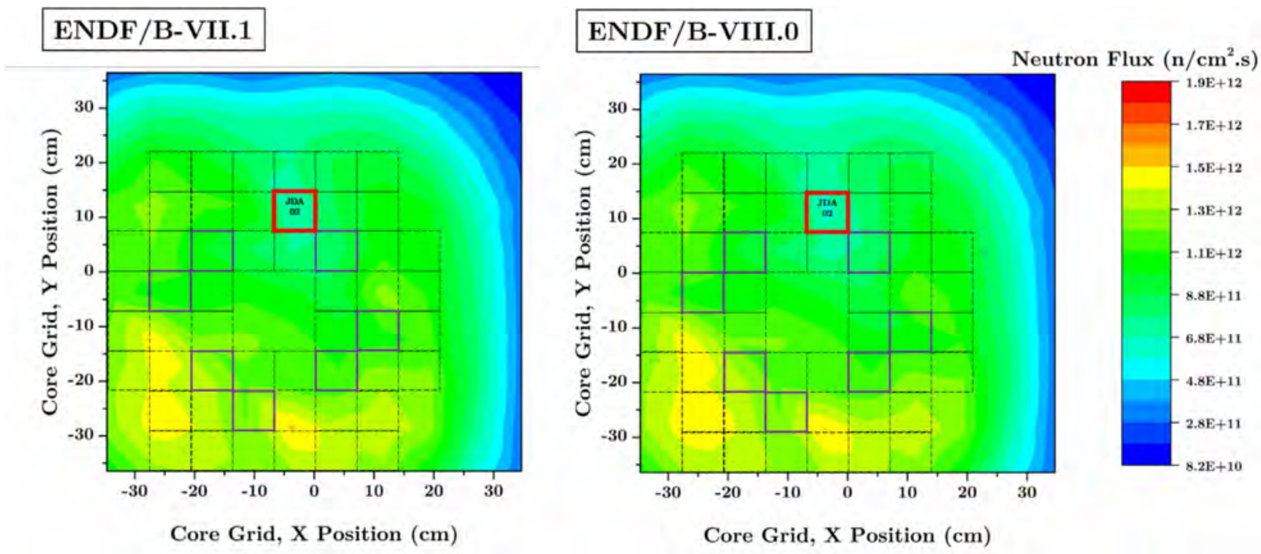

Fig. 13. Total neutron flux distribution at the initial positions of JDA-02 (0 mm) and JDA-06 (600 mm).

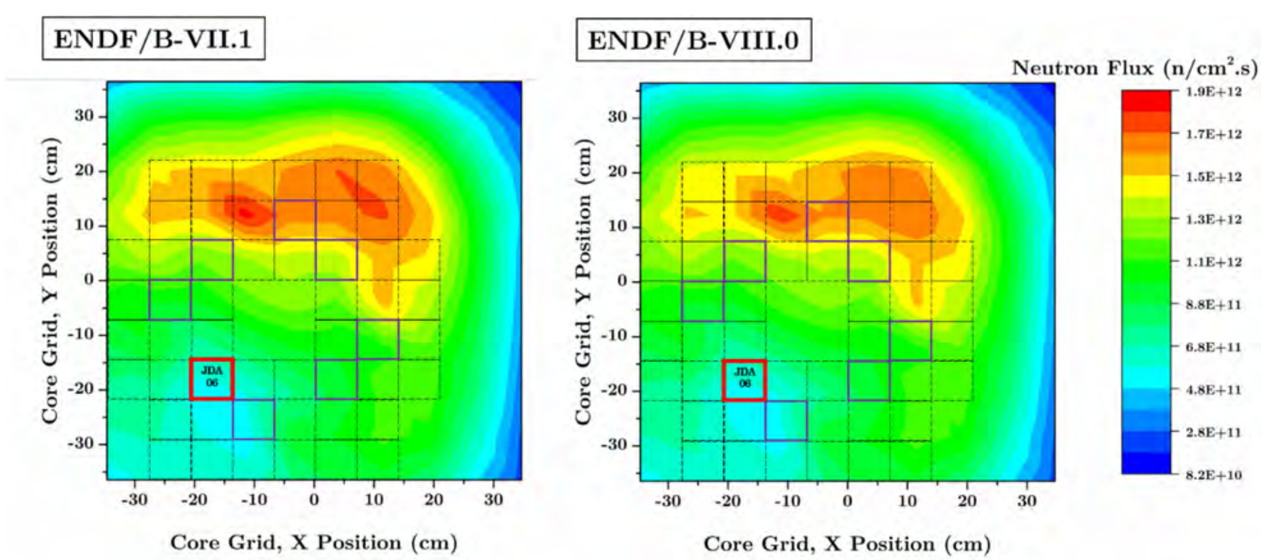

Fig. 14. Total neutron flux distribution at the final positions of JDA-02 (600 mm) and JDA-06 (0 mm).

is increased to 200,000, and the total number of cycles is 600 with 100 inactive cycles, resulting in a *k* value with a standard deviation of less than 9 pcm. The smallest difference between calculations and experiments for the integral CR worth is for JDA-03 (Fig. 7), followed by JDA-07 and JDA-05. It is also shown that the different nuclear data have less impact on these 3 control rods. However, the largest difference between calculations and experiments for the integral CR worth is shown in JDA-06 and JDA-08 (Figs. 10 and 12). Based on the Figs. 5–12, it is clear that the nuclear data of ENDV/B-VII.1 and ENDV/B-VIII.0 give the difference result on the integral CR worth of JDA-01, JDA-04, JDA-06 and JDA-08. In this paper, the impacts of these libraries are expressed by the difference of the relative error of these libraries. Based on Table 7, the relatively higher impacts are in JDA-01, JDA-04, JDA-06 and JDA-08 with the difference of 6%, 5.5%, 4.3% and 4.8%, respectively. The rest are within 1% – 2,6%. However, none of these nuclear data can give the consistently relative error closer with experimental results. For example, the calculated worth of JDA-04 using ENDF/B-VII.1 is closer to experimental worth than the worth of ENDF/B-VIII. On the other hand, the calculated worth of JDA-01 using ENDF/B-VIII.0 is closer to the experimental worth. It should be noted that the rod worth in dollars or cents is calculated by using the adjoint-weighted total effective delayed neutron fractions calculated by Serpent2.

The total control rod worth of each CR is summarized in Table 7. Compared to the experimental worth, the calculated results using ENDF/B-VII.1 nuclear data provide an average relative error of 5.1%, while a smaller difference is provided using ENDF/B-VIII.0 with the average relative error of 4.8%. It is consistent with the OPAL research reactor results in which ENDF/B-VIII.0 was shown to have a better agreement (Maul, 2018).

Figs. 13–16 illustrate the total neutron flux distributions at the initial and final conditions in each core grid during the rod worth calibration, such as JDA-02 vs. JDA-06 (Figs. 13 and

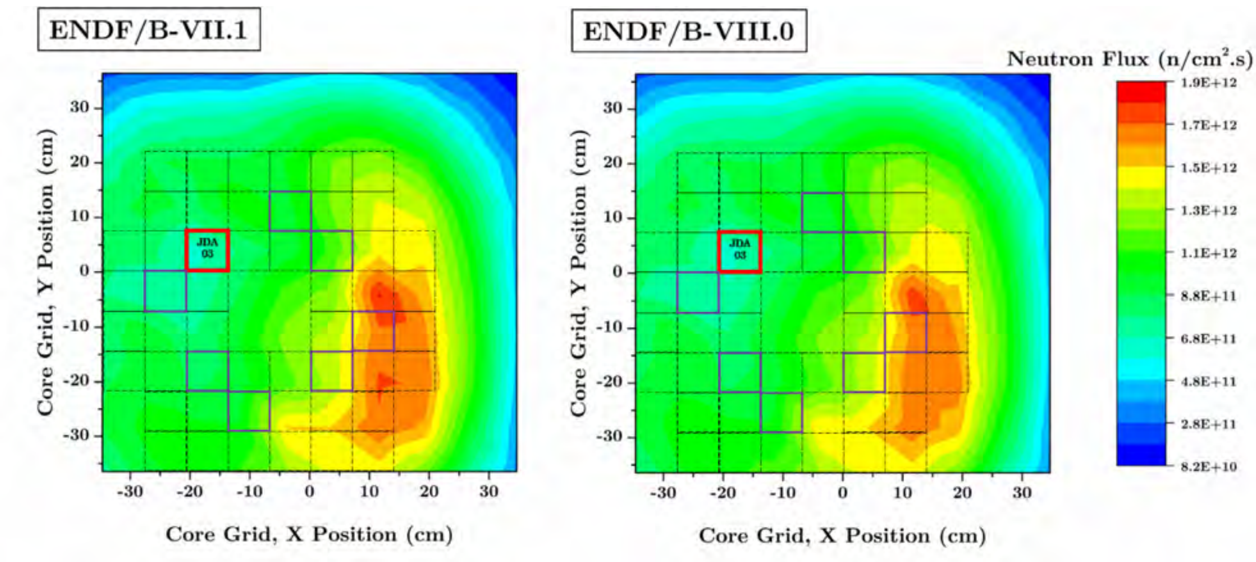

Fig. 15. Total neutron flux distribution at the initial positions of JDA-03 (0 mm) and JDA-07 (600 mm).

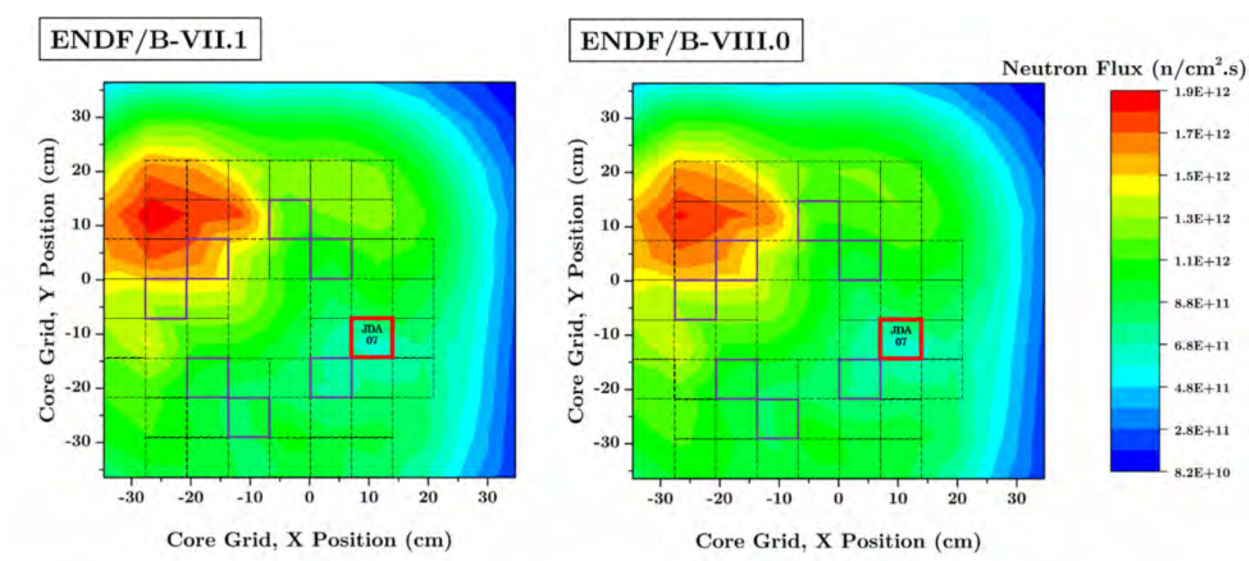

Fig. 16. Total neutron flux distribution at the final positions of JDA-03 (600 mm) and JDA-07 (0 mm).

14) and pair of JDA-03 vs. JDA-07 (Figs. 15 and 16). For the pair of JDA-02 and JDA-06, the neutron flux is high at the bottom part of the core at the initial condition (Fig. 13). However, it shifts to the upper part of the core in the final condition (Fig. 14). Meanwhile, the high neutron flux in the pair of JDA-03 and JDA-07 is at the right side of the core initially, but it shifts only to the upper left part of the core in the final condition. It confirms that the control rod interaction in the RSG-GAS is high, as analyzed in the previous work (Liem et al., 2002). Additionally, it is found that the maximum absolute difference of total neutron flux in each mesh grid between the two nuclear data is about 5.6%.

The burnup distribution at EOC is depicted in Fig. 17. Three calculated values for each FEs and CEs are shown; the first, second, and third rows are the calculation results by Serpent2 with ENDF/B-VII.1, Serpent2 with ENDF/B-VIII.0 and BATAN-FUEL code, respectively. BATAN-FUEL results are similar to the Serpent2 with the ENDF/B-VII.1 for the 2nd – 8th burnup classes. However, for the 1st burnup class of FEs at A-9, C-3F-3, H-4, and H-9 grid positions, the calculated burnup by Serpent2 code is higher than the BATAN-FUEL calculation results. This is due to the higher fission reaction rates (cf. Fig. 18) by the Serpent2 at those grid positions higher than the BATAN-FUEL calculation results, as shown by the higher power peaking factor. However, for the 2nd – 8th burnup classes of FEs, the burnup rate in the Serpent2 is lower than in the BATAN-FUEL code since the burnup change is not high compared to the 1st burnup class, although the power peaking factor is slightly higher.

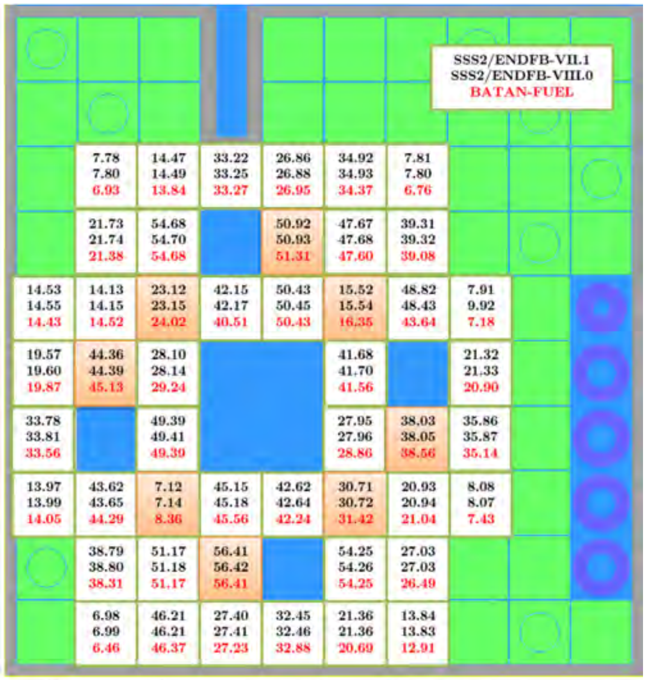

Fig. 17. Calculated burnup distribution (% loss of U-235) by Serpent2 code and BATAN-FUEL code at EOC.

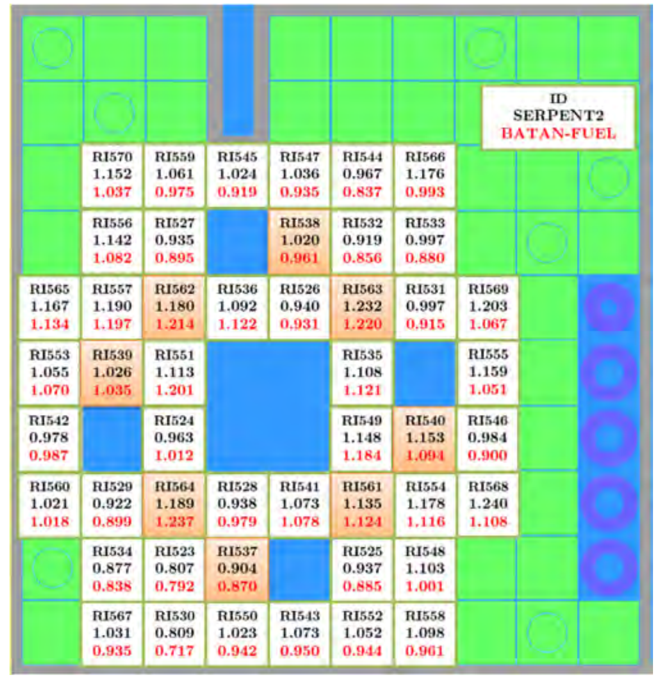

Fig. 18. Calculated power peaking factor by Serpent2 code and BATAN-FUEL code.

5. Conclusions

The experimental/measured core parameters of the RSG-GAS 88th equilibrium core, including the excess reactivity, integral control rod worth, and total control rod worth, have been confirmed by using continuous energy Monte Carlo Serpent2 code with 2 different nuclear data libraries: ENDF/B-VII.1 and ENDF/B-VIII.0. A more detailed configuration and accurate composition were used in Serpent2, such as the explicit modeling of the neutron beam tubes, impurity in the Be reflector, and the Be reflector's depletion. It is found that the relative difference between the calculated and experimental excess reactivity is about 9% or equivalent to 661 pcm, which is considered to be high. However, the calculated integral control rod worth provides a good agreement with the experimental results. The calculated total control rod worth also concurs with the experimental results. The maximum relative difference for the control rod worth is about 11.3% for JDA-06 by ENDF/B-VII.1 and about 13% for JDA-08 by ENDF/B-VIII.0. Meanwhile, the calculated burnup at EOC between BATAN-FUEL and Serpent2 agrees well, except for the 1st class burnup of FEs in which Serpent2 overestimates the burnup fraction by about 13%. This research also shows no significant impact of different nuclear data libraries, ENDF/B-VII.1 and ENDF/B-VIII, on the selected equilibrium core parameters such as the reactivity and the EOC burnup fraction. However, the significant discrepancy of JDA-06 and JDA-08 control rod worth by different nuclear data libraries deserves further investigation. Sensitivity analysis will be performed for these two cases. Moreover, to further improve the accuracy, multicycles core burnup analysis will be performed by considering the operation history, including the control rod insertion position.

CRediT authorship contribution statement

Tagor Malem Sembiring: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft. **Surian Pinem:** Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Writing - review & editing. **Donny Hartanto:** Methodology, Software, Formal analysis, Data curation, Visualization, Writing - review & editing. **Peng Hong Liem:** Conceptualization, Methodology, Writing - review & editing, Supervision.

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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