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Development of Burnup Fraction Calibration Curve for the Silicide Fuel Equilibrium Core of the RSG-GAS Reactor

S. Pinem[1*], F. Y. Sulistyo[1], P. H. Liem[2,3], A. A. R. Hakim[1], W. Luthfi[1]

[1]Research Center for Nuclear Reactor Technology, Research Organization for Nuclear Energy, National Research and Innovation Agency, Building 80th KST B.J. Habibie (PUSPIPTEK Serpong), South Tangerang,, Indonesia

[2]Cooperative Major in Nuclear Energy, Graduate School of Engineering, Tokyo City University (TCU), 1-28-1, Tamazutsumi, Setagaya, Tokyo, Japan

[3]Scientific Computational Division, Nippon Advanced Information Service, (NAIS Co., Inc.), 416 Muramatsu, Tokaimura, Ibaraki, Japan

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ABSTRACT

The reactivity value of the RSG-GAS research reactor fuel with different burnup levels has been measured. The primary objective of this study is to establish the burnup calibration curve using the equilibrium core reactivity method of the RSG-GAS reactor. The reactivity value of each fuel element was measured at the same position within the reactor core to ensure that the measured burnup corresponds to the experimental core. The reactivity value of each fuel element was then extrapolated with the known burnup of the fuel element. The total control rod worth measurement was compared with Monte Carlo Serpent2 code calculations. The experimental fuel reactivity results were compared with the calculation results, showing a maximum discrepancy of -4.88%. Based on the reactivity measurement and calculation results, a fuel burnup calibration curve was successfully developed, which can be used to determine the burnup fraction of the RSG-GAS reactor.

INTRODUCTION

The RSG-GAS reactor is a 30 MW research reactor of the open-pool type, utilizing light water as both a moderator and coolant. The reactor achieved first criticality in July 1987 and has been operating ever since. The current fuel used is silicide fuel (U_3Si_2--Al) with U-235 enriched to 19.75%. The equilibrium core configuration consists of 40 fuel elements and 8 control elements. The fuel and control elements are arranged into 8 burnup fraction groups, with an average Beginning-of-Cycle (BOC) burnup fraction of 23.3%burnup fraction and an End-of-Cycle (EOC) burnup fraction of 31.3%burnup fraction [1]. Each operational cycle has a duration of 25 days with 25 MW thermal power operation. The physical meaning of the %burnup fraction or burned U-235 fraction was also linear to the typical MWD/kg-heavy metal mainly used for a nuclear power reactor, with the earlier mainly used for a research reactor with U-235 as its initial fissile material. The analysis of RSG-GAS reactor operational safety parameters is essential to support the reliability and safety of reactor operations.

Several core parameters, such as fuel element burnup, are crucial for reactor operational safety, more efficient fuel utilization, and core performance. Burnup measurement can be conducted using various well-known methods [2]. These methods can be categorized into non-destructive and destructive techniques, such as the reactivity method, the fuel reactivity swap method, and the gamma-ray activity ratio method [3-6]. Burnup measurement of the RSG-GAS reactor fuel has been carried out using both destructive and non-destructive analysis techniques. The most accurate non-destructive method for fuel analysis is gamma spectrometry, which can be used to determine the composition of individual isotopes.

Non-destructive methods are the most used techniques for determining the fuel burnup of a research reactor [7–9]. The measured distribution of the Cs-134/Cs-137 activity ratio is used to estimate

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[*] Corresponding author.
E-mail address: suri001@brin.go.id
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the average fuel burnup. Destructive methods, on the other hand, involve dissolving the nuclear fuel and measuring the quantity of specific isotopes to determine burnup. In destructive analysis, the two primary isotopes targeted for measurement are U-235 and Cs-137 [10,11]. Both destructive and non-destructive methods require specialized equipment and extended measurement times. For the fuel that was still used in core operation, or many fuel elements need to be analyzed, destructive methods do not seem practical. Therefore, it is necessary to develop a method that is most suitable for determining fuel burnup in the RSG-GAS reactor.

The burnup measurement method based on reactivity effects requires a shorter measurement time, does not require specialized equipment, and eliminates the need for a hot cell for fuel transfer. The reactivity method can be performed under both subcritical and critical conditions. Fuel burnup measurement of the RSG-GAS reactor using the reactivity method in subcritical conditions has been conducted [12]. The objective of this study is to establish a fuel burnup calibration based on reactivity measurements at fixed positions within the core.

The reactivity value of a fuel depends only on its burnup, as its initial composition of the fuel element was identical, 250 g U-235 in the RSG-GAS fuel element. Since the fissile U-235 dominates the RSG-GAS core reactivity, while previous studies also show a linear correlation between fuel burnup and the neutron count on the fission counter [12], the linear correlation of the declared fuel burnup to the fuel reactivity was expected. By developing a fuel burnup fraction calibration curve, the fuel burnup can be determined by interpolating its reactivity value between two or more fuel elements with known burnup.

In this study, fuel reactivity measurements were conducted for three burnup fractions, ranging from low to high burnup. Measurements were limited to three fuel elements due to limitations on the number of fuel elements that could be removed from the RSG-GAS reactor core while maintaining criticality. Based on the experimentally measured reactivity curve and fuel burnup, the targeted fuel burnup can be determined by measuring the fuel reactivity. The experimental fuel reactivity was compared with calculations performed using the Serpent2 code [13]. Serpent2 is a three-dimensional, continuous-energy Monte Carlo particle transport code commonly used for various reactor physics applications, such as criticality calculations, spatial homogenization, fuel cycle studies, and reactor modelling [14]. The control rod reactivity calculation was performed using the ENDF/B-VIII.0 nuclear data library [15]. The evaluation of the control rod reactivity values was carried out for all step positions, as conducted in the experiment.

Equilibrium core of the RSG-GAS reactor

The RSG-GAS reactor initially operated with a Typical Working Core (TWC) using oxide fuel (U_3O_8-Al)). The reactor core was later converted to silicide fuel (U_3Si_2-Al) while maintaining the same fuel density as the oxide fuel. The conversion from oxide to silicide fuel was carried out through a transition core consisting of a mixture of oxide and silicide fuel elements [9,16]. During the design of the mixed-core transition, a new fuel management strategy was implemented to ensure that an equilibrium core was achieved once the reactor was fully loaded with silicide fuel. The fuel management strategy adopted after the full transition to silicide fuel follows a 5/1 loading pattern, where only five new fuel elements and one new control element are introduced at the Beginning-of-Cycle (BOC). Similar to the previous oxide fuel configuration, the equilibrium core is structured into eight burnup fractions [17,18].

The fuel element consists of 21 fuel plates; each composed of an AlMg2 cladding encasing a U_3Si_2 -Al fuel meat. The control element is designed in a fork-type configuration, consisting of two absorber blades with a width of 65 mm, a thickness of 5.08 mm, and an active length of 625 mm. The absorber plate material is made of AgInCd (80% Ag, 15% In, 5% Cd) with a thickness of 3.38 mm. The fuel and control elements are shown in Fig. 1, and the key parameters of the RSG-GAS equilibrium core are presented in Table 1. The RSG-GAS equilibrium core consists of 40 standard fuel elements and 8 control elements, arranged on a 10 × 10 grid plate with a pitch of 81.0mm × 77.1mm. The core is surrounded by reflector elements made of beryllium and aluminum, which are secured using stoppers. Beryllium reflector blocks are used as the primary reflector material surrounding the RSG-GAS reactor core. Figure 2 illustrates the configuration of six neutron beam tubes (S-1, S-2, S-3, S-4, S-5, and S-6) installed within the beryllium reflector blocks. The equilibrium core configuration is shown in Fig. 3.

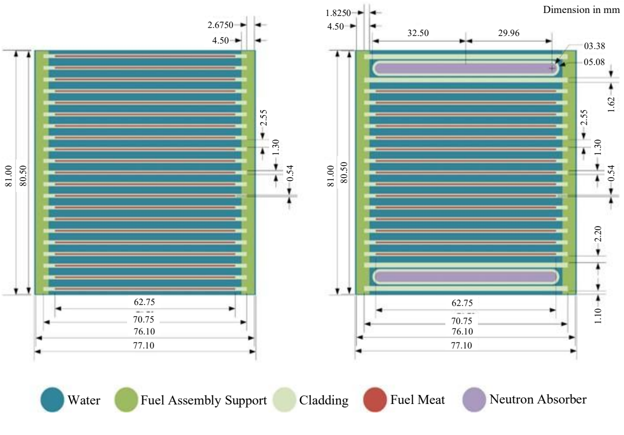

Fig. 1. Fuel element (left) and control element (right) of RSG-GAS (units in mm) [19].

Table 1. Reactor main design data of RSG GAS (silicide core)[20].

General parameters	Value
Reactor type	Pool type
Fuel element type	LEU silicide MTR
Cooling system	Forced convection downflow
Moderator/Coolant	H_2O
Reflector	Be & H_2O
Nominal power (MWth)	30
#fuel elements & #control elements	40 & 8
Nominal cycle length (FPD)	25
Average core burnup at BOC (%burnup fraction)	23.3
Average core burnup at EOC (%burnup fraction)	31.3
Average fuel discharge burn-up (%burnup fraction)	53.7
Fuel/control element dimension (mm)	77.1 × 81 × 600
Fuel plate thickness (mm)	1.3
Coolant channel width (mm)	2.55
#fuel plates per fuel element and control element	21 and 15
Fuel plate clad material	$AlMg_2$
Fuel plate clad thickness (mm)	0.38
Fuel meat dimension (mm)	0.54 × 62.75 × 600
Fuel meat material	U_3Si_2 in Al matrix
U-235 enrichment (w/o)	19.75
Uranium density in meat (g/cm^3)	2.96
U-235 loading per fuel element and control element (g)	250 and 178.57
Absorber meat material & thickness (mm)	Ag-In-Cd & 3.38
Absorber clad material & thickness (mm)	SUS-321 & 0.85

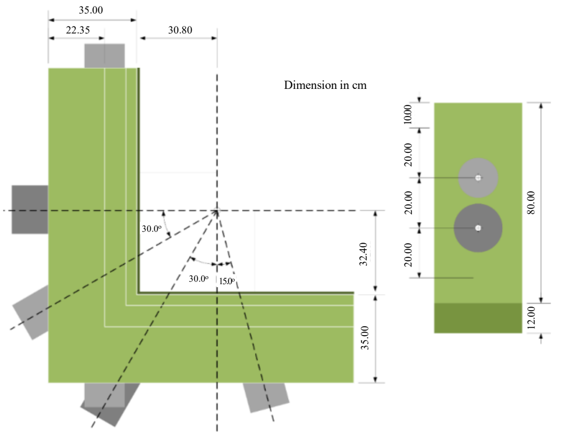

Fig. 2. Beryllium block reflector of the RSG-GAS reactor.

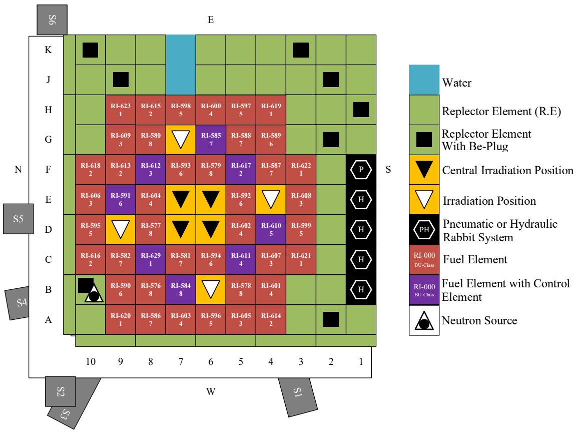

Fig. 3. Equilibrium core of the RSG-GAS reactor.

METHODOLOGIES

Control rod worth experiments

The reactivity worth of the control rods is determined using the reactivity meter method. Reactivity is measured through control rod calibration, where reactivity is expressed as a function of the control rod insertion length. Based on the point kinetics equation, it can be shown that if *P(t)* represents the power variation in a subcritical or supercritical reactor state, then the reactivity $\rho(t)$ can be calculated as Eq. (1).

$$\rho(t) = \beta + \Lambda \frac{d}{dt}[lnP(t)] - \beta \int_0^\infty d\tau\, D(\tau)P(t-\tau)/P(t) \qquad (1)$$

With *D(τ)* calculated as Eq. (2).

$$D(\tau) = \sum_j \frac{\beta_j \lambda_j}{\beta} e^{-\lambda_j \tau} \qquad (2)$$

where, β is the effective delayed neutron fraction, β_j is the jth group of delayed neutron fraction, λ_j is a decay constant of the jth group of delayed neutron precursors, and Λ is the effective neutron generation time. All quantities β, β_j, λ_j, and Λ are input parameters that have been determined beforehand [21]. The Power variation $P(t)$ was recorded as the signal amplitude taken from the neutron flux measuring channel JKT-04. The JKT-04 is a detector connected to a reactivity meter.

Reactivity measurements at various burnup fractions were conducted by removing three fuel elements from the core, as follows RI-620 (3.5%burnup fraction) from position A-9, RI-599 (31.5%burnup fraction) from position D-3, and RI-576 (52.5%burnup fraction) from position B-8. These measurements were limited to three fuel elements to ensure that the reactor remained critical during the experiment, while these three fuels could cover a wide range of burnup fractions, from low to high. The reactivity measurements for these fuel elements were performed at a fixed position, D-6, as shown in Fig. 3.

Control rods were identified using specific code numbers; for instance, JDA-01 refers to the control rod located at grid E-9. The reactivity measurement for each fuel element was carried out by determining the reactivity of the regulating rod (JDA-07).

Table 2. Control rod calibration position data of the second core at BOC.

Case	Control rod position (initial-final, mm)								Number of steps
	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	457 - 406	457 - 406	457 - 406	457 - 406	457 - 406	457 - 406	**0 - 600**	457 - 406	8
2	387 - 331	387 - 331	387 - 331	387 - 331	387 - 331	387 - 331	**0 - 600**	387 - 331	11
3	402 - 348	402 - 348	402 - 348	402 - 348	402 - 348	402 - 348	**0 - 600**	402 - 348	10
4	411 - 358	411 - 358	411 - 358	411 - 358	411 - 358	411 - 358	**0 - 600**	411 - 358	10

Control rod calibration was performed using the positive-to-negative reactivity compensation method with JDA-07 (regulating rod) withdrawn, while compensated by the other 7 control rods bank. The core temperature was maintained at 27°C during the measurements. Control rod worth experiments were conducted for 4 cases as follows:
Case 1: The initial step involved calibrating the regulating rod when the three fuel elements were removed from the core. During this calibration, the reactor was operated at a low-power, source-free condition to minimize reactivity feedback effects. At this stage, the calibrated JDA-07 (regulating rod) was inserted into the core (0 mm) while the control rods (CRs) bank (seven other control rods) was set to achieve criticality (457 mm). The JDA-07 was then gradually withdrawn with a reactivity of 10–20 cents for each step, while the control rod bank compensated for the reactivity. This process continued until the entire JDA-07 was withdrawn (600 mm) with a total of 8 steps. The positions of the regulating rod and the control rods bank during this experiment are summarized in Table 2. The number of steps shows the number sequence of giving positive reactivity (JDA-07 withdrawn) and negative reactivity (7 CRs bank inserted) within the range of 10-20 cents mentioned; *Case 2*: Then fuel element RI-620 (3.5%) was placed into position D-6, and the regulating rod was recalibrated using the same procedure: JDA-07 was fully inserted (0 mm) while all 7 CRs bank compensated at 387 mm. After 11 steps, JDA-07 was fully withdrawn, 600 mm; CRs bank was 331 mm.; *Case 3*: After completing the measurement for RI-620, the RI-620 was removed from position D-6, replaced with RI-599 (31.5%), and the JDA-07 calibration process was repeated. Initially, JDA-07 was at 0 mm while 7CRs were at 402 mm, and after 10 steps, JDA-07 was fully withdrawn (600 mm), and 348 mm for the 7CRs bank.; *Case 4*: The RI-599 was then removed and replaced by RI-576 (52.5%) at the same position as D-6, followed by the JDA-07 control rod worth calibration process. JDA-07 fully inserted 0 mm and 7CRs at 411 mm, while after 10 steps, JDA-07 was fully withdrawn (600 mm), and the 7CRs at 358 mm.

Table 2 also shows the number of steps for each calibration process, which corresponds to the number of control rod movements, such as JDA-07 withdrawn with a 10-20 cent range, followed by 7 control rods bank insertion, and so on. The regulating rod (JDA-07) worth experiments were conducted using the RSG-GAS reactivity meter, which has an uncertainty of ± 0.5 cent for each step.

Control rod worth calculation with serpent2

The Serpent2 model of RSG-GAS has been developed for the RSG-GAS equilibrium core, with its fuel element dimension and beryllium block reflector shown in Figs. 1 and 2. The core model has been used to calculate the excess reactivity and control rods' worth of the RSG-GAS equilibrium core [13]. For this study, the aforementioned serpent core model for RSG-GAS was used to follow the control rod calibration steps summarized in Table 2. The number of neutron histories per cycle was 200,000, with a total of 600 cycles and 100 inactive cycles. This setup yielded a k-value with a standard deviation of less than 9 pcm or ± 1.20 cent for calculated reactivity.

RESULTS AND DISCUSSION

The reactivity value of the fuel element was determined by calibrating the regulating rod both when the three fuel elements were removed from the core and when the fuel elements were inserted. The reactivity change was obtained from the control rod position change using the regulating rod calibration curve. The total control rod reactivity was then determined by summing all regulating rod calibration steps. The measured control rod calibration curves from experiments and Serpent2 calculations are presented in Figs. 4-7.

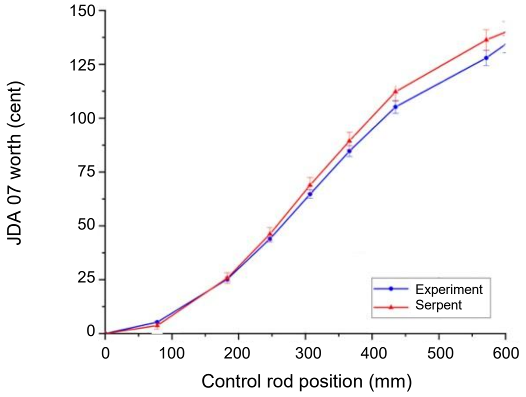

Fig. 4. The JDA-07 calibration curve when the three fuel elements were removed from the core.

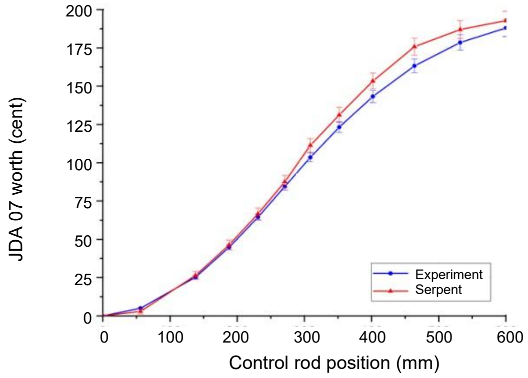

Fig. 5. The JDA-07 calibration curve with fuel element RI-620 positioned at D-6.

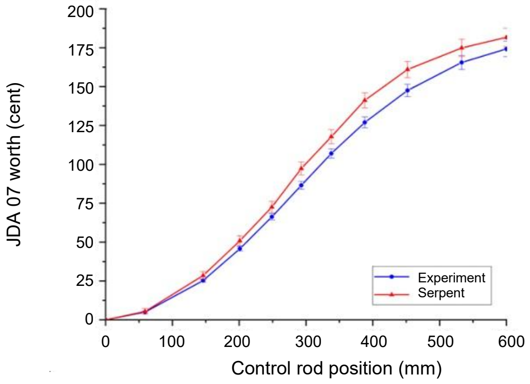

Fig. 6. The JDA-07 calibration curve with fuel element RI-599 positioned at D-6.

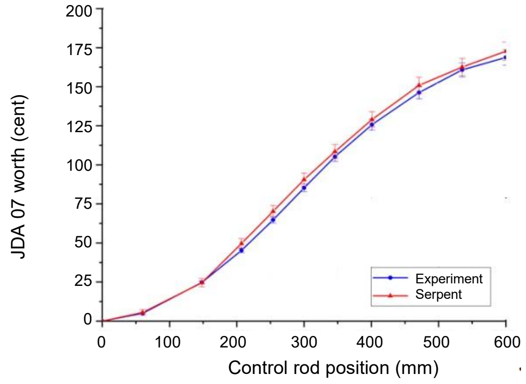

Fig. 7. The JDA-07 calibration curve with fuel element RI-576 positioned at D-6

The fuel element reactivity was determined based on the difference between the regulating rod worth when the corresponding fuel element was inserted into the reactor core, in this case at position D-6, to the regulating rod worth when the three fuel elements were removed. Let ρ_0 be the reactivity value of the regulating rod when the three fuel elements are removed, and ρ_1 be the reactivity value when fuel element RI-620 is at D-6 position in the core. The difference of (ρ_1-ρ_0) then represents the reactivity value of fuel element RI-620.

The total reactivity results from both measurements and calculations are presented in Table 3, which shows that the discrepancies between measurements and Serpent2 calculations of fuel element reactivity are within 4.59% to 4.88%. Both are lower than 5% with the source of discrepancies coming from the fuel composition being modeled with Serpent2 compared to the actual fuel elements in the core. Serpent2 used the declared burnup fraction for all 48 fuel elements in the core to calculate the fuel composition prior, while the declared burnup fraction was coming from the previous experiment (which has its own uncertainty), and the estimated burnup was calculated with the BATAN-FUEL. Hence, this result shows that the Serpent2 model can be used to estimate the fuel elements' reactivity by following the experimental methods being considered.

It should be noted that the fuel element reactivity being measured was specific to the core condition being developed during the experiment. Hence, the measured reactivity was specific to the fuel inserted into the D-6 position in the core. As the RSG-GAS used an equilibrium core with a 5FE + 1CE fresh fuel loading pattern in the core, the core parameters were maintained as long as the equilibrium core was maintained.

The linear relation between reactivity and burnup fraction from both measurements and calculations was then obtained as shown in Fig. 8. The burnup fraction calibration curve in Fig. 8 represents the relationship between reactivity (cent) on the y-axis, and fuel burnup (%burnup fraction) on the x-axis. The burnup fraction linear regression equations from the experiment are $y = -0.39817x + 54.21638$, while $y = -0.40944x + 54.36534$ is for the Serpent2 calculation. Each linear regression indicates that the R^2 value is close to 1, demonstrating a strong correlation between reactivity and fuel burnup fraction. The burnup measurement method, which is based on a linear relationship between reactivity and burnup fraction, aligns with expected theoretical behavior. Figure 8 can therefore be used as a calibration dataset for burnup fraction in the equilibrium core of the RSG-GAS reactor.

Table 3. Total reactivity of the regulating rod.

Case.	Fuel element	Total reactivity of regulating rod (cent)		Reactivity of fuel element (cent)		Differences (%)
		Experiment	**Serpent2**	**Experiment**	**Serpent2**	
1.	3 fuels removed	134.35 ± 1.41	139.97 ± 4.94	-	-	-
2.	RI-620 (3.5%burnup fraction)	188.00 ± 1.66	192.79 ± 6.11	53.65 ± 2.17	52.82 ± 7.86	-1.55
3.	RI-599 (31.5%burnup fraction)	174.25 ± 1.58	181.70 ± 5.83	39.90 ± 2.12	41.73 ± 7.64	4.59
4.	RI-576 (52.5%burnup fraction)	168.75 ± 1.58	172.69 ± 5.86	34.40 ± 2.12	32.72 ± 7.66	-4.88

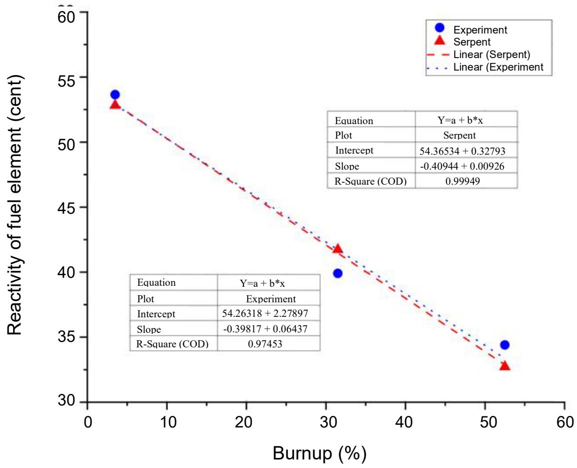

Fig. 8. Linear fitting of experimental and calculated data.

CONCLUSION

The reactivity values of fuel elements with different burnup fractions in the RSG-GAS research reactor were measured using the reactivity method at a fixed position under critical conditions. The measured fuel reactivity values were compared with calculations using Serpent2. The primary assumption in this experimental validation was that the reactivity change due to burnup is linear. The quality of the linear relationship between reactivity and burnup fraction was evaluated using linear regression analysis, and the results showed an R^2 value close to one, indicating strong linearity. The reactivity values calculated with Serpent2 were in good agreement with the experimental measurements. Based on these findings, it is concluded that reactivity measurements can be reliably used to determine the burnup fraction of the RSG-GAS equilibrium core.

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AUTHOR CONTRIBUTION

Surian Pinem: Conceptualization, Experiment, Validation, Data Curation, Formal Analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. Farisy Yogatama Sulistyo: Visualization, Formal Analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing. Peng Hong Liem: Methodology, Formal Analysis, Software, Writing - Review & Editing. Abdul Aziz Rohman Hakim: Formal Analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing. Wahid Luthfi: Visualization, Formal Analysis, Writing - Original Draft, Writing - Review & Editing. All authors read and approved the final version of the paper.

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