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Research Article

An Improved Steady-State and Transient Analysis of the RSG-GAS Reactor Core under RIA Conditions Using MTR-DYN and EUREKA-2/RR Codes

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Steady-state and transient analysis of reactor core under Reactivity-Initiated Accident (RIA) conditions are important for reactor operation safety. The reactor dynamics are influenced by neutronic and thermal-hydraulic aspects of the core. In this study, steady-state and transient analysis under RIA conditions of the RSG-GAS multipurpose reactor was carried out using MTR-DYN and EUREKA-2/RR programs. Neutronic calculations were performed using a few group cross-sections generated by Serpent 2 with the latest cross-section data ENDF/B-VIII.0. Steady-state conditions were carried out with a nominal power of 30 MW, while transient under RIA conditions occurred because the control rod was pulled too quickly while the reactor operated. These transient RIA conditions were performed for two cases, during start-up with an initial power of 1 W, and within power range with an initial power of 1 MW. Thermal-hydraulic parameters considered in this study are reactor power, the temperature of the fuel, cladding, and coolant. The calculated maximum fuel temperature at a steady state is 126.02°C. Meanwhile, the calculated maximum fuel temperature during RIA conditions at the initial power of 1 W and 1 MW are 64.38°C and 137.14°C, respectively. There are no significant differences in thermal-hydraulic parameters between each used program. The thermal-hydraulic parameters such as the maximum temperature of the coolant, cladding, and fuel under this postulated RIA condition are within the acceptable reactor operation safety limits.

1. Introduction

RSG-GAS is a research reactor located at the Science and Technology Research Center (Puspiptek) Complex Serpong—Indonesia, with a nominal thermal power of 30 MW that achieved its first criticality in July 1987. RSG-GAS reactor is a pool-type research reactor fueled with low enriched uranium, beryllium as a reflector, and light water as primary coolant and moderator. Initially, the fuel was uranium oxide (U_3O_8–Al) with a uranium density of 2.96 g U/cm^3 and enriched to 19.75%. However, to improve the performance of the reactor, its fuel was converted to silicide fuel of identical uranium density in 1999 [1, 2]. This multipurpose reactor is designed for radioisotope production, neutron activation analysis (NAA), nuclear reactor physics research, the study of materials characteristic of neutrons, and irradiation for the industry.

Under normal conditions, the reactor core cooling system uses forced circulation, and the coolant flows through the active core from top to bottom. The coolant flows into the active core via the coolant sub-channel from the plate-type fuel element. The reactor cooling system is also equipped with a natural circulation valve in the lower plenum. During its normal operation, heat generated in the core is removed primarily by the forced cooling system.

Reactivity-initiated accident (RIA) conditions are part of the important things to consider related to the safety of nuclear reactor operations because these conditions can cause an increase in the fission rate that increases reactor power and its temperature [3–6]. Typically, mechanical failure on the control rod driving mechanism can cause the control rod to pull out unexpectedly. As a result, the core reactivity will increase rapidly due to reduced neutron absorption and leading to power excursions. The direct impact of these power excursions is the destruction of the reactor core component, which can result in the release of radioactive materials into the environment in severe conditions. This accident is categorized as basic reactor design accidents for research and power reactors. The reactor design seeks to make the RIA probability as low as possible and design the core to respond as quickly as possible to stop the increase in reactor power if an accident related to this condition occurs. Steady-state analysis and transient RIA condition analysis of the RSG-GAS reactor have been carried out previously using various programs using a few group cross-section data of fresh fuel elements [7–10].

The RSG-GAS reactor in daily routine uses Batan-FUEL [11] and Batan-3DIFF [12] for its neutronic calculation related to fuel management. The cross-sections used by both mentioned programs were generated by WIMS/D-5 [13] using the ENDF/VII.0 cross-section library. After operating for 100 fuel cycles, the RSG-GAS cross-section (existing XS) data is updated to increase its capability to calculate neutronic parameters. The cross-sections were generated with Serpent 2 [14] using the latest cross-section library, ENDF/VIII.0. The few group cross-section data for the fuel region was generated using a two-dimensional lattice model. For the non-fuel region, it was directly generated from the three-dimensional core model. The calculation results of criticality and other neutronic parameters with these new cross-sections are better than the previous calculation [15]. For this reason, it is necessary to analyze the thermal-hydraulics behavior of the RSG-GAS reactor with these new cross-sections (new XS). This study aims to investigate the steady-state and transient under RIA conditions on the RSG-GAS core not to exceed the safety limit, further protecting the public from radioactive release. Calculations were performed using the MTR-DYN [16] and the EUREKA-2/RR codes.

A coupled 3-D program of neutronic and thermal-hydraulic, MTR-DYN, has been developed for the thermal-hydraulic evaluation of plate-type research reactors [6, 7, 17]. The time-dependent few group neutron diffusion problems are solved by factorizing the neutron flux using the adiabatic model. Some transient characteristics such as reactivity-initiated accident (RIA), reduced coolant flow rate, and several combinations of accident scenarios can be analyzed using the MTR-DYN code [16].

EUREKA-2/RR is a coupled thermal-hydraulics and point kinetics, which can analyze the transient phenomena of the reactor core as reactivity changes caused by pulling control rods, changes in coolant flow, and changes in coolant temperature. EUREKA-2/RR can also simulate fast transient behaviors in reactivity accidents [18].

FLUENT[19] has the capability to use the finite volume method to solve the governing equation on calculating the temperature of the model, which refers to the conservation of energy. Conservation of energy, as the first law of thermodynamics, stated that the total energy change in a system equals the difference between the heat transferred to the system and the work done by the system on its surroundings. The numerical conservation of energy also considers the state equation and its thermodynamic relations and can be solved numerically by FLUENT with supporting additional data such as the material properties of the fuel element, coolant water, the boundary condition (heat flux of fuel element, the temperature of coolant) and initial condition to start the iteration until reaching the convergence criteria.

On the other hand, EUREKA2/RR determines fuel temperatures (solid structure) by solving the heat generation in the fuel along a radial direction and considering it as one-dimensional heat conduction. Heat conduction is approximated by the finite-difference method.

MTR-DYN has also used the finite-difference method, but the module is developed specifically for Material Testing Reactor (MTR) calculations with single-phase coolant flow. Heat conduction equations in fuel rods are discretized in time and space using the finite-difference method. Heat conduction is considered only in the radial direction. Fluid dynamics are modeled under single-phase flow conditions. The mass flow rate in each coolant channel is assumed to be known and specified by a code user. As a result, we need to solve only mass continuity and energy conservation equations. They are discretized in space using the finite-difference method and in time by the implicit scheme.

The steady-state calculations performed by COOLOD-N2 [20] program will be used as a reference to compare the MTR-DYN [16], EUREKA-2/RR [20], and FLUENT [19] calculation results. While for transient under RIA conditions, the MTR-DYN and EUREKA-2/RR calculation results were compared against each other. The aim is to validate the approach of both thermal-hydraulic calculation models through code-to-code comparison.

2. Equilibrium Core of RSG-GAS

The latest equilibrium core of the RSG-GAS reactor uses low-enrichment silicide fuel (U_3Si_2–Al) with a nominal power of 30 MW. The fuel elements are based on MTR technology, and each fuel element consists of 21 fuel plates. Each fuel plate consists of an $AlMg_2$ cladding material, which encloses the dispersed fuel meat U_3Si_2–Al [21]. A fork-type absorber blade is combined with a fuel plate to make a control element. Similar to the fuel element with 21 fuel plates, the control element comprises 15 fuel plates, and 3 fuel plates at each end of the fuel zone are removed to make space for the absorber blades. In addition, two aluminum plates replace two of the three removed fuel plates as a guide for the absorber blade. The standard fuel and control elements are shown in Figure 1 [22]. The equilibrium core

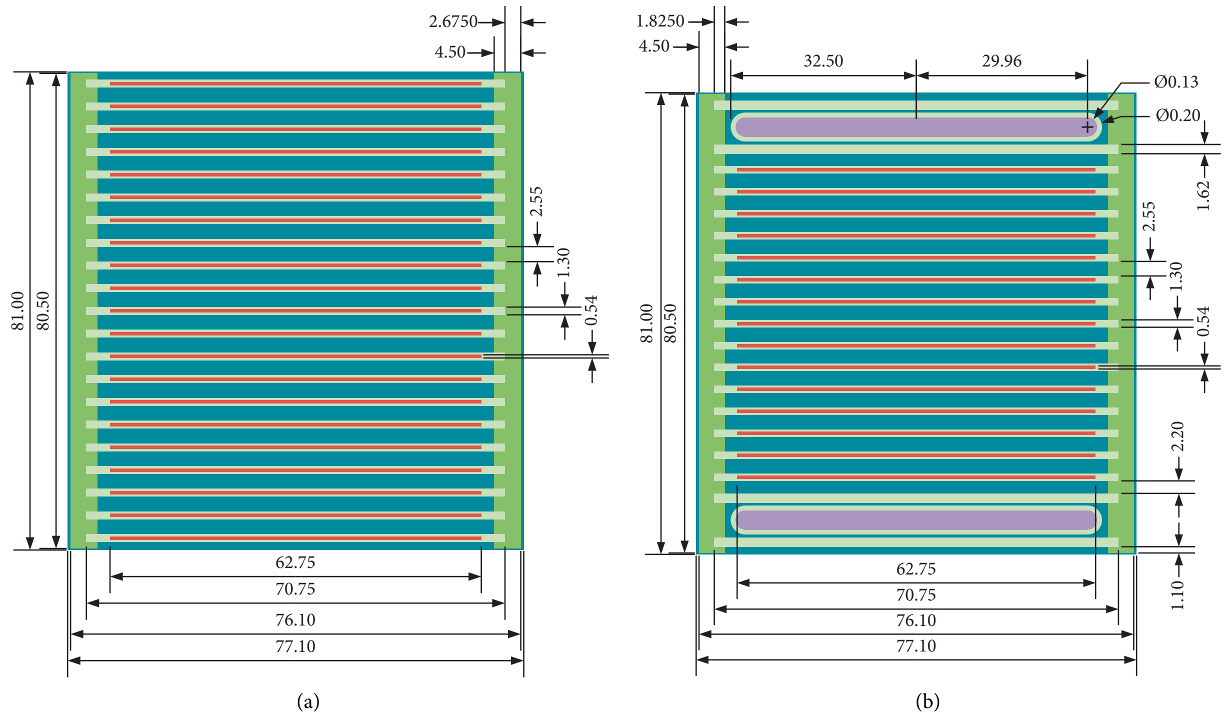

Figure 1: Standard fuel element (a) and control element (b) layout [22].

consists of 40 standard fuel elements and eight control elements arranged on a 10×10 grid with a pitch of 81.0 mm × 77.1 mm, surrounded by reflector elements, as shown in Figure 2.

The thermal-hydraulic analysis and evaluation of reactor design ensure that heat transfer is assured between the fuel cladding and the reactor coolant. This analysis also considers local variations for dimensions, generated power, and flow distribution. With its control and protection system, the reactor core ensures that the local peak power density does not cross the limit and cause fuel damage during normal or transient operation. Table 1 shows the nuclear design parameters of the RSG-GAS silicide core.

3. Methodology

RIA conditions related to continuous unintentional pulling of control rods due to equipment malfunction or operator mistake could be a potential hazard to the RSG-GAS reactor. This accident gives a positive reactivity, and as a result, reactor power would rise rapidly, so the reactor had to be tripped (SCRAM) by the Reactor Protection System (RPS). This protection system automatically shuts down the reactor as feedback to accidental positive reactivity insertion to protect the reactor core.

Transient analysis under RIA conditions was carried out on two reactor operation ranges, the start-up range, and the power range. In the start-up range, the reactor has an initial power of 1 W when the first trip signal for reactivity insertion is generated within a reactor period of intermediate-to-short (≤5 s) or within neutron flux density of intermediate-to-high (≥3%). The second trip signal that makes the reactor scram comes from the positive floating limit value that reaches the power range. Since the floating limit value on the power range will be effective after the power reaches ~15% of its nominal power (4.5 MW), the transient event will last long before the reactor scrams.

The transient analysis within the power range was carried out with 1 MW as initial power. The first trip signal comes from the floating limit value that is exceeded accidently. The second trip signal made the reactor scram when the power reading from compensated ionization chamber (CIC) instrumentation system exceeded 114% of the nominal power, 34.2 MW, due to high neutron flux.

For conservative transient analysis, reactivity insertion is determined from the integral control rod worth curve gradient, as shown in Figure 3. For the safety of operation, 15% integral reactivity is added so that the reactivity insertion will be 0.036385 $^{\$}$/s for existing cross-sections and 0.03038 $^{\$}$/s for new cross-sections with a control rod withdrawn speed of 0.0564 cm/s. The delay time between the first trip and the scram is 0.5 s, the control rod is fully inserted within 0.5 s, and the coolant inlet temperature is 44.5°C. Steady-state and transient calculations under RIA conditions are performed using the MTR-DYN and EUREKA-2/RR programs.

The MTR-DYN is a coupled neutronic and thermal-hydraulic program that has been developed to analyze the steady-state and transient under RIA conditions for an MTR-type reactor like the RSG-GAS reactor. MTR-DYN uses a few group cross-sections generated by Serpent 2 using the latest ENDF/B-VIII.0 library. Coupled neutron and thermal-hydraulic modules could give the best estimation of

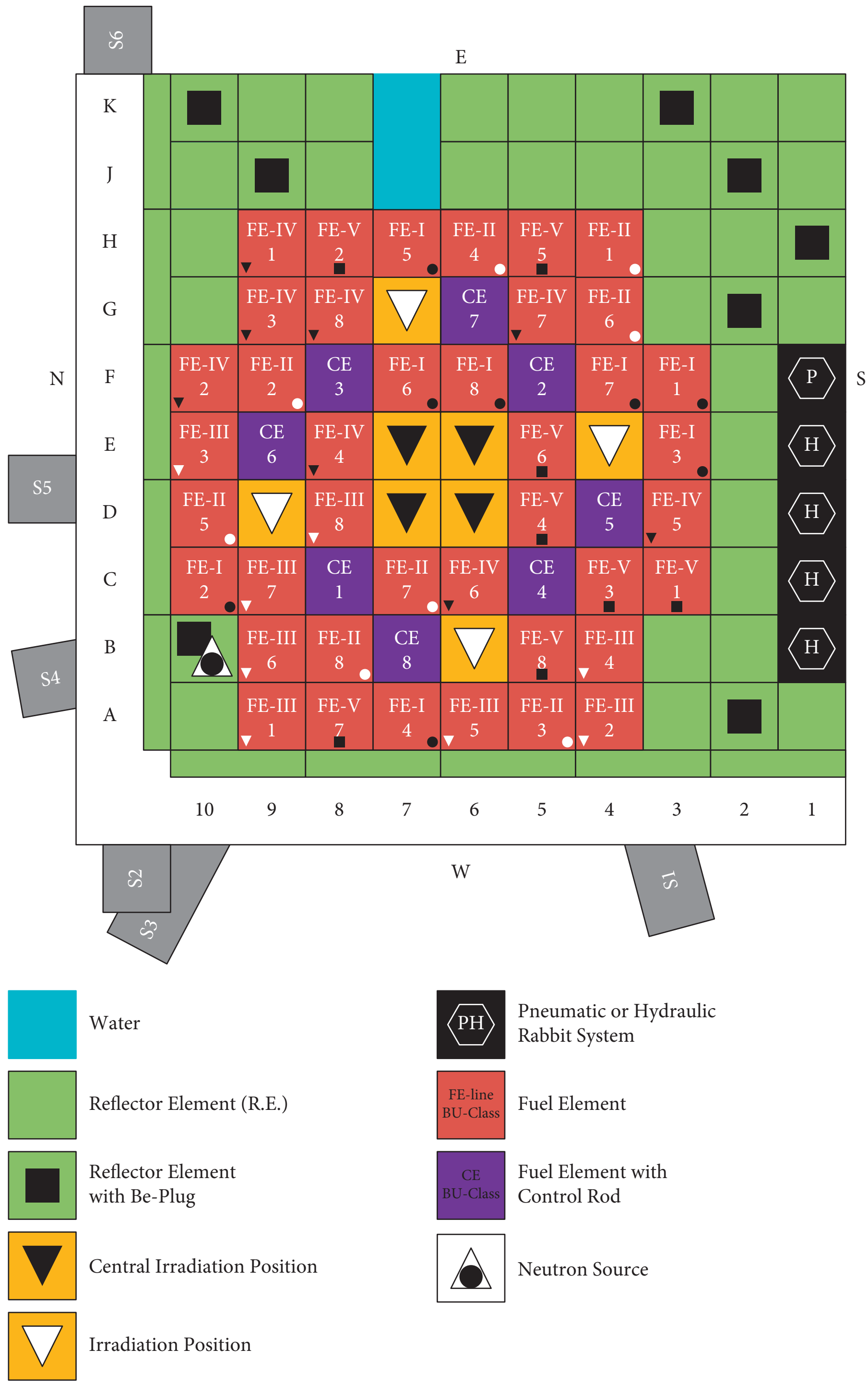

Figure 2: Equilibrium core of the RSG-GAS reactor [22].

fuel temperature, cladding, and also coolant. Figure 4 shows the schematic diagram of the MTR-DYN code.

In the neutronic calculation model of MTR-DYN, the spatial time-dependent multigroup neutron diffusion problem is solved by the flux factorization approach, where the spatial, time-dependent neutron flux is split into time-dependent amplitude and shape functions. The flux factorization approach demands a significantly shorter computation time than the direct calculation method without sacrificing the calculation accuracy.

The reactivity addition that triggers a criticality transient is simulated by perturbing the neutron cross-sections, which is very accurate for large reactivity addition such as control-rod withdrawal events. Therefore, the user is responsible for preparing the neutron cross-section sets for both the initial and perturbed conditions. Furthermore, the temperature

Table 1: Nuclear design parameters [22].

Types	MTR
Number of standard fuel elements at the typical working core	40
Fuel plates per standard fuel element	21
Number of fuel control elements at the typical working core	8
Fuel plates per fuel control element	15
Active length, (cm)	60
Type of fuel	U_3Si_2–Al
Enrichment, %	19.75
Uranium density in meat, (g/cm^3)	2.96
Cladding material	$AlMg_2$
Type of absorber	Fork type
Material absorber	Ag–in–Cd
Thickness (mm)	3.38
Cladding material	Steels
Thermal-hydraulic design	
Heat generation in reactor core, (MW)	30
Total flow rate of primary system, (kg/s)	860
Design value of minimum flow rate, (kg/s)	800
Effective flow rate for fuel cooling plates, (kg/s)	618
Nominal inlet temperature, (°C)	40.5
Average temperature increases in reactor core, (K)	10.7
Average outlet temperature in reactor core, (°C)	50.57
Outlet maximum temperature of the hot channel, (°C)	75.3
The surface area of fuel plates, (m^2)	72.29
Available heat flux, (W/m^2)	41.5 × 104
Maximum heat flux for normal operation, (W/m^2)	263.3 × 104

changes introduce Doppler feedback reactivity, fuel to moderator ratio changes, etc., which must be included in the cross-section sets if the code is to calculate the feedback reactivity. In the present version, to be consistent with the thermal-hydraulic calculation module, cross-section sets for a typical MTR-type research reactor are prepared so that users from research reactor utilities can readily execute the code. Users are free to replace the cross-section sets to simulate other types of research reactors.

Since several types of research reactors exist, in fact, there is no general module for thermal-hydraulic calculation. However, a more general neutronic calculation module can be employed. In the present version of MTR-DYN, a Material Testing Reactor (MTR) type thermal-hydraulic calculation module was developed to provide the users with (1) a means to validate the neutronic models adopted in the code and (2) a clear description of how to develop other thermal-hydraulic calculation modules suitable to treat various types of research reactors. In this case, we use the adiabatic solution on MTR-DYN to solve the neutronic and reactivity perturbation model.

EUREKA-2/RR also can perform transient analysis under RIA conditions since this program was developed to analyze the neutronic and thermal-hydraulic transient behavior of water-cooled research reactors with its thermal-hydraulic and point kinetic solver. EUREKA-2/RR can analyze the transient response due to changes in reactivity caused by control rods, changes in coolant flow, and changes

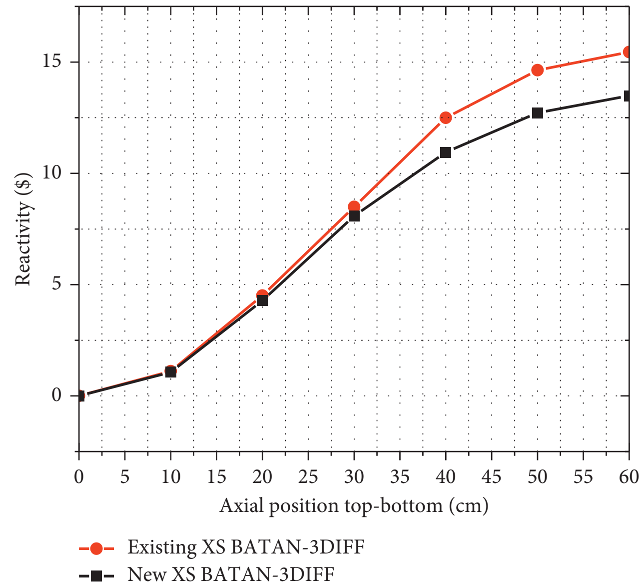

Figure 3: Integral control rod worth curve for reactivity insertion under transient conditions.

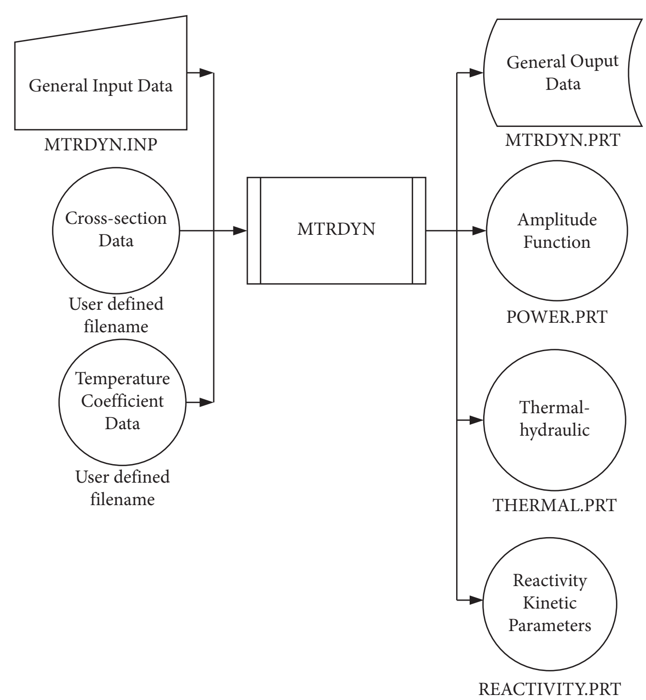

Figure 4: Flow chart diagram for MTR-DYN code [16].

in coolant temperature. Hence, it could also use to calculate a transient behavior under RIA conditions. In addition, time-dependent power generated can be calculated from the reactor kinetics equation with Doppler, moderator, and void reactivity feedbacks.

The RSG-GAS model on EUREKA2/RR consists of the fuel elements, upper plenum, and lower plenum only. The model includes 40 standard fuel elements and eight control fuel elements, but the central irradiation position (CIP) and beryllium reflector are not included. The core is then divided

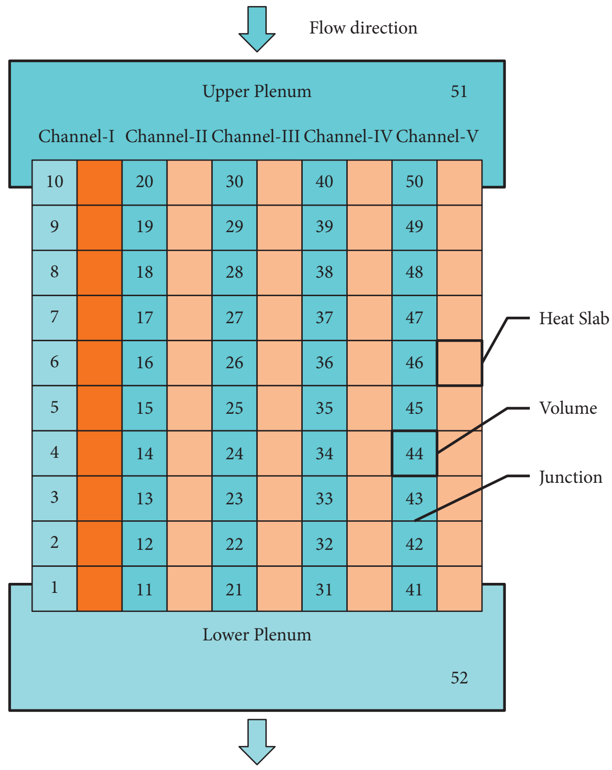

Figure 5: Schematic diagram of RSG-GAS model for EUREKA-2/RR.

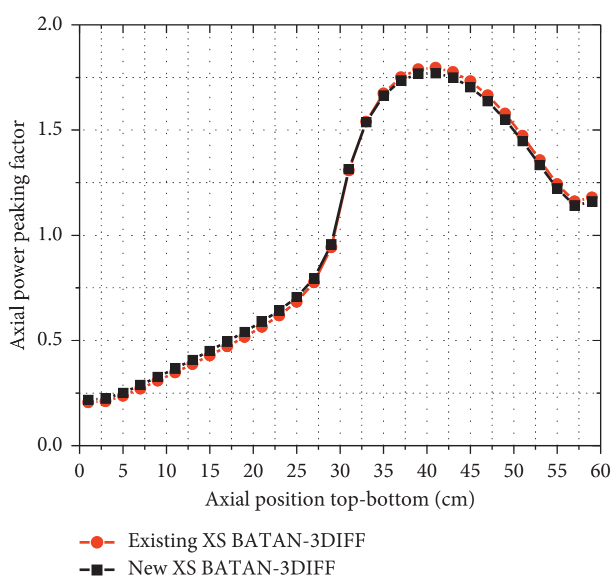

Figure 6: Calculated axial power peaking factor.

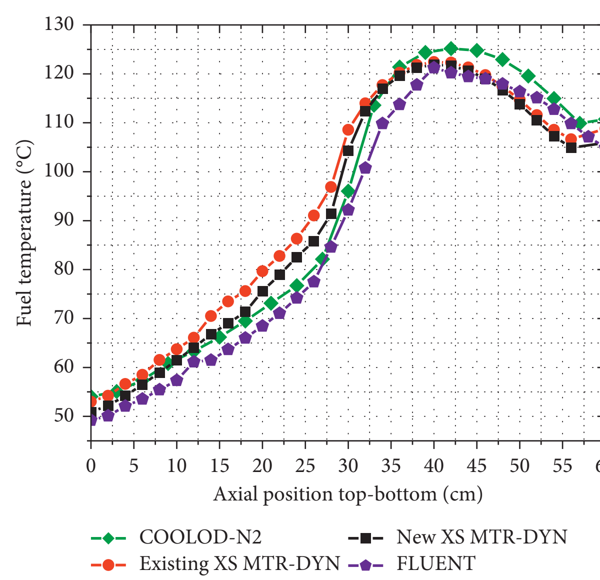

Figure 7: Calculated axial temperature distribution on RSG-GAS hot-channel.

into five heat channels; each has a different heat generation, as well as coolant mass flow rate and hydraulic diameter. Each fuel element is surrounded by a coolant that also acts as a neutron moderator. The heated slab represents a fuel plate, with Channel-I being the hottest sub-channel from a maximum radial power peaking factor, while Channel-II, Channel-III, and Channel-IV represent the average standard fuel element channel. Channel-V represents all eight control elements. Based on the axial power distribution factor, all channels are divided into 10 axial regions, with each region connected by a junction. Figure 5 shows the coolant flows from the upper plenum, which is then distributed to each volume channel that represents the active core and then flows to the lower plenum under normal conditions.

Table 2: Calculated thermal-hydraulic parameter on steady-state condition.

Hottest channel	COOLOD-N2	EUREKA-2/RR	Existing XS MTR-DYN	New XS MTR-DYN	FLUENT
Operating power, (MW)	30.0	30.0	30.0	30.0	30.0
Inlet coolant temp, (°C)	44.5	44.5	44.5	44.5	44.5
Max. Coolant temp, (°C)	68.63	67.92 (1.03%)*	67.01 (2.36%)*	66.29 (3.41%)*	66.82 (2.63%)*
Max. Cladding temp., (°C)	121.66	123.10 (−1.18%)*	121.44 (0.18%)*	121.62 (0.03%)*	121.26 (0.32%)*
Max. Fuel temp, (°C)	125.11	126.02 (−0.73%)*	122.41 (−2.15%)*	122.60 (2.01%)*	123.10 (1.60%)*
Saturation temp, (°C)	117.32	117.39	—	—	—
MDNBR	1.62	1.69	—	—	—

* (COOLOD-N2—Code)/COOLOD-N2 × 100%

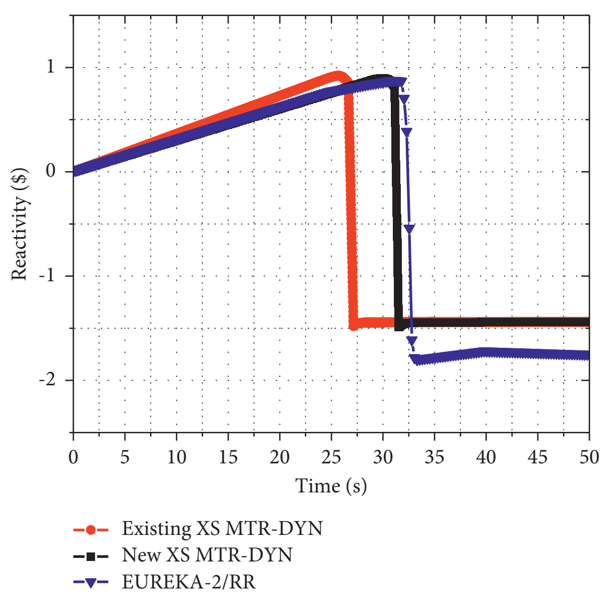

Figure 8: Reactivity inserted for RIA transient analysis within start-up range.

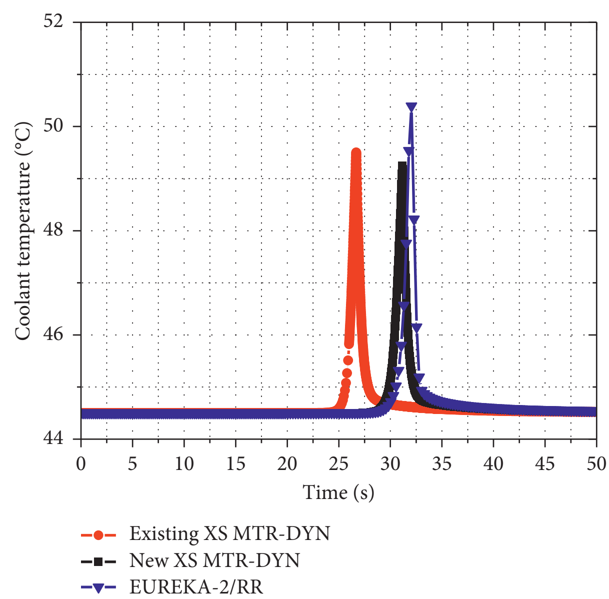

Figure 10: Coolant temperature during RIA transient at initial power 1 W.

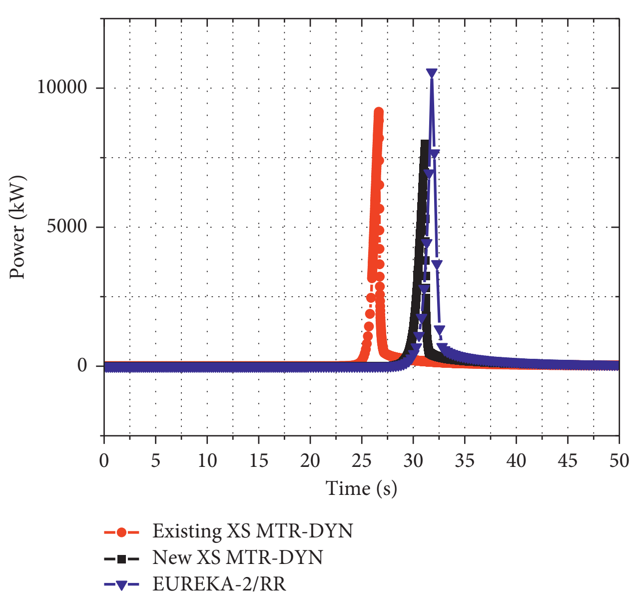

Figure 9: Reactor power response for RIA transient analysis within start-up range.

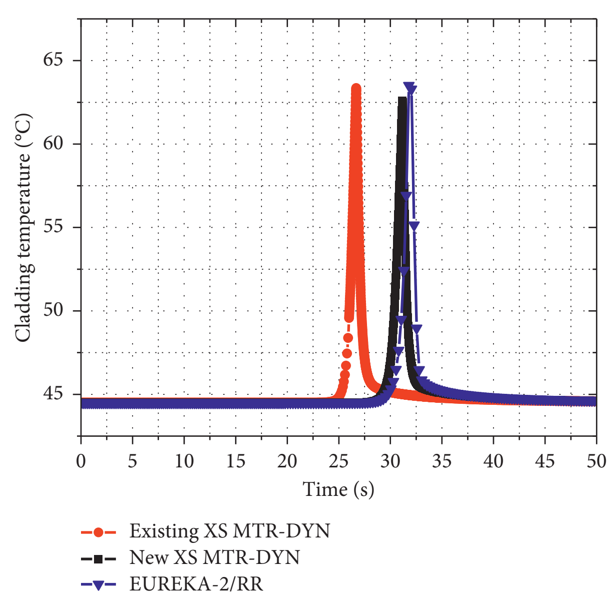

Figure 11: Cladding temperature during RIA transient at initial power 1 W.

To ensure the reliability of transient calculations, the steady-state parameters are referred to from the COOLOD-N2 calculation result. COOLOD-N2 code performs well on steady-state analysis for plate-type research reactors [18]. The code calculates fuel temperature in forced convection cooling mode. The axial fuel plate temperature distribution is calculated from a bulk coolant temperature and an axial power distribution. This code could calculate the onset nucleate boiling temperature, heat flux, and pressure drop in a reactor core. Neutronic parameter data such as kinetic parameters and reactivity coefficient were calculated by Batan-3DIF using cross-section data generated by Serpent-2. The axial power distribution from the neutronic calculation is shown in Figure 6. The axial power peaking factor of 1.745 occurs at the control rod inserted 30 cm into the core.

4. Result and Discussion

4.1. Steady State Thermal-Hydraulics. Thermal-hydraulic parameters were carried out on the RSG-GAS core at a nominal power of 30 MW, coolant with an inlet temperature of 44.5°C, and pressure of 1.8 bar. Under steady-state conditions, calculated thermal-hydraulic parameters include maximum coolant temperature, cladding temperature, and fuel temperature. Calculated axial fuel temperature distributions for the hottest channel are shown in Figure 7. The calculated maximum coolant temperature, cladding, and fuel under steady-state conditions by the COOLOD-N2 program are considered reference data. Furthermore, the calculation results of EUREKA2/RR, MTR-DYN, and FLUENT are shown in Table 2. Based on Table 2, COOLOD-N2 results are: the maximum coolant temperature is 68.63°C, the maximum cladding is 121.66°C, and the maximum fuel temperature is 125.11°C. The maximum fuel temperatures are still lower than the safety limit reported in the RSG-GAS Safety Analysis Report (SAR), which is 200°C [21]. The MRTDYN calculation results using the existing XS and the new XS are quite similar in trend, with fuel temperature from the top side of fuel to peak temperature being close to COOLOD-N2, but from peak temperature to the bottom side of fuel being close to FLUENT. EUREKA-2/RR gives a closer value relative to COOLOD-N2 because the axial temperature distribution calculated by COOLOD-N2 is used as an input by EUREKA-2/RR. Since MTR-DYN and FLUENT are using different approaches to treat the axial power distribution, a significant difference is shown in Table 2, but the difference is less than 3.5%. MTR-DYN and FLUENT are underestimating the maximum coolant temperature, cladding temperature, and fuel temperature. The Minimum Departure from Nucleate Boiling Ratio (MDNBR) is 1.62 and 1.69 using COOLOD-N2 and EUREKA-2/RR, respectively, which is greater than the MDNBR design criteria of 1.5 [20]. It means the reactor has adequate safety margins.

4.2. Transient Analysis

4.2.1. Inadvertent Control Rods Withdrawal in the Start-Up Range. The scope of this work is to improve the safety analysis of the RSG-GAS reactor under RIA conditions, in which the reactor protection system (RPS) with its safety feature must ensure the coolant flowing to the core does not boil. The transient analysis was carried out in the start-up range with an initial power of 1 W. A reactivity accident was assumed by pulling all eight control rods simultaneously at maximum speed until the reactor scram by RPS. During the reactivity accident, the reactor cooling system was assumed to remain operational. The used accident model has a reactivity insertion rate (control rod withdrawn) of 0.036385$/s for existing XS and 0.03038$/s for new XS. The total reactivity inserted into the reactor is shown in Figure 8, in which the positive reactivity increases until the signal level trips at 31.34 s (MTR-DYN) and 31.8 s (EUREKA-2/RR).

In this model, the reactor scram is due to the floating limit after reaching 15% of RSG-GAS nominal power, 4.5 MW. Based on Figure 9, which shows generated power on this start-up range transient analysis, it can be seen that the maximum power achieved is 10.57 MW after 31.8 s by EUREKA-2/RR. The calculation of MTR-DYN using the existing XS reaches its peak power of 9.14 MW after 26.66 s, and the new XS shows that the maximum power reaches 9.85 MW after 31.14 s. The relative difference between existing XS to new XS for calculated maximum power and duration to reach this value are 7.76% and 16.8%, respectively. The difference in maximum power and time to reach the maximum power between EUREKA-2/RR and new XS MTR-DYN is 7.30% and 2.11%, respectively. The increasing power trend shows a good agreement between the two codes, and it is due to the reactivity feedback that comes from the fuel element.

The temperature distributions of coolant, cladding, and fuel are shown inFigures 10–12, respectively. The calculated maximum temperatures for coolant, cladding, and fuel are 50.39°C, 63.51°C, and 64.38°C, respectively, calculated by EUREKA-2/RR. All maximum fuel temperatures remain below the melting point, and core integrity remains intact because the surface temperatures of the cladding are also lower than its melting point.

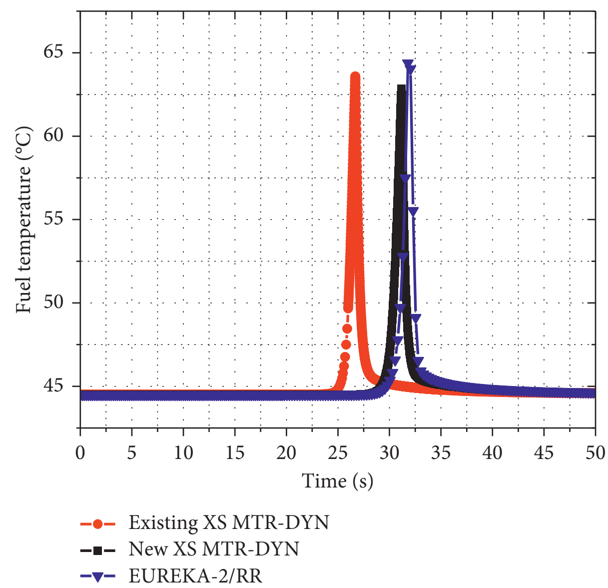

Figure 12: Fuel temperature during RIA transient at initial power 1 W.

Table 3: Maximum temperature of the coolant, cladding, and fuel element during RIA transient at initial power 1 W.

Parameters	Existing XS MTR-DYN	New XS MTR-DYN	EUREKA2/RR
Time of arrival of the scram power (s)	26.66	31.14 (16.80%)*	31.80 (19.27%)*
Peak power (MW)	9.14	9.85 (7.76%)*	10.57 (15.64%)*
Maximum coolant temperature (°C)	49.95	49.25 (−1.40%)	50.39 (0.88%)*
Maximum clad temperature (°C)	61.35	62.60 (2.03%)*	63.51 (3.52%)*
Maximum fuel temperature (°C)	61.62	62.84 (1.97%)*	64.38 (4.47%)*
MDNBR	—	—	8.90

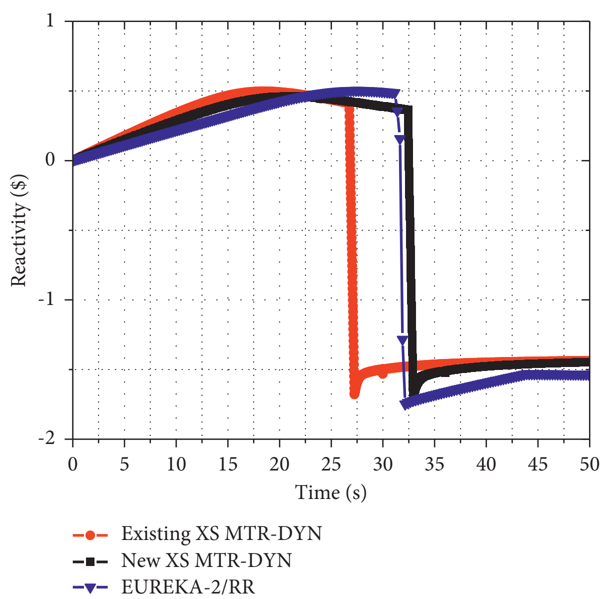

Figure 13: Reactivity inserted for RIA transient analysis within power range.

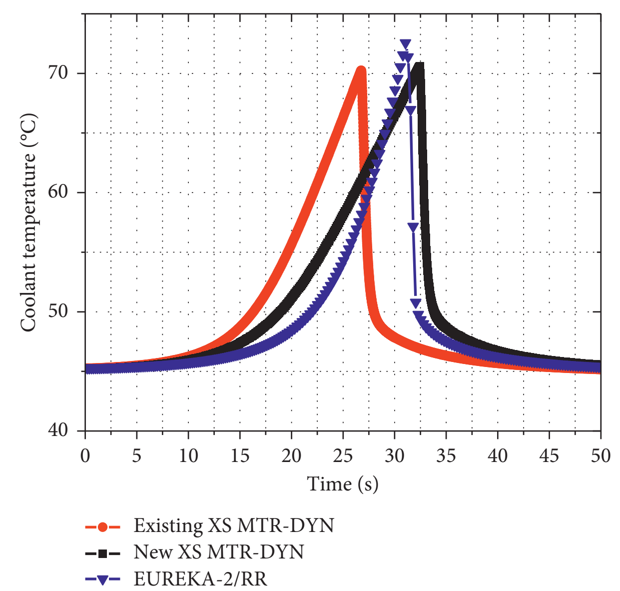

Figure 15: Coolant temperature during RIA transient at initial power of 1 MW.

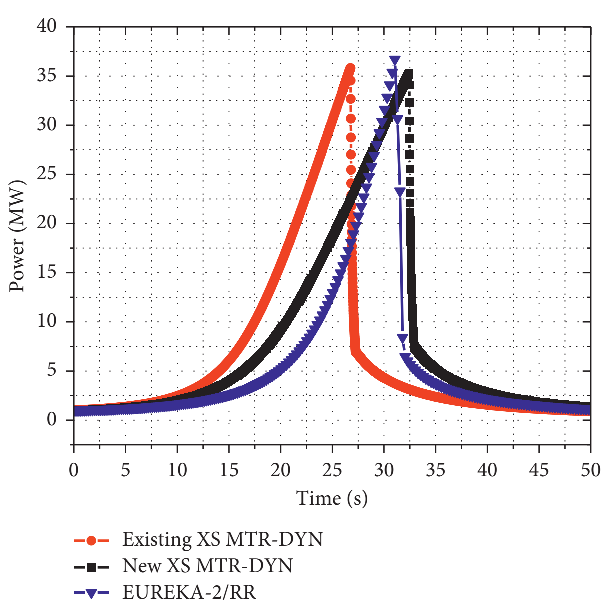

Figure 14: Reactor power response for RIA transient analysis within power range.

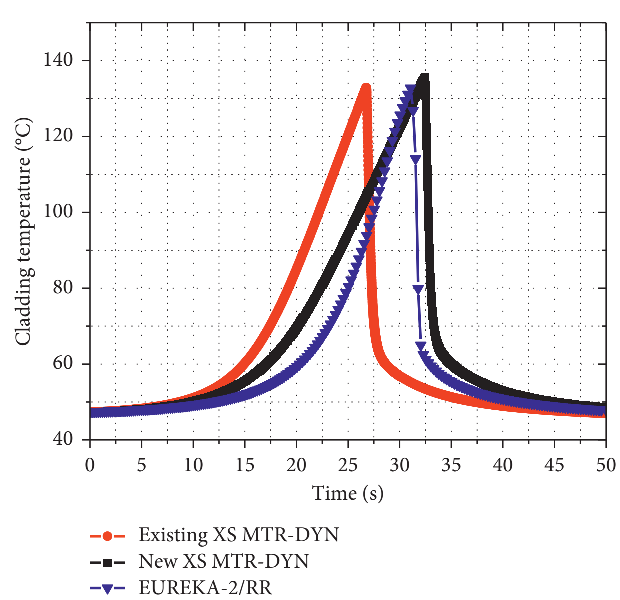

Figure 16: Cladding temperature during RIA transient at initial power of 1 MW.

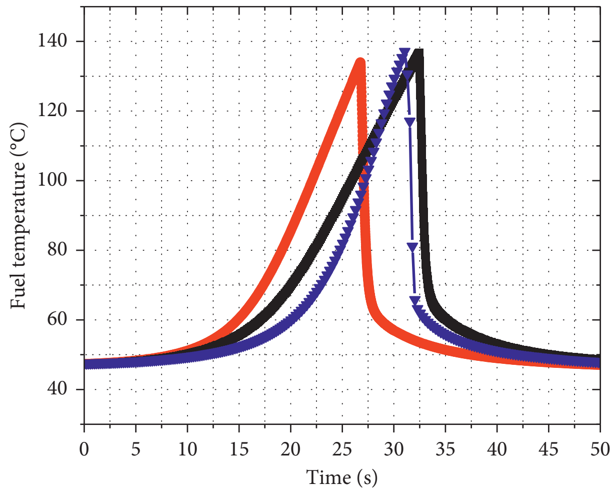

FIGURE 17: Fuel temperature during RIA transient at initial power of 1 MW.

TABLE 4: Maximum temperature of coolant, cladding, and fuel element during RIA transient at initial power of 1 MW.

Parameters	Existing XS MTR-DYN	New XS MTR-DYN	EUREKA2/RR
Time of arrival of the scram power (s)	26.76	32.43 (21.18%)*	31.05 (16.03%)*
Peak power (MW)	35.81	35.32 (–1.36)*	36.70 (2.48%)*
Maximum coolant temperature (°C)	70.24	70.60 (0.51%)*	72.57 (3.31%)*
Maximum clad temperature (°C)	132.85	135.53 (2.01%)*	132.76 (0.06%)*
Maximum fuel temperature (°C)	134.00	136.71 (2.02%)*	137.14 (2.34%)*
MDNBR	—	—	1.60

The calculated maximum temperature of coolant, cladding, and fuel elements is shown in Table 3. It shows that the coolant temperature is still lower than the coolant boiling point. The maximum fuel temperature is also far from the maximum limit from RSG-GAS SAR, which is 200°C [21]. The calculated maximum temperature of the coolant, cladding, and fuel elements under RIA conditions within the start-up range, with initial power of 1 W using MTR-DYN, there is a maximum relative difference of 2.03% between existing XS dan new XS. Comparing EUREKA-2/RR to MTR-DYN with existing XS, there is a maximum difference of 4.47% on the calculated maximum power. The coolant peak temperature calculated by MTR-DYN with the new XS is around 1.40% lower than MTR-DYN using the existing XS temperature. At the same time, cladding and fuel peak temperatures are higher than the MTR-DYN with existing XS by 1.97% and 2.07%, respectively. The calculated MDNBR by EUREKA-2/RR is 8.90, greater than the design criteria of 1.5, which means the transient in the start-up range is still within the operating safety limit.

4.2.2. Inadvertent Control Rods Withdrawal in the Power Range. The reactivity insertion within the power range, with an initial power of 1 MW, was simulated by pulling all the control rods from the core. After the power reached 114% of the nominal power, which was 34.2 MW, the reactor was scrammed by the RPS. The total reactivity insertion postulated, in this case, is shown in Figure 13. The transient reactor power is shown in Figure 14, which shows that after reaching 34.2 MW (trip signal), the power still rises continuously above the trip level due to the scram delay time of 0.5 s. The maximum power achieved is 35.81 MW after 26.76 s on MTR-DYN using existing XS and 35.32 MW after 32.43 s on MTR-DYN using new XS. The maximum power achieved was 36.70 MW after 31.05 s on EUREKA2/RR. There are 21.18% and 16.03% differences in calculated duration to the peak power of MTR-DYN with existing XS and new XS to EUREKA2/RR.

Figures 15–17show the temperature changes during RIA transient with an initial power of 1 MW on the hottest channel in the reactor core for coolant, cladding, and fuel temperature, respectively. The maximum temperatures for coolant, cladding, and fuel are 70.24°C, 132.85°C, and 134.00°C, respectively, which came from MTR-DYN using the existing XS. The maximum difference between MTR-DYN with existing XS and new XS to EUREKA2/RR is 2.02% and 3.31%.

The calculated maximum temperature from MTR-DYN and EUREKA2/RR is shown in Table 4, which shows the maximum coolant temperature of 72.57°C, still lower than the boiling temperature of the coolant. The maximum cladding and fuel temperatures are 135.53°C and 137.14°C, respectively, which are lower than the RSG-GAS SAR's temperature limit. In other words, the reactor core is still within a safe condition even if RIA conditions happened on power range, especially 1 MW. The MDNBR calculated by EUREKA-2/RR is 1.60 greater than the MDNBR design criteria of 1.5.

5. Conclusion

Steady-state analysis was carried out for the RSG-GAS reactor that operated at 30 MW thermal. The steady-state calculation was carried out with EUREKA-2/RR, MTR-DYN, and FLUENT and then compared to COOLOD-N2. The results show that the reactor operates within all operation safety limits, and there was no significant difference between MTR-DYN with the existing cross-section and the new cross-section, and also between each code compared. Transient analysis under RIA conditions at start-up range (1 W) and power range (1 MW) is also carried out by control rod fully withdrawn, which then automatically inserted (scram) after reaching power limit, under forced circulation mode. The results show that core power and maximum temperature of the fuel, cladding, and also coolant are still lower than the temperature limit of the RSG-GAS SAR report. The improvement in the calculation results with our new cross-section data is the same reactor safety outcome when the reactivity feedback is delayed in time compared to existing cross-section data, which gives more confidence in the worst-case scenario. In the end, the RSG-GAS could operate safely under postulated RIA conditions if only the reactor protection system works normally.

Data Availability

The research data cannot be shared due to privacy restrictions and can only be made available upon request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this study.

Authors' Contributions

Surian Pinem and Sukmanto Dibyo conceptualized the study, developed the methodology, provided the software, performed the formal analysis, wrote the original draft, and reviewed and edited the article. Wahid Luthfi wrote the original draft, performed data visualization, reviewed, and edited the article. Veronica Indriati Sri Wardhani developed the methodology and reviewed and edited the article. Donny Hartanto developed the methodology, performed the formal analysis, and reviewed and edited the article.

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