REACTIVITY INSERTION ACCIDENT ANALYSIS DURING URANIUM FOIL TARGET IRRADIATION IN THE RSG-GAS REACTOR CORE

by

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Analysis of the steady-state and reactivity insertion accident is very important for the safety of reactor operations. In this study, steady-state and reactivity insertion accident analysis when the low enriched uranium foil target is irradiated in the reactor core has been carried out. The analysis is carried out by the best estimate method by using a coupled neutronic, kinetic, and thermal-hydraulic code, MTR-DYN. The MTR-DYN code is based on the 3-D multigroup neutron diffusion method. The cell calculations for the target are carried out by the WIMSD/5 and MTR-DYN code. After reactivity insertion, the coolant, fuel, and clad temperature are observed. The calculation results for the initial power of 1 W showed that the maximum temperature of the coolant, clad, and fuel are 49.76 °C, 65.01 °C, and 65.26 °C, respectively. Meanwhile, when the reactivity insertion at the initial power of 1 MW, the maximum temperature of the coolant, clad, and fuel are 72.23 °C, 140.79 °C, and 141.97 °C, respectively. Based on those calculation results during irradiation low enriched uranium foil target, the temperature in the steady-state and reactivity insertion accident does not exceed the allowable safety limit.

Key words: reactivity insertion analysis, safety limit, low enrichment uranium foil, MTR-DYN code

INTRODUCTION

Reactor Serba Guna G. A. Siwabessy (RSG-GAS) is material testing reactor (MTR) type with a nominal thermal power of 30 MW and an average neutron flux of $2\ 10^{14}$ cm^2s^{-1}. The RSG-GAS reactor is used for research, isotope production, material testing, and neutron activation analysis. The facilities are utilized by the RSG-GAS reactor are one central irradiation position (CIP), four irradiation positions, five rabbit system facilities, a power ramp test facility, six beam tube facilities, and neutron doping transmutation. The RSG-GAS reactor is originally designed to use the low enriched fuel (^{235}U) of 19.75 % with an oxide fuel type (U_3O_8-Al) with a density of uranium of 2.96 gcm^{-3}. Since 2002, the reactor uses fuel silicide (U_3Si_2-Al) with the same density as the oxide fuel type [1].

The RSG-GAS reactor is utilized for the irradiation of some targets, such as the target of fission product molybdenum with the low enriched uranium (LEU), to produce the ^{99}Mo, $^{99/99m}Tc$, TeO_2, iridium, Sm_2O_3, Gd_2O_3, and MoO_3 [2, 3]. Currently, the RSG-GAS reactor irradiates the LEU electroplating target used for the production of the ^{99}Mo radionuclide in the core routinely. Previous research showed that the maximum mass of LEU electroplating targets of 72 g can be used in the reactor [3]. The market studies showed that the Asia Oceania region needs 380 000 Ci per year of ^{99}Mo [4-6] , while the domestic market needs 70 000 Ci per year of ^{99}Mo. Therefore, the LEU target becomes dominant in the utilization of the RSG-GAS reactor.

In optimizing the production of the ^{99}Mo radionuclide in the RSG-GAS reactor, some calculations should be carried out. Neutronic parameters have been obtained by using the in-house BATAN-3DIFF code. The code, already verified and validated for the first core of RSG GAS gave good results compared to the experiment [7]. The neutronic calculation result shows that the LEU foil target that can be irradiated is 108 g in the reactor core [8]. However, it is also necessary to perform a safety analysis such as the reactivity insertion accident (RIA) to ensure the irradiation fulfills the safety criterion. Usually, the RIA analysis is carried out by the hot-spot analysis [9-11], where the maximum radial and axial power peaking factors (PPF)

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are multiplied to be the hot spot factor. This factor is used to be the input of the kinetic-thermohydraulic analysis. The hot-spot analysis is a conservative approach, but it is not realistic because the position of maximum radial and axial PPF is not in the same location.

In this study, we proposed to use the best estimate method by using the coupled neutronic-kinetic-thermal hydraulic code. The realistic condition can be realized by the best estimate method [12, 13]. The objective of this study is to analyse the steady -state and the RIA condition during the maximum irradiation of the LEU foil target in the reactor core. We assumed that an accident is initiated by eight control rods simultaneously withdrawn with the maximum speed until the reactor protection system scrams the reactor, by dropping the control rods into the core. The safety criterion for the anticipated operational transients in the RSG-GAS is that the maximum fuel *meat* temperature in fuel *meat* is less than 200 °C and that no boiling occurs in the reactor core.

The steady-state and RIA parameters were calculated by applying WIMSD/5 [14] and MTR-DYN [15] codes, respectively. The MTR-DYN code has been developed for the safety analysis of a material research reactor (MTR) such as an RSG-GAS reactor. The macroscopic cross-sections were generated by using the WIMSD/5 code. The reactivity accident was carried out using the MTR-DYN code, a 3-D coupled neutronic-kinetic-thermohydraulic code [16]. The MTR-DYN code is a space and time-dependent, few group neutron diffusion-based on research reactor transient analysis code. The heat conduction equation in a fuel element as a function of time and space is solved by the finite-difference method, assuming heat conduction is only in the radial direction. Space functions are solved by finite difference methods and time functions with implicit schemes.

METHODOLOGY

Description of LEU foil target

The LEU foil target has dimensions of 7.6 cm × 8.8 cm × 0.0125 cm with a uranium enrichment of 19.8 %. The LEU foil is covered with 0.0015 cm thick nickel foil and placed between two aluminum tubes welded from both ends. The diameter of the inner and outer aluminum tubes is 2.621 cm, and 2.799 cm, respectively, and the length of the Al tube is 16.2 cm. The maximum weight of the target LEU foil that can be inserted into the tube is 3.0 g. The LEU foil targets are inserted into a rig that can contain three targets. The rig is inserted into the stringer, which has an inner diameter of 3.3 cm and an outer diameter of 3.6 cm. Uranium is arranged in capsules, as shown in fig. 1.

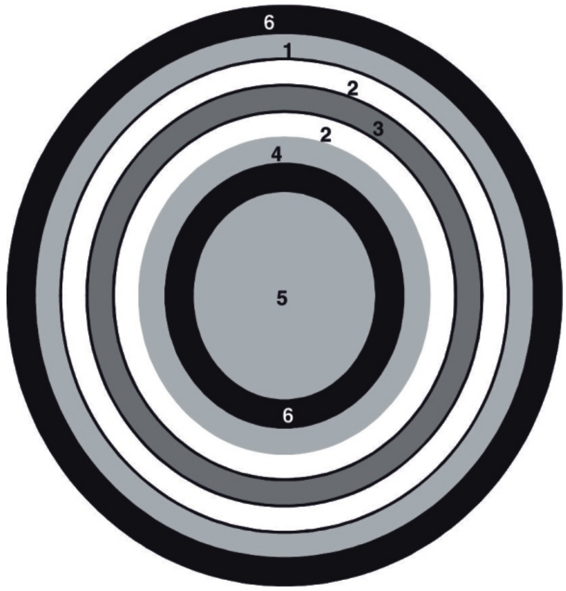

Figure 1. Drawing for the arrangement of uranium foil target irradiation at the reactor: *1 – aluminum, 2 – nickel, 3 – uranium foil, 4 – aluminum, 5 – aluminum rod, and 6 – water*

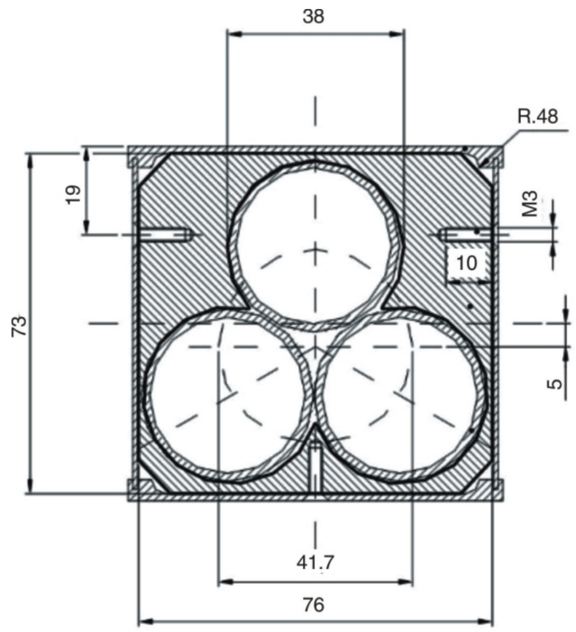

Figure 2. Stringer for irradiation of LEU target foil (units are in mm) [8]

The insertion of reactivity was carried out when the LEU foil target is in the RSG-GAS reactor irradiation facility. A stringer is used to accommodate a rig shown in fig. 2. The rig is placed into a stringer with a diameter of 3.3 cm and an outer diameter of 3.6 cm and can be occupied by nine targets maximally. The stringer is inserted into CIP (D-6, E-6, D-7, and E-7) with the number of LEU foil on the core as much as 108 g, as shown in fig. 3.

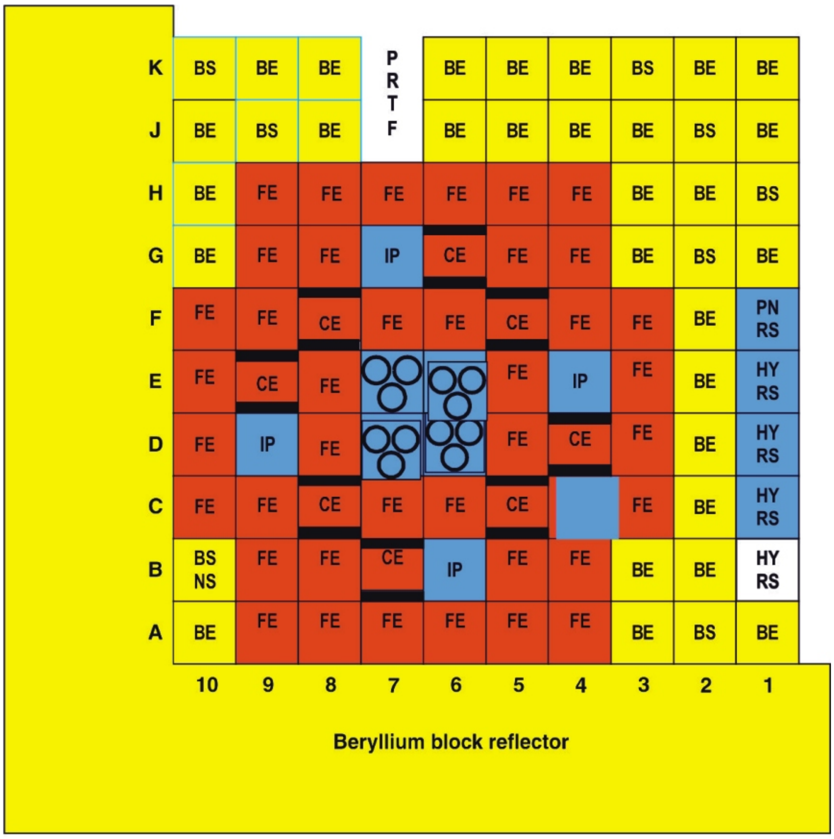

Figure 3. Configuration of the RSG-GAS reactor core [8], Note: FE – fuel element, CE – control elemet, BE – Be reflector element, BS – Be reflector element with plug, IP – iradiation position, CIP – central iradiation position, PNRS – pneumatic rabbit system, HYRS – hydraulic rabbit system, PRTF – power ramp test facility

Analytical code description

The MTR-DYN code [15] was designed to modeling the transient criticality behavior of a research reactor when the reactivity addition and primary cooling system disturbance occurs. The MTR-DYN code solves the space time-dependent multigroup neutron diffusion in the 3-D cartesian geometry coupled neutronic with a thermal-hydraulics module. The code consists of two main modules, *i. e*., the neutronic and kinetic calculation modules, and the thermal-hydraulic calculation module. The adiabatic model is used for the neutronic and kinetic calculations module.

The thermal-hydraulic module uses a sub-channel single-phase flow in a 1-D planar geometry model. The flow rate of cooling water in the downward direction and the equation of momentum and energy are resolved in the direction of the flow. Model of the 1-D heat transfer perpendicular to the direction of the water coolant flow is used to solve the conductive heat transfer inside the fuel plate and convective heat transfer between the surface of the fuel plate and the water coolant. Neutronic and thermal-hydraulic couplings allow the MTR-DYN code to accurately calculate coolant, fuel, and clad reactivity temperature feedback as well as density reactivity feedback. Space and time-dependent control rod movements on the core are also treated accurately, which provides the best-estimated value of maximum fuel temperature, clad, and coolant during the transient.

The MTRDY code [15] needs a complete macroscopic cross-section for absorption, fission, diffusion, and scattering and their derivatives to fuel temperature, temperature, and density moderator. The WIMS/D5 code is used to generate the macroscopic absorption cross-section, Σ_a, the transmission cross-section, ν_f, the diffusion coefficient, D, the scattering, Σ_s. The transient analysis needs delayed neutron data [17], and the data is taken from the Tuttle data [18] and the delayed neutron spectrum is taken from Saphier [19].

The neutron few-group cross-section for LEU foil target, fissile, and non-fissile materials is generated by the WIMSD/5 cell calculation code. The WIMSD/5 code collapses the 69-neutron energy group to the four neutron energy groups by the neutron collision probability calculation. The neutron cross-section is a function of the fuel burn-up level, water density, fuel temperature, and the existence of important neutron poisons, xenon, and samarium. Cross-section data with the core geometry, boundary conditions, thermohydraulic input data (coolant flow rate, inlet temperature, and pressure in the core), derivative constant, and transient scenario data are given to the MTR-DYN code to perform the steady-state and transient calculations. A diagram of steady-state and transient calculations using the MTR-DYN code is shown in fig. 4.

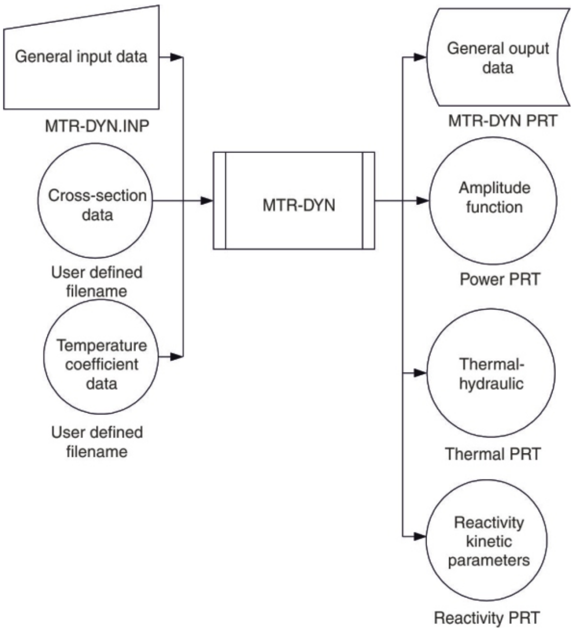

Figure 4. The MTR-DYN flow chart diagram for reactivity insertion case [14]

Steady-state and postulated RIA conditions

The reactivity accidents are postulated to occur due to all control rods unexpected withdrawal or because of equipment damage or operator error. The reactor protection system will automatically shut down the reactor and thus limit the transient level of unintentional control rod withdrawal to protect the reactor core. The amount of reactivity insertion is determined from all control rod near the center of the active core. The maximum gradient near the center of all control rod height is 0.41 % Δkk^{-1} cm^{-1} (Δkk^{-1} is reactivity unit). The maximum control rod speed is 0.0564 cms^{-1}, so the maximum rate of reactivity insertion is 0.03734 $\$s^{-1}$, including a 15 % safety addition.

Reactivity transient at low power (start-up)

It is assumed that the reactor is operating in the low power range at the 1 W initial power. The accident is initiated by assuming that all control rods are simultaneously withdrawn and, the reactivity increase due to a decrease in neutron absorber increases power reactor. To terminate power increase, the RSG-GAS reactor has a shutdown system that becomes effective at 15 % of the nominal power level. Transient analysis at high power is carried out at 1 MW initial power. At the high power, the increased power is triggered by the signal of overpowering reactor protection. The trigger value is 114 % of full power. In the calculation, at an inlet temperature of 44.5 °C, coolant pressure is 0.2 MPa, the cooling rate of the core is 522.30 kgs^{-1}, and the delay time of 0.5 seconds is used as input data.

Table 1. The steady-state calculation for the without target and with the target

Parameters	Without LEU target	With LEU target
Operating power [MW]	30	30
Coolant flow rate [$kgm^{-2}s^{-1}$]	1829.49	1690.79
Coolant velocity [ms^{-1}]	2.794	2.832
Average power density [Wm^{-3}]	1.75 10^{+8}	1.69 10^{+8}
Power peaking factors		
Axial	1.761	1.762
Radial	1.23	1.24
Steady-state temperatures [°C]		
Maximum coolant temperature	67.29	68.47
Maximum clad outer temperature	122.11	127.51
Maximum clad inner temperature	123.48	128.92
Peak centreline temperature	124.46	129.92

RESULTS AND DISCUSSION

Table 1 shows the steady-state calculation with and without the LEU target. The cooling flow rate in the core without LEU target is higher than with LEU target because the average power density without LEU target is higher than with LEU target. As the LEU target is fission material, the average power density in the core becomes lower than 4.4 %. The slightly lower power density and the lower coolant flow rate make the steady-state temperature with a target slightly higher than without a target. By irradiating the LEU target, the calculated maximum coolant temperature, maximum clad outer temperature, maximum clad inner temperature, and peak centerline temperature are higher by 1.75 %, 4.42 %, 4.41 %, and 4.39 %, respectively. All maximum temperatures are not exceeding the temperature safety limit.

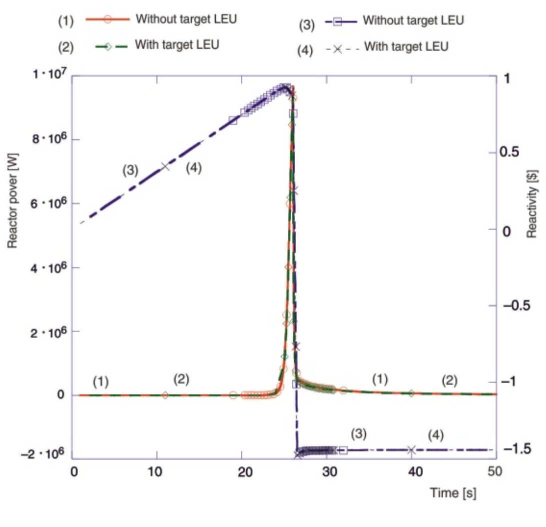

Figure 5. Net reactivity and power response at initial power 1 W

The RIA analysis is carried out for two conditions, the core with and without LEU target. Net reactivity and power as a function of transient time for 1 W initial power is shown in fig. 5. After insertion reactivity, reactor power increases significantly. and after reaching 4.5 MW reactor shuts down by the reactor protection system. It can be seen that the reactivity increases linearly because there is no negative reactivity feedback coming from the fuel element.

For the core with a target, the maximum power of 9.32 MW is achieved at the time of 26.03 seconds, meanwhile, for the core without a target, the maximum power is 9.67 MW at the time of 26.06 seconds. There is no significant difference that occurs in the power transient due to the presence of an LEU target in the core.

The maximum transient temperature for fuel and coolant are shown in fig. 6. Table 2 shows that the maximum temperature of the coolant, clad, and fuel are 49.76 °C, 65.01 °C, and 65.26 °C, respectively, for the core with LEU target. The temperature of the coolant increases by 1.34 % compared to the coolant temperature without a target in the core. Meanwhile, the temperature of cladding and fuel is not significantly increased when the LEU target is irradiated in the core. The temperature rise is very sharp because of the small negative feedback reactivity at the low power. In the transient reactivity with 1 W initial power, there is no significant increase in temperature due to irradiation of the LEU target in the reactor core. Based on the results shown in tab. 2, no boiling occurred, because the maximum temperature is less than the boiling limit.

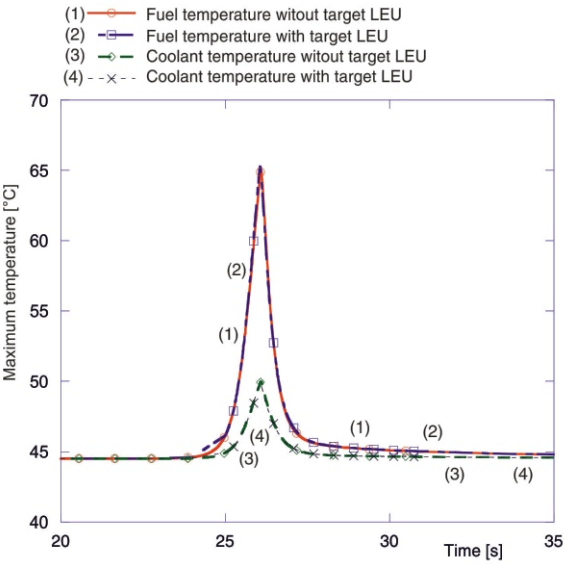

Figure 6. Coolant and fuel temperature during transient at initial power 1 W

Table 2. The maximum temperature at coolant, cladding, and fuel

Parameters	Without LEU target	With LEU target	Difference [%]
Maximum coolant temperature [°C]	49.09	49.76	1.34
Maximum clad temperature [°C]	64.77	65.01	0.37
Maximum fuel temperature [°C]	65.02	65.26	0.37

Insertion of reactivity at the initial power of 1 MW is simulated by the withdrawal of all control rods and the time response of net reactivity and reactor power during transient shown in fig. 7. The net reactivity is increased linearly from 0 $ (reactivity unit) to a maximum value of 0.49 $ during 18.00 seconds, and power increases exponentially from 1 MW to maximum power then starts to decrease because of the negative feedback reactivity until the reactor scram at 26.41 seconds.

After reactivity insertion for 10 seconds, the reactor power increased significantly, and when the power reached 118 % the nominal power, the reactor was scrammed by the reactor protection system. The maximum power of 35.46 MW was achieved within 30.38 seconds, with target condition, while the maximum power of 35.60 MW was achieved in 29.36 seconds, without target condition. In this process, transients depend on the amount of reactivity insertion and negative reactivity feedback.

The calculation results of the maximum temperature of coolant and fuel during transient at 1 MW initial power are shown in fig. 8. Compared to reactivity insertion at the low power, the power rise is flatter at the high power, because of the effect of the negative feedback reactivity. There are no significant differences that occurred in the power transients due to the presence of the target in the reactor core.

The calculation result of the maximum temperature is shown in tab. 3. The maximum temperature coolant, clad, and fuel with LEU foil target irradiated in the

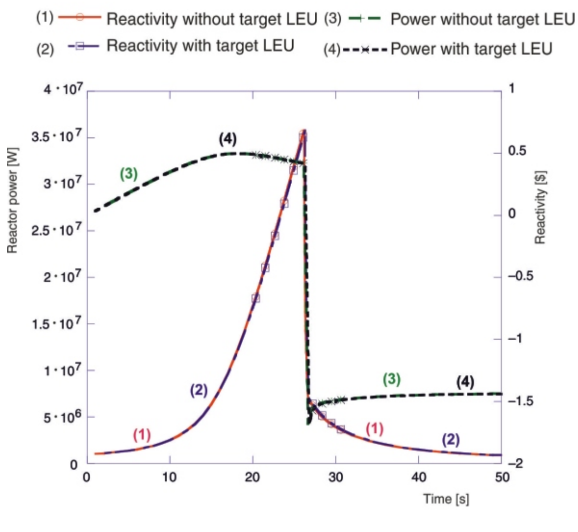

Figure 7. Net reactivity and power response at initial power 1 MW

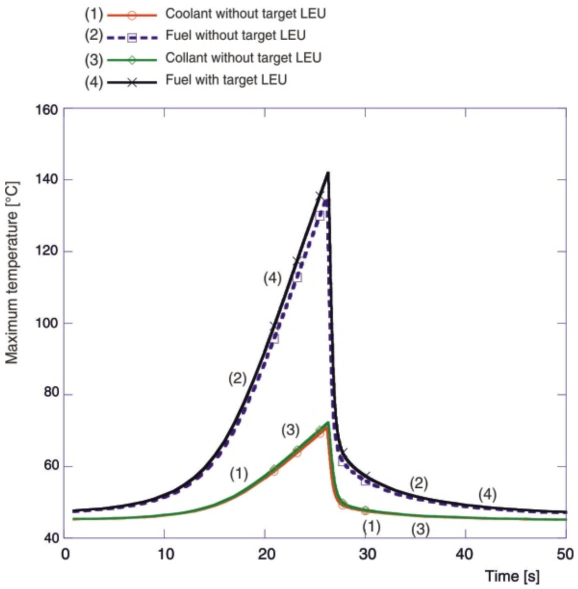

Figure 8. Coolant and fuel temperature during transient at initial power 1 MW

Table 3. Maximum temperature with initial power1 MW

Parameters	Without LEU target	With LEU target	Difference [%]
Maximum coolant temperature [°C]	70.86	72.23	1.93
Maximum clad temperature [°C]	133.95	140.79	5.11
Maximum fuel temperature [°C]	135.11	141.97	5.07

core are 72.23 °C, 140.9 °C, and 141.97 °C, respectively. The maximum coolant temperature increases by 1.93 % with the LEU target in the core. The maximum temperature of the clad and fuel increases by 5.11 % and 5.07 %, respectively, when the LEU targets are in the core. The increase of temperature with the LEU target in the core is within permitted safety limits.

CONCLUSION

The calculation with the LEU target on the reactor core is carried out in steady-state and RIA conditions. Transient conditions are calculated by the withdrawal of all control rods when the LEU foil target is irradiated in the irradiation facility. Calculations result showed that during RIA at 1 W initial power, and 1 MW initial power the coolant temperature only increases to a maximum of 72.23 °C, which is less than the saturation temperature. The results of the maximum temperature of fuel and cladding do not exceed the safety limits. The negative temperature reactivity coefficient and Doppler feedback reactivity have an important role in increasing the maximum temperature of the cladding. By irradiating the 108 g of LEU foil target in the reactor core, the RSG-GAS reactor can be to operated safely.

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AUTHORS' CONTRIBUTIONS

The computational work of MTR-DYN and WIMS/D was carried out by S. Pinem and T. M. Sembiring, respectively. The conceptualization, methodology, and formal analysis were made by all authors. T. Surbakti and S. Pinem made the original draft, while the finalization was carried out by T. M. Sembiring. S. Pinem, T. Malem Sembiring and T. Surbakti equally contributed as the main contributors of this paper.

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АНАЛИЗА АКЦИДЕНТА УНЕТЕ РЕАКТИВНОСТИ ТОКОМ ОЗРАЧИВАЊА МЕТЕ ОД УРАНИЈУМСКЕ ФОЛИЈЕ У ЈЕЗГРУ RSG-GAS REAKTORA

Анализа стационарног стања и акцидента уношењем реактивности веома је важна за сигурност рада реактора. У овом раду спроведена је анализа акцидента реактора у стабилом стању и при унетој реактивности када се нискообогаћена уранијумска фолија озрачује у језгру реактора. Анализа је обављена методом најбоље процене применом спрегнутог неутронског кинетичког и термохидрауличког MTR-DYN кода, где је MTR-DYN код заснован на методи тродимензионалне мултигрупне неутронске дифузије. Прорачун ћелије са метом обављен је помоћу WIMSD/5 и MTR-DYN кодова. Након уношења реактивности, праћене су температуре хладиоца, горива и кошуљице. Резултати прорачуна за почетну снагу од 1 W показали су да су максималне температуре хладиоца, кошуљице и горива 49.76 °C, 65.01 °C и 65.26 °C. Међутим, када је унета реактивност при почетној снази од 1 MW, максимална температура хладиоца, кошуњице и горива износи 72.23 °C, 140.79 °C и 141.97 °C. На основу ових резултата прорачуна, током озрачивања фолијумске мете од нискообогаћеног уранијума, температура у удесима при стабилном стању и унетој реактивности не прелази дозвољену границу сигурности.

Кључне речи: анализа унеӣе реакӣивносӣи, īраница сиīурносӣи фолија од нискообоīаћеноī уранијума, MTR-DYN код