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Analysis of Reactivity Insertion as a Function of the RSG-GAS Fuel Burn-up

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A B S T R A C T

Analysis of the control rod insertion is important as it is closely related to reactor safety. Previously, the analysis has been carried out in RSG-GAS during static condition, not as a function of the fuel fraction. The RSG-GAS reactor in one cycle is a function of the fuel burn-up. It is necessary to analyze RSG-GAS core reactivity insertion as a function of the fuel burn-up to determine the behavior of the reactor, especially in uncontrolled operations such as continuous pulling of control rods. This analysis is carried out by the computer simulation method using WIMSD-5B and MTR-DYN codes, by observing power behavior as a function of time due to neutron chain reactions in the reactor core. Calculations are performed using point kinetics equation, and the feedback effect will be evaluated using static power coefficient and fuel burn-up function. Analyzes were performed for the core configuration of the core no. 99, by lifting the control rod or inserting positive reactivity to the core. The calculation results show that with the reactivity insertion of 0.5% Δk/k at start-up power of 1 W and 1 MW, safety limit is not exceeded either at the beginning, middle, or end of the cycle. The maximum temperature of the fuel is 135°C while the safety limit is 180°C. The margin from the safety limit is large, and therefore fuel damage is not possible when power excursion were to occur.

1. INTRODUCTION[*]

A nuclear reactor will operate at a constant power level if the rate of neutron production due to fission is offset by the loss of neutrons due to absorption or leakage. Any deviation from the equilibrium conditions will result in the reactor power level being time-dependent. Estimating the level of reactor power as a function of time due to the influence of changes in reactor multiplication factor is important, as it is related to the safety of reactor operations [1-3].

According to the aforementioned issue, it is necessary to analyze the insertion of control rods as a static function of feedback, which has been done in the RSG-GAS core [4, 5]. However, analysis of control rod insertion as a function of fuel burn-up has never been done previously. This analysis aims to determine the behavior of the RSG-GAS reactor, especially in uncontrolled operations such as continuous pulling of control rods, which can be caused either by instrumentation failure or operator error. In this paper, we will discuss RSG-GAS reactor behavior with the insertion of reactivity. The latter is carried out by inserting a positive reactivity which value is close to the reactivity of

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the delayed neutron fraction. This calculation was performed using the RSG-GAS core configuration number 99 with 250 gr silicide fuel element[6, 7]. To determine the effect of kinetic parameters on power changes, the calculation is done at the beginning of the cycle, the middle of the cycle, and the end of the cycle. If the insertion of reactivity given to the reactor core is positive, then the dominant role in changing the reactor power is the delayed neutron lifetime. But if the reactivity insertion is negative, the dominant role in changing the reactor power is the delayed neutron fraction [8, 9].

Calculations in the present work are performed using point kinetic equations, which are solved analytically, and the analysis is limited to the reactor kinetics problem. In the calculation, the effects of feedback reactivity through static power will be analyzed[10-12]. Analysis of insertion reactivity as a function of the RSG-GAS fuel burn-up has never been carried out. It is necessary to understand the characteristics of the RSG-GAS core to determine the behavior of the reactor core when the control rod is lifted-up continuously. Static power feedbacks are determined using the WIMSD-5B and Batan-2DIFF computer codes[13]. The calculation of the diffusion group constants as a function of the fuel burn-up is performed by the WIMSD-5B program, and the neutronic parameter of the core calculation is done by the Batan-2DIFF program. Meanwhile, calculation of control rod insertion as a function of fuel burn up is carried out with the MTR-DYN code. Distribution of power and temperature as the characteristics of the reactor core and the results of calculations are expected to be far below the safety limits.

2. BRIEF DESCRIPTION OF RSG-GAS

Multipurpose Reactor G. A. Siwabessy (RSG-GAS) is a type of MTR reactor (Material Testing Reactor) which is the first in the world to be operated directly using low-enriched uranium (LEU) fuels. Initially, RSG-GAS used uranium oxide as fuel, but with current technological developments, RSG-GAS uses uranium silicide with a density of 2.96 g/cm^3 and low uranium enrichment, 19.75% as fuel[13]. Neutronic design parameters can be seen in Table 1.

The RSG-GAS fuel element is based on MTR technology. Each standard fuel element consists of 21 plates. The fuel cladding material is $AlMg_2$ frame and two cover sheets of the same material, which wrap the U_3Si_2-Al meat dispersion plate. The control fuel element is designed as a fork-type. The uranium part that contains the fuel element in the control fuel element standard is identical to the part in the fuel element standard. The fuel element on the control element standard consist of 15 plates. Three left and right fuel edge plates are provided for space for the insertion of the absorber blade. The absorber device consists of two Ag-In-Cd blades coated in stainless steel (material 1.4541, the same as SS321)[14].

The control system functions to control the neutron flux in the reactor, by moving the absorber device in a vertical direction in and out of the control element. The beryllium element consists of a lower end fitting, a rectangular beryllium rod, and a handle on the top. Figure 1 is the core configuration of RSG-GAS.

Table 1. Neutronic Design Parameters[15]

Core Characteristics	Values
Amount of fuel elements	40
Amount of control elements	8
Amount of absorbers	8
Cycle length (at full power), MWD	680
The average fuel burnup, BOC, % loss of ^{235}U	25.60
Average burnup at EOC,% loss of ^{235}U	32.53
Average discharged fuel burnup, % loss of ^{235}U	55.50
Max. burnup,% loss of ^{235}U	59.91
Excess reactivity at BOC, %	7.69
Reactivity for experiments,%	3.00
Total reactivity value of 8 control rods,%	- 14.07
Shut-down reactivity margin, %	- 2.35
Stuck rod condition, %	$\geq$ - 0.5
Coefficient of fuel temperature, %Δk/k	-1.92×10^{-5}
Coefficient of moderator temperature, %Δk/k	-7.60×10^{-5}
Corfficient of moderator void, %Δk/k	-1.36×10^{-3}
Delayed neutron fraction	0.007186
Lifetime for prompt fission neutrons, μs	64.51

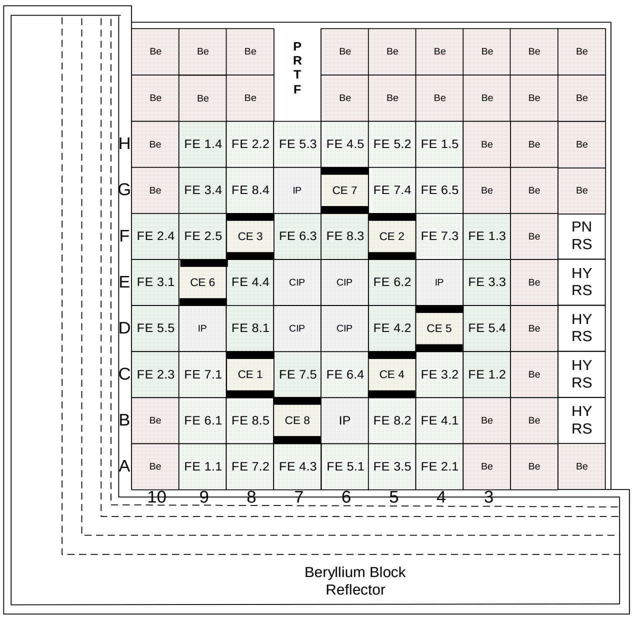

Fig. 1. RSG-GAS core configuration[16]

3. METHODOLOGY

This research began by calculating the total control rod reactivity value of the RSG-GAS core with the Batan-3DIFF program. The results obtained indicate the slope of the reactivity value of the control rod is in the middle. The reactivity accident was carried out using the MTR-DYN neutronic-thermalhydraulic couple program[17]. It uses dynamical reactor modeling without simplification, where space and energy variables are maintained. Thus, outside interference such as control rods and other parameters can be included as a function of location. Likewise, reactivity feedback (temperature, voids, etc.) is handled as a function of location, meaning that changes in fuel temperature or moderator at a certain position in the reactor can give a different feedback effect from other positions. Thermal-hydraulic calculations are also performed as a function of position.

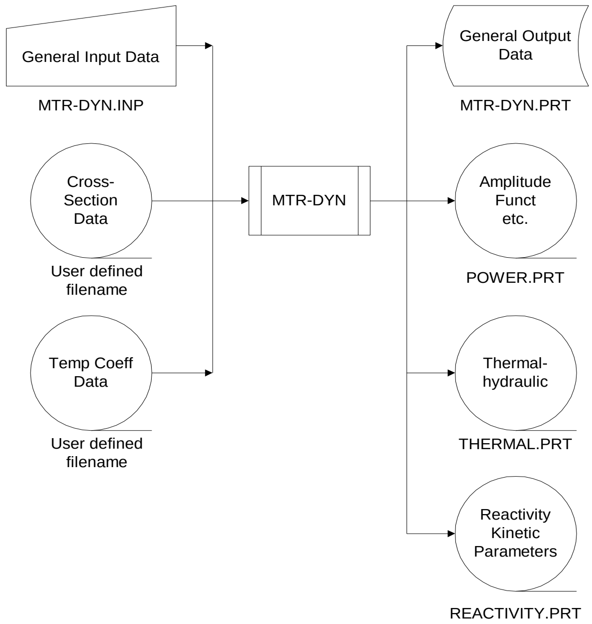

Fig. 2. Structure of input/output of the MTR-DYN code[6, 17]

The reactivity accident is postulated to occur due to accidental pulling of all control rods, in turn can be caused by equipment damage or operator error, which is a potential cause of hazard in reactor operation. The reactor protection system will shut down automatically the reactor, thereby limiting the transient level of accidental withdrawal of control rods to protect the reactor core. The RSG-GAS reactor is designed to be shut-down automatically when the period of the ionization instrumentation system is compensated for less than 10 s. In this simulation, it is assumed that the control rod speed gives a positive reactivity to the reactor core for 0.03926 \$/s[7]. The assumption comes from the maximum value of control rod speed times the differential reactivity of control rod. The delay time of the control rod falls is 0.50 seconds. The simulation is carried out at the power at 1 W and 1 MW as a function of the fuel burn-up. The stucture of the MTR-DYN code can be seen in Figure 2.

4. RESULTS AND DISCUSSION

The calculation results of the control rod reactivity values can be seen in Figure 3. The S curve shows that the shape of the control rod design is correct, and the slope value can be calculated as $\Delta\rho/\Delta h$. This slope value also shows the amount of positive reactivity given to the core when there is a problem of pulling the control rod at maximum speed.

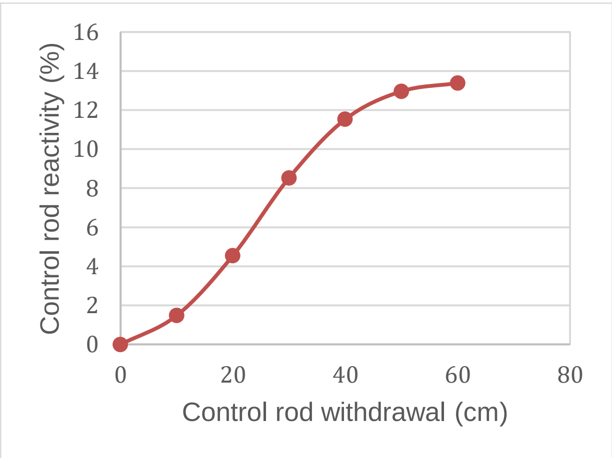

Fig. 3. Control rod reactivity worth

Table 2 shows that the individual and total control rods reactivity of the RSG-GAS core. The control rods' reactivity worth was obtained from calculated and experimental results. The total value of control rod reactivity between experimental and calculation differs for about 4.5%. This showed that the calculation model had been done well. The calculation result is considered a good agreement if the difference between calculation and experiment is below 10%

Table 2. Control rod reactivity worth for RSG-GAS core

CR Position	Calculation (%)	Experiment (%)	Deviation (%)
B-7	1.485	1.394	6.512
C-5	1.774	1.756	1.042
C-8	1.689	1.390	21.476
D-4	1.666	1.892	11.922
E-9	1.766	1.595	10.721
F-5	1.684	1.813	7.120
F-8	1.880	1.804	4.241
G-6	1.486	1.622	8.373
Total CR reactivity	13.865	13.265	4.525
Shut-down reactivity	5.979	6.120	2.299
Excess reactivity	7.886	7.145	10.369
Stuck-rod	4.206	4.229	0.549

The slope reactivity value of the RSG-GAS core control rods can be seen in Figure 4. This value multiplied by the maximum speed of the control rod will produce the core reactivity value when the control rod is withdrawn at maximum speed. The maximun speed of of the RSG-GAS control rod is 0.0564 cm/s[7] and slope = 0.3401 %/cm.

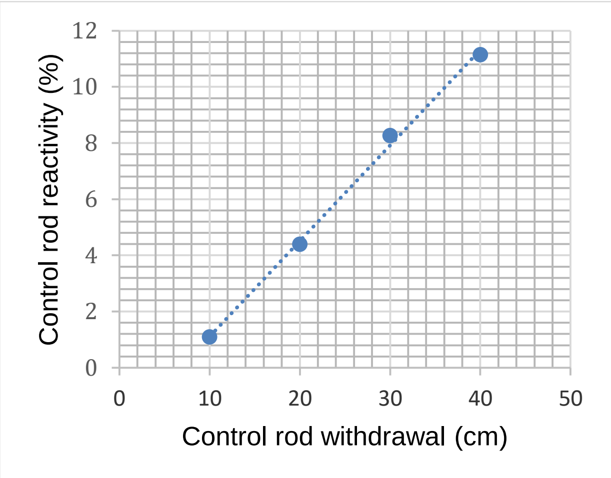

Fig 4. Slope of control rod reactivity

For the first case, the reactivity insertion at an initial power of 1 MW is simulated by pulling all the control rods from the top of the core, and the reactor will trip at 118% nominal power. The amplitude and reactivity functions obtained during transients for the initial power of 1 MW are shown in Figure 5. From this result, it can be seen that the shape of the amplitude function is slightly sloping due to the large feedback reactivity of the fuel element. At 0.0 MWD fuel fraction, the maximum power reached 35.90 MW after 25 s. Meanwhile, at 123 MWD fuel burnup, the maximum power reached 35.81 MW after 25.46 s. For fuel burnup 246 MWD, the maximum power reached 35.75 MW after 25.95 s. Next, at fuel burnup 369 MWD, the maximum power achieved is 35.66 MW after 26.45 s. For fuel burnup 492 MWD, its maximum power achieved is 35.56 MW after 26.98 s. Last, at fuel burnup 615 MWD, maximum power achieved is 35.49 MW after 27.53 s. When control rod of the RSG-GAS continues to be lifted-up, the reactor power rises and reaches a maximum of the trip setting value at high power (118% x 30 MW = 35.4 MW) and the reactor will scram, but it takes 0.5 s for the system to drop the control rods into the core. The results of this calculation show that with the increased fuel burnup the maximum power achieved is reduced, but the scram time is longer. It means that if the amount of uranium is reduced in the core (high burn-up), it takes longer time to reach the maximum power.

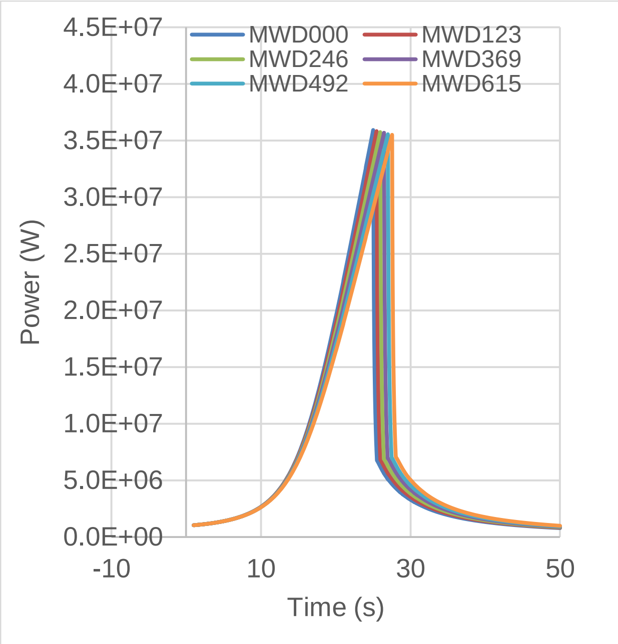

Fig. 5. Power of the reactor with insertion at 1 MW

The fuel temperature distribution during transients with an initial power of 1 MW with various fuel burnup is shown in Figure 6. At the 0.0 MWD fuel burnup, the maximum temperature reached 135°C after 25 s. Meanwhile, at the fuel burnup 123 MWD, the maximum temperature reached 134.43°C after 25.46 s. For fuel burnup 246 MWD, the maximum temperature reached 133.98°C after 25.95 s. Next, at the fuel burnup 369 MWD, the maximum temperature reached 133.53°C after 26.45 s. For fuel burnup 492 MWD, the maximum temperature reached 132.29°C after 26.98 s. Last, at fuel burnup 615 MWD, the maximum temperature reached 132.28°C after

27.53 s. As the fuel burnup of the RSG-GAS core increases, the maximum fuel temperature achieved decreases. Nevertheless, all fuel temperature distribution values are far below the operating safety limit of 180°C[8].

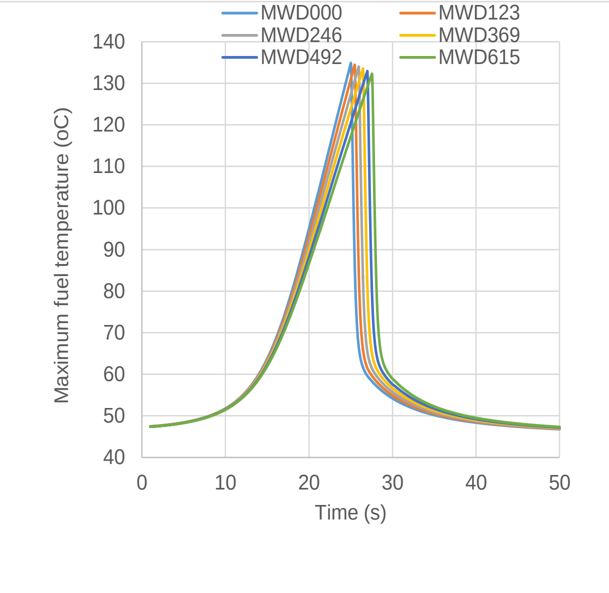

Fig. 6. Maximum fuel temperature during transients with an initial power of 1 MW

For the second case, reactivity insertion at initial power of 1 W is simulated by pulling all control rods from the top of the core, and the reactor will trip at 4.5 MW power. The amplitude function and reactivity obtained during transients for the initial power of 1 W are shown in Figure 7. From this result, it appears that the shape of the amplitude function is rather sharp because the large feedback reactivity of the fuel element at low power has not yet occurred. At the 0.0 MWD fuel burnup the maximum power reached 10.11 MW after 24.97 s. Meanwhile, at the 123 MWD fuel burnup, the maximum power reached 9.76 MW after 24.98 s. For fuel fraction of 246 MWD, the maximum power reached 9.51 MW after 25.00 s. Next, at the fuel burnup 369 MWD, the maximum power reached is 9.19 MW after 25.01 s. For fuel fraction of 492 MWD, it reached a maximum power of 8.95 MW after 25.03 s. Last, at fuel burnup of 615 MWD, it reached a maximum power of 8.78 MW after 25.04 s.

The same with the first case, when the control rod of the RSG-GAS continues to be lifted-up, start-up at low power (1 W), the reactor power rises and reaches a maximum of the trip setting value 4.5 MW and the reactor will scram, but it takes 0.5 s for the system to drop the control rods into the core. Also identical with the previous case, the results of this calculation show that with the increased fuel burnup, the maximum power achieved is reduced, but the scram time is longer. It took longer time to reach maximum power as the amount of uranium is reduced in the core (high burn-up).

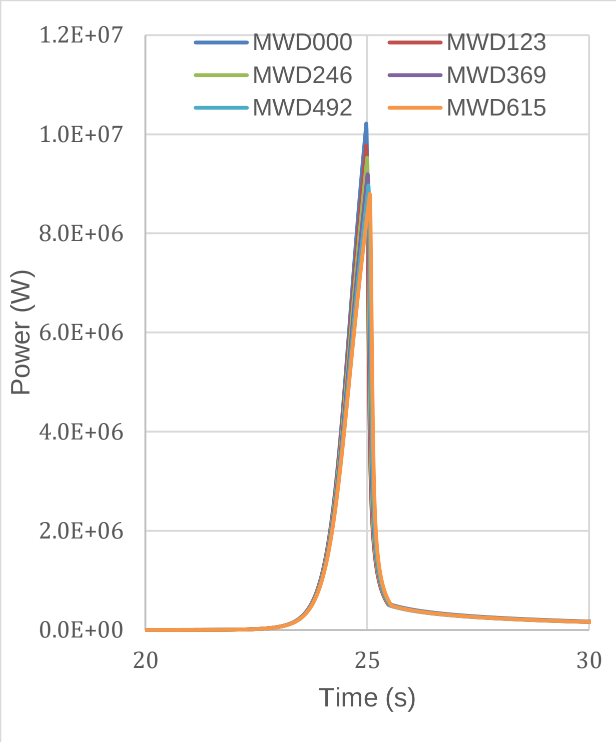

Fig. 7. Power of reactor with insertion at 1 W

Fuel temperature distribution during transients with an initial power of 1 W with various fuel burnup is shown in Figure 8. At the 0.0 MWD fuel burnup the maximum temperature reached 65.95°C after 25.01 s. Meanwhile, at fuel burnup 123 MWD the maximum temperature reached 64.99°C after 25.01 s. For fuel burnup 246 MWD, maximum temperature reached 64.57°C after 25.03 s. Next, at fuel burnup 369 MWD maximum temperature reached 64.01°C after 25.04 s. For fuel burnup 492 MWD, maximum temperature reached 63.46°C after 25.06 s. Last, at fuel burn-up 615 MWD maximum temperature reached 63.21°C after 25.09 s. As the burn-up of the fuel increases, the maximum fuel temperature reached decreases. Compared to the first case (initial power 1 MW). the difference is obvious that in the graphs of the first case, increase in fuel temperature and power are sloping due to reactivity feedback. But in the second case, the graph is steep since there is no reactivity feedback. It explains the usefulness of feedback reactivity to maintain reactor safety in the event of a control rod withdrawal accident.

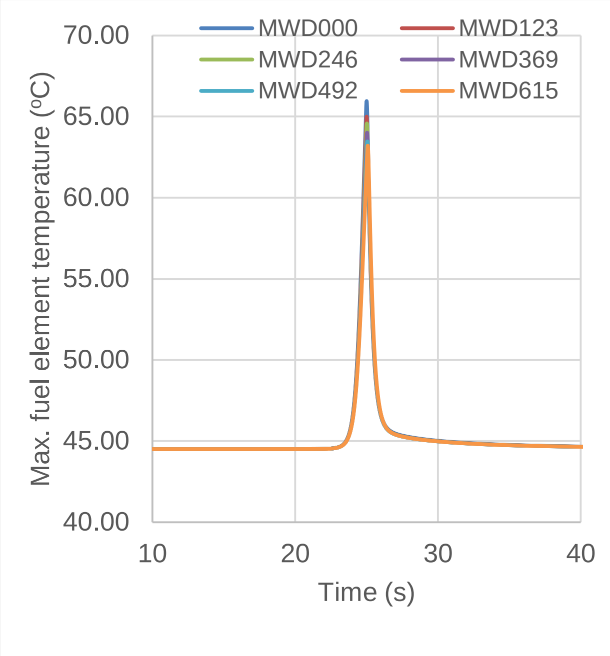

Fig. 8. Maximum fuel temperature during transients with an initial power of 1 W

5. CONCLUSION

The calculation results are carried out in transient conditions by pulling the control rod with various fuel burn-ups. A transient test with reactivity insertion simulation is one of the research reactor safety tests. This test simulates a rapid increase in power by pulling out the control rod. The calculation result showed the maximum fuel temperature does not exceed the allowable safety limit. For research reactors, physical barriers must be maintained so that uncontrolled radioactive releases do not occur due to damage to the fuel elements' cladding. The maximum fuel temperature value is obtained 135°C, where this value is still below the permitted limit of 180°C [8]. Besides the Doppler feedback reactivity, the negative temperature reactivity coefficient has an important role in increasing the maximum fuel temperature.

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AUTHOR CONTRIBUTION

Tukiran Surbakti carried out core modelling in the MTR-DYN code, Lily Suparlina carried out cell calculation using WIMSD-5B. Surian Pinem participated as a reviewer and data analysis, Tukiran Surbakti is the lead author of this paper, Surian Pinem and Lily Suparlina as co-author. All authors read and approved the final version of the manuscript.

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