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Safety Analysis of the TRIGA 2000 U_3Si_2-Al Fuel Core Under Reactivity Insertion Accidents

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ABSTRACT

The TRIGA 2000 reactor in Bandung is planned to change its fuel type from the TRIGA fuel rod type to the U_3Si_2-Al plate type of low enriched uranium of 19.75 % with uranium density of 2.96 gU/cc. A study on the neutronic parameters from the equilibrium core has been done. To ensure safe operation of the new fuel, thermodynamic evaluation of the core needs to be done. The purpose of this study is to conduct a reactor safety analysis of reactivity insertion during withdrawal of the control rod and to study the effect of this reactivity insertion on the power and the maximum temperature of the fuel and the cladding. Reactivity insertion accident is the main factor of the design basis accidents in nuclear reactor design. A simulation of transient for reactivity insertion has been carried out using a coupled neutronic and thermal-hydraulic MTR-DYN code. The code was developed based on three-dimensional multigroup neutron diffusion theory. The coupled space and time-dependent problem were solved by adiabatic model. Transient analysis was performed for a reactivity insertion of 32.33 pcm/s with the assumption that all of the control rods were rapidly withdrawn. For the insertion at a low power of 100 W, the maximum power achieved was 2.74 MW while a maximum power of 2.3 MW was achieved for the power transient of 1 MW. The maximum temperature of the coolant, the cladding, and the fuel for TRIGA 2000 core does not exceed the allowable safety limit for reactivity insertions.

INTRODUCTION

The TRIGA MARK II Bandung reactor has been operated since 1964 under a thermal power of 250 kW. To enhance radioisotope production capability and other research activities, the reactor power was up-rated to 1 MW in 1971. With the increasing demand of medical radioisotopes, the TRIGA MARK II serves as a backup reactor in case the RSG-GAS is in outage condition. To fulfill the task, the TRIGA MARK II reactor power was again increased to 2 MW in 2000 and the name of the reactor was changed to TRIGA MARK 2000 Bandung reactor.

At present, the TRIGA 2000 Bandung reactor is still operating using the standard TRIGA fuel elements (FE) supplied by General Atomics (GA). Currently, however, the GA as the sole supplier of TRIGA reactor standard FEs has decided to cease the production, so the reactor operation now uses the available burnt FEs and a limited number of fresh FEs purchased in the past. On the other hand, PT INUKI (a BATAN subsidiary company) has long time experience in producing plate type FEs for domestic material testing reactor (MTR) of the RSG-GAS reactor. In relation to this expertise in domestic FEs manufacturing, to assure long-term continuation of the reactor operation, BATAN initiated a core conversion program in 2015, namely, a switch to the use of the domestically manufactured MTR plate-type FEs for replacing the GA FEs.

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The core design calculation of TRIGA 2000 has been carried out using U_3Si_2-Al fuel meat (density of 2.96 g/cc) with low enrichment uranium (LEU, slightly less than 20 %). This fuel is identical with the one presently used in the RSG-GAS.

As for the neutronics and the in-core fuel management aspects, the equilibrium core design of the TRIGA 2000 has been obtained using the in-house Batan-FUEL code [1]. The code has been verified and validated as well as used successfully for the core conversion program of the RSG- GAS reactor [2,3]. It was found that the optimum configuration was a compact 5 x 5 core consisting of 16 FEs with 4 control rods [4,5]. The neutronic parameters calculated in the previous work were the equilibrium core reactivity coefficients, control rod worth curves, radial and axial power peak factors, kinetic parameters and xenon reactivity worth. Meanwhile, the compact core remains surrounded by the original graphite reflector that provides high neutron flux for irradiation facilities. Since the design of the TRIGA 2000 reactor must satisfy various postulated events to ensure that the steady state and transient core do not exceed the safety limits, thermal-hydraulic analysis has also been conducted to determine the nominal and minimal coolant flow rates during steady-state operation and transient conditions, followed by some accident analyses such as loss of flow accident (LOFA) [6-8].

One of the main safety concerns in research reactors is the clad meltdown, which can cause the release of fission products into the environment. Excessive insertion of reactivity can cause accidents leading to fuel clad meltdown. In the past, many researchers conducted analysis on the reactivity insertion accidents (RIA) under controlled and un-controlled conditions, and they compiled the results in safety analysis reports [9-12].

This paper reports the steady-state and RIA analyses. The steady-state analysis is required to provide accurate initial conditions for the RIA consequent analysis. For the TRIGA 2000 reactor, the RIA is postulated to be initiated by accidentally withdrawing of the control rod. The maximum reactivity insertion due to the withdrawal of the control rod is determined based on the speed of the control rod and the worth gradient of the control rod. The objective of this study is to ensure that the parameters related to core (fuel) safety do not exceed the safety limits during the postulated RIA. The safety limits or criteria used are derived from the MTR-type fuel safety similar to the RSG-GAS, i.e., (1) the maximum fuel temperature must be less than 200 ^{o}C and (2) no coolant boiling occurs on the reactor core.

In the this work, reactivity insertion analyses were conducted using the WIMSD/5 [13] and codes have been tested and verified using MTR-type fuels related to reactivity insertion parameters for the safety of research reactors [15]. WIMSD/5 is a general purpose transport theory based on lattice code for the determination of cell averaged macroscopic and other lattice parameters for overall space dependent reactor calculations. The MTR-DYN code solves the space and time-dependent: few group neutron diffusion in 3-D cartesian geometry coupled with a thermal-hydraulics module. Therefore, the code is basically divided into two main modules, i.e., the neutron-dynamics calculation module and the thermal-hydraulics calculation module dedicated to MTR-type research reactors.

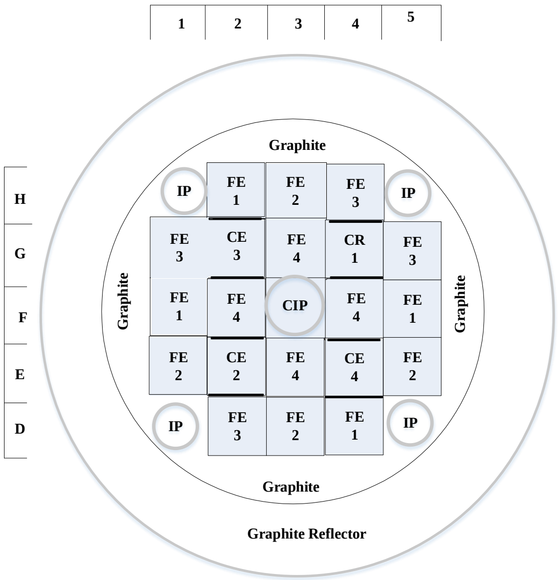
As for the neutron-dynamics calculation module, there are two options (approximations) available, namely the point reactor model and the adiabatic model (from less to most accurate order), whereas a sub-channel single phase flow in 1-D planar geometry model is available for the thermal-hydroulics calculation module. The water coolant flow is in the downward direction and the energy and momentum equations are solved in the flow direction. The conductive heat transfer inside the fuel plate and the convective heat transfer between the fuel plate surface and the water coolant are solved in 1-D heat transfer model perpendicular to the water coolant flow direction.

In the next section, a short description of the TRIGA 2000 reactor is given. In the section of Calculation Method, a brief explanation of the above-mentioned analytical codes is provided, followed by description on the steady-state and postulated RIA analyses. In the section of Results and Discussion, the steady-state and the RIA analysis results are presented and discussed. The summary of the present work and the planned future work are given in the last section (Conclusion).

CALCULATION METHODS

Triga 2000 reactor description

As shown in Fig. 1, the TRIGA 2000 reactor core configuration consists of 16 standard fuel elements (FE) and 4 control fuel elements (CE), which are arranged in 5 x 5 core grid. There is one flux trap at the center of the core and four irradiation facilities at the corners of the core. The FE consists of 21 identical fuel plates with a total uranium-235 content of 250 g. In each fuel plate, the uranium meat matrix (with a density of 2.96 g/cc and uranium enrichment of less than 20 %) is cladded with $AlMg_2$. The CE is similar to the FE but it consists of only 15 fuel plates. The FE and CE main data used in TRIGA 2000 fuels are shown in Table 1 while the FE is described in Fig. 2 and the CE that consists of 15 fuel plates is described in the Fig. 3. The neutronic parameters for the equilibrium core is shown in Table 2.



Note : FE = Fuel Element, CE = Control Element, IP = Irradiation Position, CIP = Central Irradiation Position

Fig. 1. Core configuration with 16 fuel elements and 4 control fuel elements [4].

Table 1. Standard fuel element (FE) and control fuel element (CE) specifications [4]

Types	MTR
No. of plate per fuel element	21
No. of plate per control element	15
Fuel zone thickness, mm	0.54
Fuel zone width, mm	62.75
Fuel zone length, mm	600.0
Type of fuel	U_3Si_2-Al
Enrichment, %	19.75
Uranium density in meat, g/cm^3	2.96
Cladding material	$AlMg_2$
Fuel plate thickness, mm	1.3
Fuel plate width, mm	625.0
Type of absorber	Fork type
Material absorber	Ag-In-Cd
Absorber thickness, mm	3.38
Cladding material	Steels
Reflector elements	Graphite

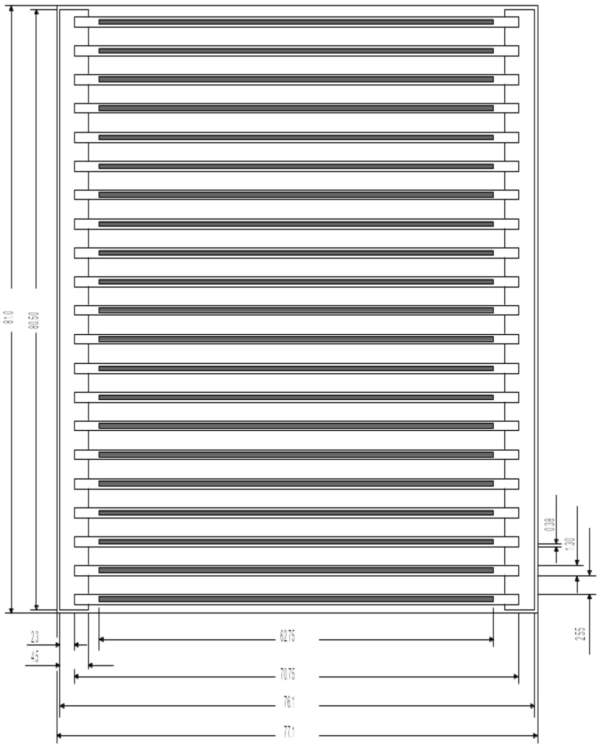


Fig. 2. Standard fuel element (unit mm) [4].

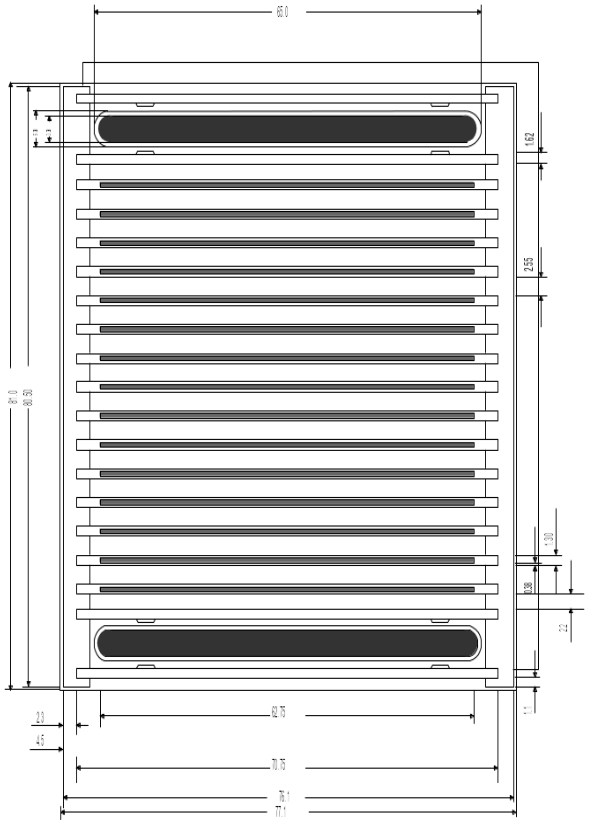


Fig. 3. Control fuel element with absorber blades inserted (unit mm) [4].

Table 2. Core parameters of the TRIGA 2000 reactor using MTR plate fuel type [4]

Core parameters	Equilibrium core
Mass ^{235}U per standard fuel element (g)	250
Uranium density (g/cc)	2.960
Power (MWth) / cycle length (days)	2/120
Reactivity for one cycle (%Δ*k*/*k*)	2.183
Reactivity xenon equilibrium (%Δ*k*/*k*)	2.348
Reactivity cold to hot (%Δ*k*/*k*)	0.532
Excess reactivity (%Δ*k*/*k*)	6.61
Total control rod values (%Δ*k*/*k*)	-20.60
Shutdown reactivity (stuck rod) (%Δ*k*/*k*)	-6.56
Power density (W/cc)	28.305
Average radial power peaking factor	1.225
Maximum discharged burn-up (%)	26.485

Methodology

Coupling the neutron-dynamics and thermal-hydraulics modules enables the MTR-DYN to treat accurately the space-dependent fuel & clad temperature reactivity feedback as well as the coolant temperature and density reactivity feedback. The space and time-dependent control rod movement in the core can also be treated accurately, which provides the best-estimate values of the maximum fuel, clad and coolant temperatures. The input-output structure of MTR-DYN code is shown in Fig. 4.

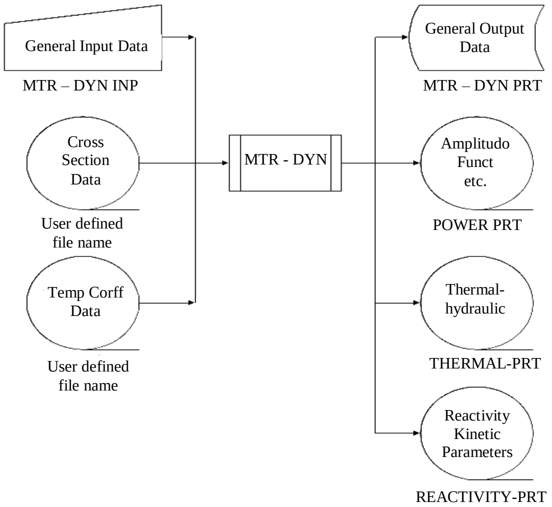


Fig. 4. Structure of input/output of the MTR-DYN code [14].

The WIMSD/5 code was used to generate the cross-section sets (group constants) of fuel and other materials on the reactor core using ENDF/B.VII.1 library. The WIMSD/5 code was accompanied by 69 energy group library, resonance and other nuclear parameters for the neutron collision probability calculation used in the effective cross-section set generation. Then, the 69 neutron energy groups were collapsed into 4 groups with energy boundary conditions of neutron of 10 MeV, 821 keV, 5.531 keV and 0.625 eV. The MTR-DYN requires 4 groups neutron diffusion macroscopic cross-section sets consisting of effective diffusion coefficient D, absorption cross-section Σa, fission production cross-section production νΣf, scattering cross-section Σs and fission spectrum.

The above-mentioned few group effective cross-section sets are generated as a function of the initial fuel composition (enrichment and uranium loading), burn-up level, xenon and samarium concentrations, fuel temperature, and coolant temperature (the coolant density effect is included in the coolant temperature). These data along with the core geometry, boundary conditions, thermal-hydraulic input data (coolant flow rate, temperature, and pressure) and transient scenario data are provided to the MTR-DYN code for performing steady-state and transient core calculations. Several important results from the neutron dynamic calculation such as the keff, reactivity and its components, forward and adjoint neutron flux, power profiles, effective kinetics parameters, etc. are written out as time-dependent values. As for the thermal-hydraulic calculation results, the average, the maximum and the detailed space-dependent for fuel, clad, coolant temperature and pressure are written out as time-dependent values.

The MTR-DYN code will stop the transient calculation at a point where boiling of coolant occurs and give a warning to the user. The thermal property library (water-steam) of the MTR-DYN code covers both temperature and pressure ranges used for a pressurized water reactor and boiling water reactor, therefore the properties of water for such boiling condition can be provided. However, in a research reactor safety design, boiling is not allowed and the MTR-DYN will stop just before the boiling phenomenon occurs.

In the calculation of reactivity transient as shown in Fig. 4, the input data required include core configuration, cross-section, temperature reactivity coefficient, derivative constant, amount of insertion reactivity and flow rate. The maximum reactivity insertion is determined from a gradient of the control rod curve and the control rod speed. The transient analysis is carried out after the flow rate calculation in the steady-state state has been done. In the case of reactor operation safety, calculations are performed using the highest radial and axial peak power factors. Derivative constant data are determined by generating macroscopic cross section as a function of fuel temperature and moderator (H_2O) temperature.

The minimum flow rate of the primary cooling system is 70 kg/s and about 85% of the total flow rate or 59.5 kg/s flow cools the reactor core [16]. In this context, the term active flow rate is defined as a flow that is directly in contact with the fuel element plate. Reactivity insertion is done by the withdrawal of the control rod at an initial power of 100 W and 1 MW to determine the effect of feedback reactivity. The effect of reactivity feedback is important for the safety of reactor operation.

A postulated accident occurs because of the withdrawal of all control rods at the maximum speed that can be achieved by the control rod drive motor. This accident provides a positive reactivity, and as a result, the power will rise quickly until the reactor scrams. The trip signal that causes a flux-trap reactor comes from a too high neutron flux (overpower 118 % nominal power) with a delay time of 0.5 s and the control rod time to below 0.5 s. The calculation used coolant inlet temperature of 35 ^{o}C and a pressure of 1.8 MPa [16].

RESULTS AND DISCUSSION

Steady state analysis

Thermal-hydraulic analysis in the steady state condition of TRIGA 2000 core with U_3Si_2-Al silicide fuel with a density of 2.96 g/cc was carried out with MTR-DYN under forced convection cooling at a rated thermal power of 2 MW. Calculation results in steady state condition are shown in Table 3. The analysis was carried out when all control rods were 40 cm from the bottom because in this condition the value of power peaking factor (ppf) is maximum. The calculated maximum coolant temperature was 50.54 ^{o}C, cladding 85.16 ^{o}C and fuel 85.36 ^{o}C. Since the cladding temperature is much lower than the onset of nucleate boiling of 120 ^{o}C, no boiling happens in the core. The results of the maximum temperature distribution are shown in Fig. 5.

Table 3. Results of thermal hydraulic analysis of the equilibrium core of TRIGA Plate

Parameters	**Results**
Operating power (MW)	2.00
Coolant flow rate (kg/s)	59.50
Coolant velocity (m/s)	0.77
Average power density (W/m^3)	2.83E+07
Power peaking factors	
Radial	1.16
Axial	1.66
Kinetic Parameters	
Effective delayed neutron fraction	7.15×10^{-3}
Average neutron lifetime (μs)	59.83
Doppler temperature reactivity coefficient (%Δ*k*/*k*/K)	-1.91×10^{-3}
Moderator temperature coefficient (%Δ*k*/*k*/K)	-8.00×10^{-3}
Void (water density) reactivity coefficient (%Δ*k*/*k*/%void)	-3.86×10^{-3}
Thermal-hydraulics data	
Inlet temperature (^{o}C)	35.00
Oulet temperature (^{o}C)	43.05
Maximum coolant temperature (^{o}C)	50.54
Maximum clad outer temperature (^{o}C)	84.88
Maximum clad inner temperature (^{o}C)	85.16
Maximum fuel temperature (^{o}C)	85.36

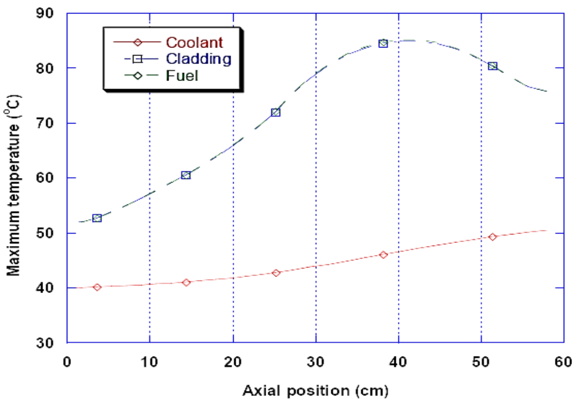


Fig. 5. Distribution of maximum temperature at steady state condition with the operating power (2 MW).

Transient analysis

Continous control rod withdrawal due to equipment damage or operator error can be a potential hazard for reactor operation. The reactor protection system is made by providing reactor core automatic shutdown and limiting accidental withdrawal of the control rods to protect the reactor core. The design of the TRIGA 2000 reactor allows the reactor to turn off automatically when the period of the instrumentation system is less than 10 s. If the period meter is assumed not to function, the scram by the time period cannot be expected to cause the occurance of the transient withdrawal of the rod. The amount of reactivity was determined from all four the control rod near to the center of the active core. The maximum gradient for the four control rod of TRIGA 2000 is 0.5732 % Δk/k/cm including the addition of 15 % for operation safety. The maximum speed of the control rod is 0.0564 cm/s, so the maximum reactivity insertion due to the withdrawal of the control rod is 32.33 pcm/s. Insertion of reactivity was carried out at 100 W and 1 MW to determine the effect of feedback reactivity at low and high power. The reactivity response due to reactivity insertion 32.33 pcm/s is shown in Fig. 6. The reactivity increases linearly until 0.849$ because there is no feedback reactivity at low power.

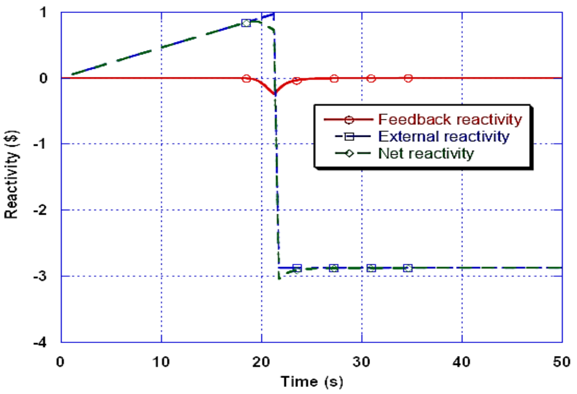


Fig. 6. Core reactivity response to reactivity insertion 2.33 pcm/s at initial power 100 W.

The increase in reactivity causes the supercritical reactor so that there is an increase in reactor power and scram will occur after reaching 2.2 MW of power. The time histories of the reactor power and energy released at the initial power of 100 W are shown in Fig. 7. The maximum power is achieved at 2.74 MW and occurs after 21.31 seconds delay. The increased power is very sharp because feedback reactivity is still inconsiderable.

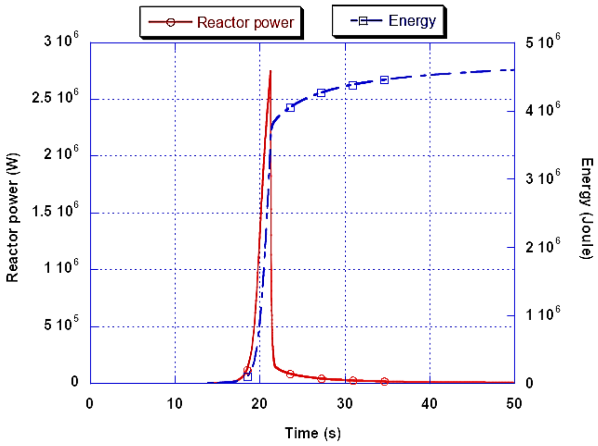


Fig. 7. Power profile and reactivity during reactivity insertion at initial power 100 W.

The calculation results of the distribution of coolant, cladding, and fuel temperature are shown in Fig. 8. The maximum coolant temperature is 51.23 °C, the cladding is 86.89 °C and the maximum temperature in the fuel element is 87.10 °C. This result shows that the core temperature at the time of reactivity insertion at low power, due to the withdrawal of the control rod, is still within safe limits.

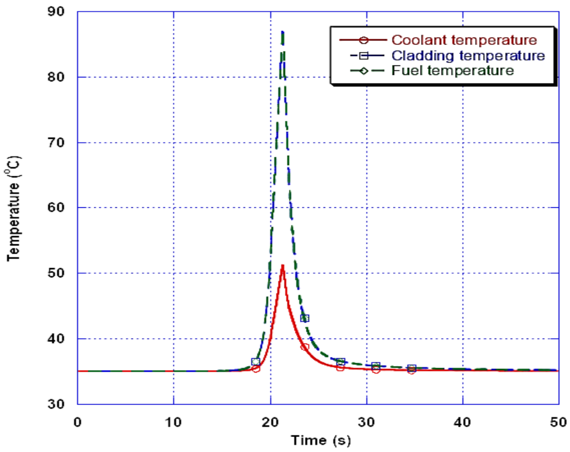


Fig. 8. The maximum temperature during reactivity insertion at initial power 100 W,

Insertion of reactivity in the power area was carried out at an initial power of 1 MW to determine the reactivity transient behavior. Reactivity response to an insertion of 32.33 pcm/s at the initial power of 1 MW is shown in Fig. 9. Transient reactivity depends on the amount of reactivity insertion and feedback reactivity mechanism. The net reactivity that is inserted into the core increases linearly and very quickly, which causes the supercritical reactor to increase the reactor power.

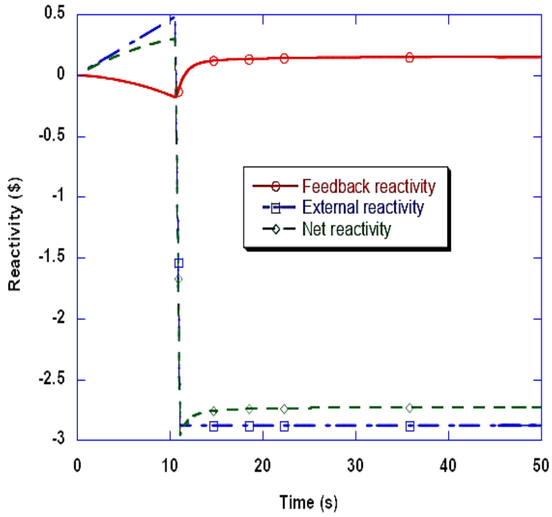


Fig. 9. Core reactivity response to reactivity insertion of 32.33 pcm/s at initial power 1 MW.

The power response increases exponentially and is slowed down by the effects of rapid Doppler feedback as shown in Fig. 10. During control rod withdrawal, the energy released does not cause an increase in reactor power due to an increase in coolant temperature. The maximum power achieved is 2.30 MW and occurs after 10.69 s. When the initial power is high (1 MW), the first peak occurs much earlier around 10.69 s compared to 21.31 s for the peak when the initial power is 100 W. However, the simulation shows that at reactivity insertion at 100 W the maximum power value achieved is 2.74 MW, which is greater than the 1 MW high power of 2.3 MW.

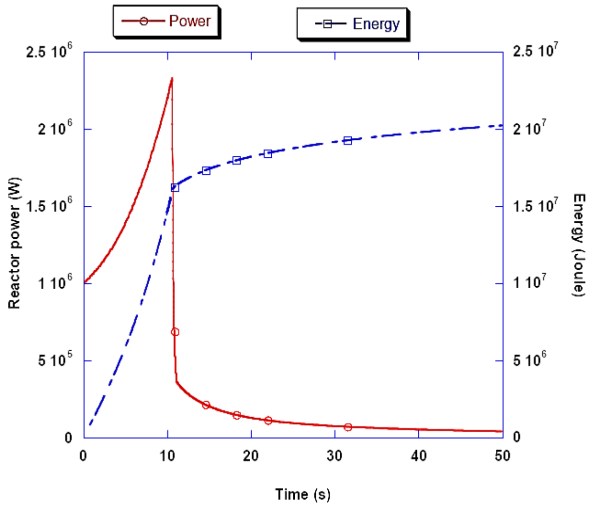


Fig. 10. Power profile and core reactivity during reactivity insertion at initial power 1MW.

The results of the calculation of the maximum coolant temperature, cladding and fuel are shown in Fig. 11. The maximum temperature for coolant is 51.96 ^{o}C, cladding 88.73 ^{o}C and around 88.96 ^{o}C in the fuel element. These results indicate that the core temperature at the time of high-power reactivity insertion due to the withdrawal of the control rod is still within safety limits.

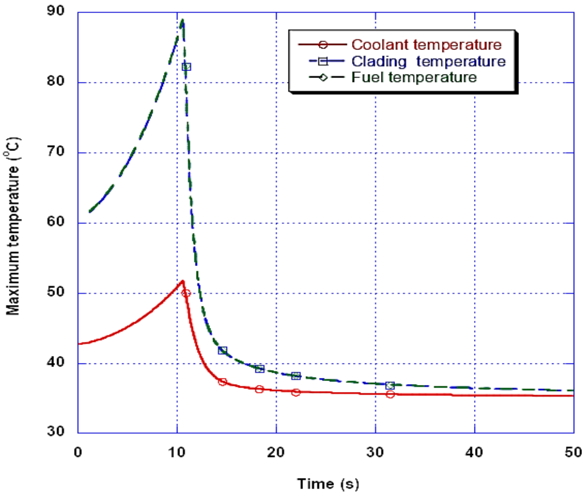


Fig. 11. The maximum temperature during reactivity insertion at initial power 1 MW.

CONCLUSION

An evaluation of reactivity insertion has been done for the safety of reactor operation. Based on the analysis results of the neutronic and thermodynamic parameters, it is indicated that the operation TRIGA 2000 core with silicide fuel is within safety limits. Therefore, other activities related to the preparation of the Safety Analysis Report (SAR) can proceed to confirm weather the TRIGA Bandung reactor can be converted to plate-type fuel reactor.

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