TRANSIENT CALCULATION ON TRIGA 2000 OF PLATE-TYPE FUEL ELEMENT USING RELAP5, EUREKA2/RR, AND MTR-DYN CODES

by

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The TRIGA 2000 reactor Bandung is proposed to convert from rod-type fuel to plate-type fuel because there are no manufacturers in the world that still produce rod-type fuel. Calculating the safety parameters and their reliability related to reactor operation has become an important thing to do. The objective of this study was to perform the reactor transient calculation of TRIGA 2000 that uses plate-type fuel. The reactor core modification is based on the capability of the existing primary coolant system, without changing its flow rates. Thermal-hydraulics calculations related to reactivity insertion accident and loss of flow accident were analyzed using EUREKA2/RR, MTR-DYN, and RELAP5 codes. The chosen loss of flow accident scenario is a decrease in flow caused by a sudden stop of the pump power supply, while reactivity insertion accident is conducted by the withdrawal of control rods with maximum reactivity insertion of 32.33 10^{-5} s^{-1}. The calculated parameters are reactivity, reactor power, and temperature of the coolant, cladding, and fuel in the hottest channel position. In general, from a safety point of view, those computer codes were capable of performing the transient calculations with appropriate results. Based on the calculation results, during the transient condition of both reactivity insertion accident and loss of flow accident scenario, the reactor operation safety parameters do not exceed the allowable safety limit.

Key words: TRIGA 2000 reactor, plate-type fuel, transient calculation, operation safety

INTRODUCTION

The TRIGA MARK 2000 reactor Bandung (TRIGA 2000) has been operated since 1964 using rod-type fuel produced by General Atomic USA. Currently, this rod-type fuel is no longer being produced, so core conversion to facilitate changing fuel to plate-type fuel becomes important [1, 2]. To convert the core, it is necessary to replace the core support so that plate-type fuel can be used in TRIGA 2000 core. The fuel element to be used is U_3Si_2-Al with 19.7 % enriched uranium and 2.96 gcm^{-3} uranium density. This silicide fuel is currently used in the RSG-GAS multi-purpose reactor and together with its control elements is produced locally by PT. Industri Nuklir Indonesia (INUKI). The neutronic calculations and core fuel management have been carried out in this core conversion. Based on the results of neutronic calculations, the plate-type fuel can be used in the TRIGA 2000 reactor [3-5].

Along with those neutronic calculations, some thermal-hydraulic calculation related to the safety of this conversion is required [6, 7]. Reactor thermal-hydraulic calculation is very important for reactor safety, and it is necessary to use various numerical simulation codes as a solver to this calculation [8, 9]. Based on the earlier study, it is recommended that core coolant flow need to be modified from upward natural circulation to downward forced circulation. Furthermore, the reactor core will be converted without changing the primary coolant flow rates. It is due to the existing primary coolant pump capability [10]. So, reactor thermal power is determined to be 1 MW.

As part of licensing the TRIGA MARK 2000 core conversion, safety analysis on reactivity insertion accident (RIA) and loss of flow accident (LOFA) which are postulated to occur in the reactor is needed as part of safety analysis report documents. Thermal hydraulic analysis conducted using several computer codes is often used to evaluate the safety of reactor operation. To achieve this purpose, a calculation of RIA and LOFA scenarios by using some numerical simulation codes is necessary [11, 12]. Various computer codes have been frequently used to calculate core parameters during steady-state and transient operation either in research reactors or nuclear power plants.

The RIA could be analyzed using the MTR-DYN code [11], which is a coupled neutronic and thermal-hydraulic code that has been developed for transient cal-

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culation when there are some disturbances related to reactivity that occurred on a research reactor. Meanwhile, the EUREKA2/RR code is also capable of calculating the transients behavior of RIA [12, 13]. Furthermore, LOFA could also be analyzed using EUREKA2/RR by adding a bypass flow model [14]. On the other hand, the RELAP5 code [15] is also widely used to calculate the transient behavior of the light water reactor cooling system, including the thermal-hydraulic characteristics of the research reactor [16].

The objective of this study is to calculate transient parameters of reactor that converted to use plate-type fuel. The RIA is calculated using both EUREKA2/RR and MTR-DYN. Meanwhile, the LOFA scenario is carried out using EUREKA2/RR and RELAP5 codes. The calculated parameters consist of reactivity, reactor power, and temperature of the coolant, cladding, and fuel at the hottest channel positions. Those parameters are important to calculate to ensure the safety of reactor operation.

REACTOR CORE DESCRIPTION

The TRIGA 2000 is an open-type research reactor in which the core is surrounded by a graphite reflector. In the conversion core, using the plate-type fuel, the equilibrium core uses 16 standard elements (FE) and 4 control fuel elements (CE) with 4 classes of fuel burn up as shown in fig. 1.

Table 1. Fuel element specifications

No	Design parameter	Values
1	Uranium fuel meat	
	Width [mm]	62.75
	Length [mm]	600.00
2	Length of fuel plate [mm]	625.00
3	Width of cooling channel [mm]	67.10
	Gap [mm]	2.557

The center of the core is used as central irradiation position (CIP), while irradiation position (IP) is on the edge of the core. The fuel element consists of 21 fuel plates and each fuel plate consists of an $AlMg_2$ frame sheet and two cover sheets with the same material, which enclose the U_3Si_2-Al dispersed fuel meat plate. The control element consists of 15 fuel plates and has the same external cross-section dimensions as the fuel element. Two of the three fuel element plates were replaced with aluminum plates. The absorber consists of two Ag-In-Cd blades coated with stainless steel (material 1.4541, same as SS321). The shape and specification of plate-type fuel elements are shown in tab. 1 and fig. 2.

The TRIGA 2000 has two primary cooling pumps for removing the heat from the primary coolant system to the secondary coolant system [17, 18]. In converting the reactor core, a natural circulation flap

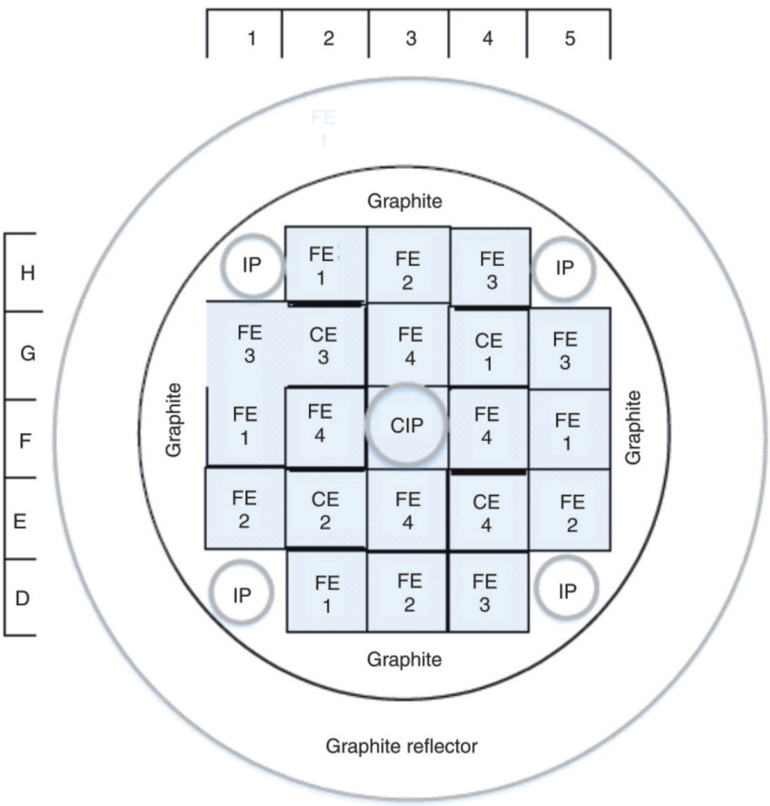

Figure 1. The equilibrium core configuration [3]
Note: IP = Irradiation position, CIP = Central irradiation positit

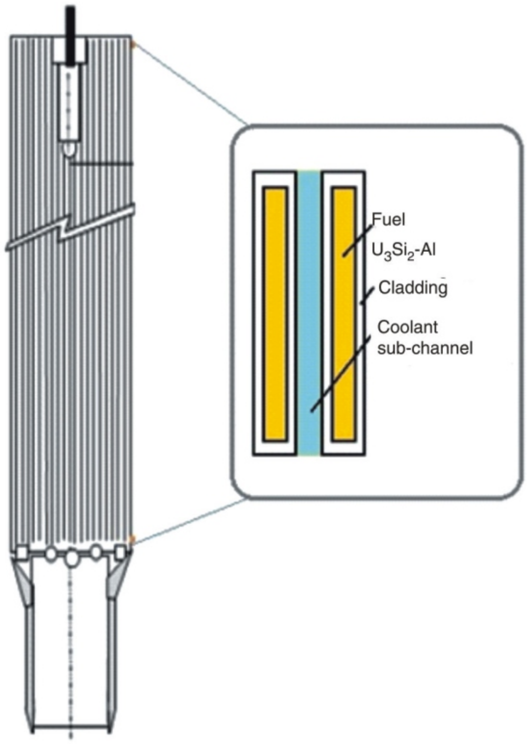

Figure 2. The plate-type fuel element [3]

Table 2. Input data of operating parameter for calculation

	Operating condition	Value
1	Thermal reactor power [MW]	1.00
2	Primary coolant mass-flow rate [kgs^{-1}]	50.0
3	Flowrate passes through the active core [%]	84.0
4	Inlet coolant temperature to the core [°C]	35.0
5	Inlet coolant pressure to the core [MPa]	0.158

will be installed in the core cooling system. At normal operation, the core coolant flow is in a downward direction.

METHODOLOGY

Steady-state calculation

In general, to calculate RIA and LOFA transient, there are two steps in the calculation process, the calculation for steady-state and transient conditions. Related to the safety aspect, the calculation is focused on the thermal-hydraulic parameter of the hottest channel in the core. Furthermore, this calculation uses the input data shown in tab. 2. Figure 3 is a schematic chart of the used methodology in the calculations.

The first step of the calculation is determining the steady-state parameters as an initial condition prior to the transient modeling. The steady-state benchmarking is calculated by the COOLOD-N2 code. This code has been well verified to analyze steady-state thermal-hydraulic of research reactor [19, 20].

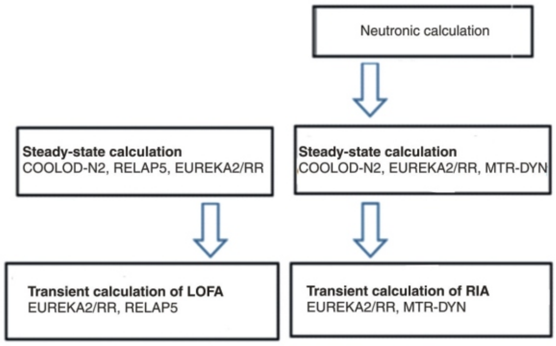

Figure 3. Schematic of steady-state and transient calculation

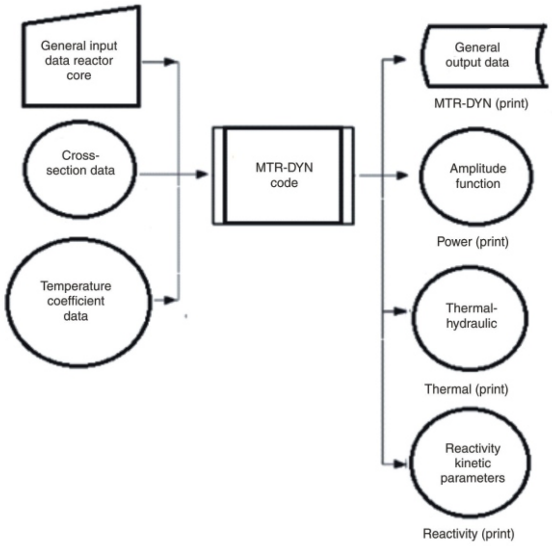

Figure 4. Flow chart diagram for MTR-DYN

The next step is to perform RIA calculation using EUREKA2/RR and MTR-DYN codes [11]. Meanwhile, thermal hydraulics of LOFA is calculated by EUREKA2/RR and RELAP5.

The MTR-DYN is a 3-D model of coupled neutronic, and thermal-hydraulic code used to calculate RIA. The reactivity addition to triggering a criticality transient is simulated by perturbation in a neutronic calculation, which is very accurate for large reactivity addition like in control rod withdrawal events. Therefore, the user is responsible for preparing neutron cross-section data for both initial and perturbed conditions. The macroscopic cross-section of core materials was generated using WIMSD/5 code [21], ENDF/B.VII.1 library and it collapsed its 69 groups of neutron energy into 4 neutron energy groups. Coupled neutron-dynamics and thermal-hydraulics modules could give the best estimation in the temperature of the fuel, cladding, and the coolant [22, 23]. Figure 4 shows the calculation diagram of the MTR-DYN code.

The EUREKA2/RR is a coupled point kinetic, neutronic, and thermal-hydraulics code that was de-

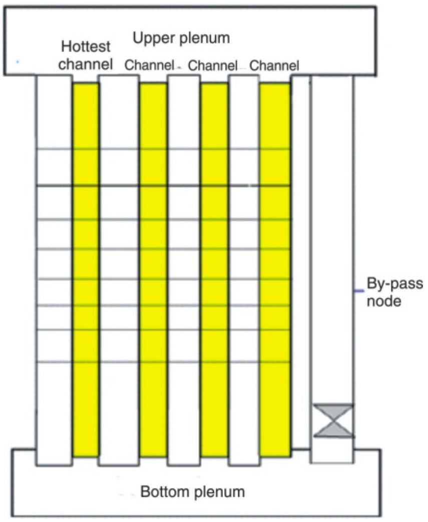

Figure 5. Analysis model for EUREKA2/RR

veloped by JAEA Japan. It can be used to calculate the reactivity accident on research reactors. The code was modified by adding a heat transfer package for research reactors, and this code is suitable for a system that operates with low temperature and pressure. In EUREKA2/RR, the modeling of the core consists of the upper plenum, bottom plenum, standard fuel element, and control element. The core model was divided into 4 channels regions, with one of the channels in the hottest channel position. In the LOFA model, a bypass node is added to simulate the model of natural circulation in case of reverse flow current direction as shown in fig. 5.

The RELAP5 is also a computer code widely used to simulate a light water reactor for thermal-hydraulic analysis, interactions of a control system, and transport

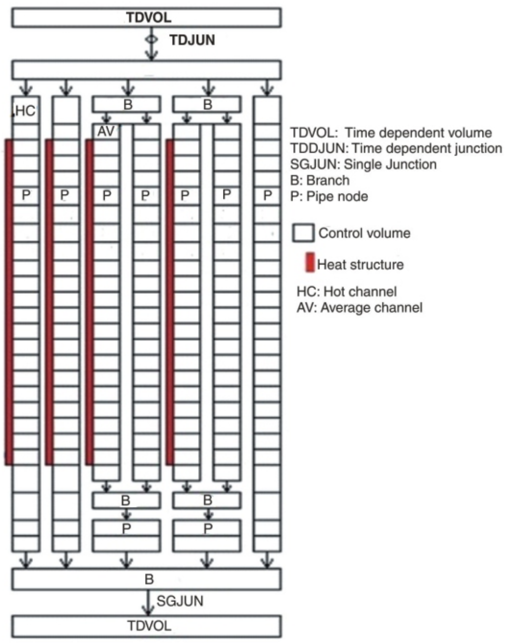

Figure 6. Nodalization for RELAP5

of fluids. This code was developed by the IDAHO National Engineering Laboratory (INEL) in the USA. Furthermore, the Innovative System Software (ISS) developed this code as RELAP/SCDAPSIM/Mod3.4 [15]. In this code, for this study, the reactor core was modeled into a hot and average channel, with a time-dependent volume as a model of water above the reactor core, and water below the reactor core is represented as the heat sink as shown in fig. 6.

Reactivity insertion accident

The RIA is carried out by withdrawing the control rod continuously, with a maximum reactivity insertion rate of 32.3 10^{-5} s^{-1}. The reactor will shut down when the linear power coming from the neutron flux detector exceeds 118 % of the nominal power. The reactivity insertion transient is carried out at 1 MW initial power, the core is cooled with a forced convection model with an inlet coolant temperature of 35 °C.

Loss of flow accident scenario

The LOFA scenario is postulated as a decrease in flow caused by a sudden stop in the coolant pump power supply. Therefore, the reactor must be protected against the LOFA. The reactor protection system (RPS) initiates by sending a Scram signal to the reactor when the primary coolant flow rate reaches 85 % of its normal value of 50 kgs^{-1}, and the delay time for reactor Scram is 0.5 seconds. The Scram means that the reactor is shut down by dropping the control elements into the core. During the LOFA transient, the residual coolant flow rate decreases rapidly, in which the downflow of the primary cooling system only takes 9.0 seconds [14, 17].

RESULT AND DISCUSSION

Result of steady-state condition

The purpose of calculating the steady state is to know the parameters on the initial state of the reactor which operates under normal conditions. The calculation results of steady-state parameters using various codes are shown in tab. 3. It shows a good agreement between all codes used in calculating coolant velocity, heat flux, and temperature of cladding and fuel. The highest difference of 5.6 % occurs in the outlet coolant temperature between EUREKA2/RR and MTR-DYN code. All codes were used to give consistent results for steady-state calculation, and all parameters are still within the limits of the safety of the reactor in normal operation.

Tabel 3. Operating parameter of steadystate

Hottest channel	COOLOD-N2	EUREKA2/RR	RELAP5	MTR-DYN
Coolant velocity [cms^{-1}]	65.37	69.09	69.20	69
Fuel temperature [°C]	57.72	56.40	57.70	58.04
Saturation temperature, TSAT [°C]	113.12	115.67	114.16	114
Onset nucleat boiling temperature, T^*_{ONB} [°C]	116.38	117.62*	116.12*	115.96*
Cladding temperature, [°C]	57.42	55.60	56.97	57.94
Outlet coolant temperature [°C]	43.04	43.71	43.80	43.08
DNBR**	5.37	7.96	6.15	–
Heat flux [Wm^{-2}]	83517	83273	83482	83840

* TONB is calculated by Bergles-Rohsenow corelation; ** DNBR – Departure from Nucleate Boiling Ratio

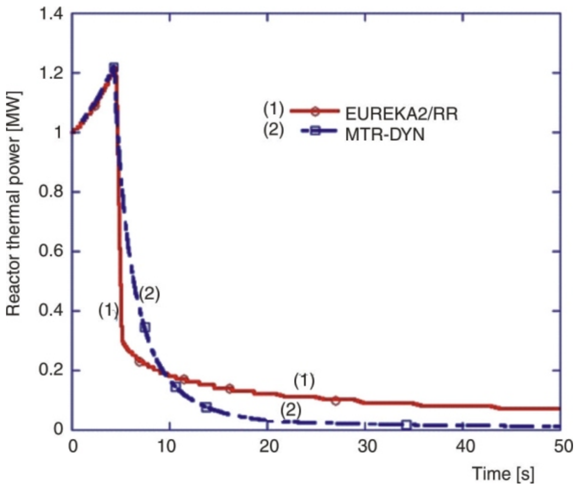

Figure 7. Reactor power profile during RIA transient

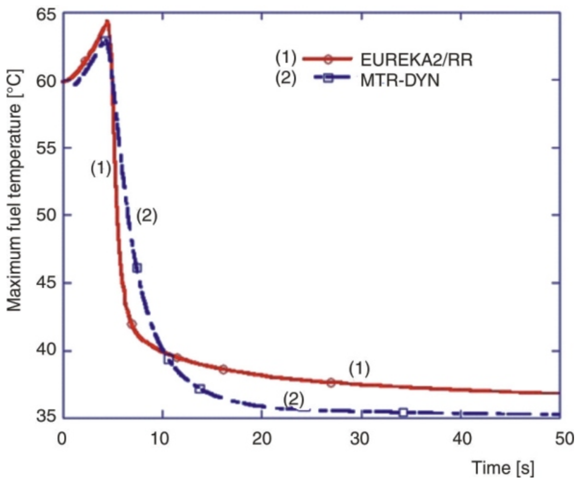

Figure 8. Maximum fuel temperature profile during RIA transient

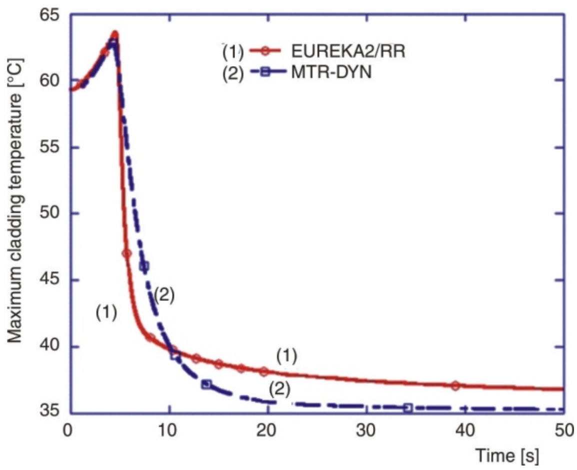

Figure 9. Maximum cladding temperature profile during RIA transient

Result of RIA transient

The RIA calculation is very important to be analyzed as a design basis accident for TRIGA 2000, especially in terms of converting it to use plate-type fuel. In this study, it was performed using both MTR-DYN and EUREKA2/RR codes. The calculation was started as reactivity insertion occurring in the reactor at initial power of 1 MW. In RIA transient, the reactor power is dependent on core reactivity, as well as feedback reactivity. So, a change in reactor power is affected by a change in core reactivity. The results of transient core power calculation are shown in fig. 7. As shown in this figure, the maximum power generated by MTR-DYN is 1.22 MW which is achieved after 4.31 seconds. Meanwhile, based on the calculation by the EUREKA2/RR, the maximum power of 1.22 MW is achieved after 4.40 seconds. A comparison of peak time and peak power between MTR-DYN and EUREKA2/RR codes shows that ther were no significant differences.

The maximum temperatures of fuel and cladding are shown in figs. 8 and 9. The calculated maximum fuel temperature from EUREKA2/RR and MTR-DYN is 64.33 °C and 62.92 °C, respectively. Furthermore, maximum cladding temperatures are 63.65 °C and 62.79 °C, respectively. So, the maximum temperature of this transient is still in good agreement and consistent with the results of EUREKA2/RR and MTR-DYN.

As we know, the maximum temperature is represented by the outlet cooling flow. This is the temperature at which the maximum is reached along with the axial flow. The outlet coolant flow temperature profile during the RIA transient is shown in fig. 10. This figure shows a small difference of 1.1 °C at the beginning of transient (steady-state calculation), but the curve pattern of EUREKA2/RR with MTR-DYN confirms a good agreement.

Calculated maximum temperatures of coolant, cladding, and fuel are shown in tab. 4. The maximum

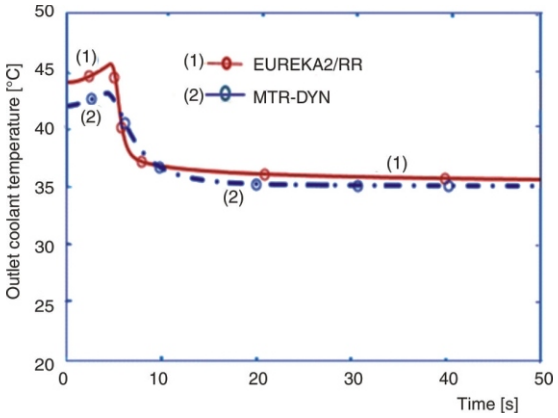

Figure 10. Outlet coolant flow temperature during the RIA transient

Table. 4. Maximum temperature of coolant, cladding, and fuel element

Parameters	EUREKA2/RR	MTR-DYN	Difference [%]
Fuel temperature [°C]	64.33	62.92	2.19
Cladding temperature [°C]	63.65	62.79	1.35
Coolant temperature [°C]	45.76	44.93	1.81

difference between EUREKA2/RR and MTR-DYN calculations is 2.19 %. Based on tab. 4, there is no boiling in the reactor coolant because the maximum temperature of the coolant is still below the boiling temperature. The maximum temperature of fuel and cladding is 64.33 °C and 63.65 °C, respectively, on EUREKA2 /RR, which is still below the fuel and cladding melting points of 200 °C and 600 °C. These results indicate that reactor operation due to RIA is still within safety limits.

Result of LOFA transient

The reactor power calculation is also performed in the LOFA transient, the Scram triggered as primary coolant flow rate reaches 85 % after 0.8 seconds. As depicted in fig. 11, the curve pattern of reactor power shows the EUREKA2/RR is in good agreement with the RELAP5.

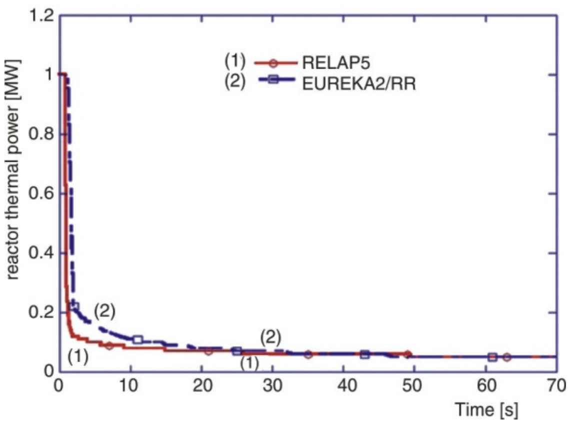

Figure 11. Power profile during LOFA transient

Figures 12 and 13 show the results of temperature transient of fuel and cladding respectively. In those figures, the temperature between the fuel and the cladding is slightly different. Peak temperatures occurring just after the beginning of the transient due to the coolant flow rate decreasing rapidly. Fuel and cladding temperature reach 58.97 °C and 58.74 °C on EUREKA2/RR. Meanwhile, the fuel and cladding temperatures reach 61.48 °C and 60.64 °C on RELAP5. The Scram of the reactor causes the temperature to decrease. Otherwise, coolant flow decreases rapidly, while cladding temperature increases for a moment. Furthermore, the residual decay heat is cooled by natural convection.

The outlet coolant temperature during LOFA transient is shown in fig. 14. This figure shows that by decreasing the outlet coolant temperature, the difference at a maximum temperature between the EUREKA2/RR and RELAP5 is 0.4 °C. The difference in the transient curve from these two codes is caused by several reasons such as nodalization effect, numerical solution, and initial conditions, but a decrease in the temperature curve indicates the consistent trend of the two codes.

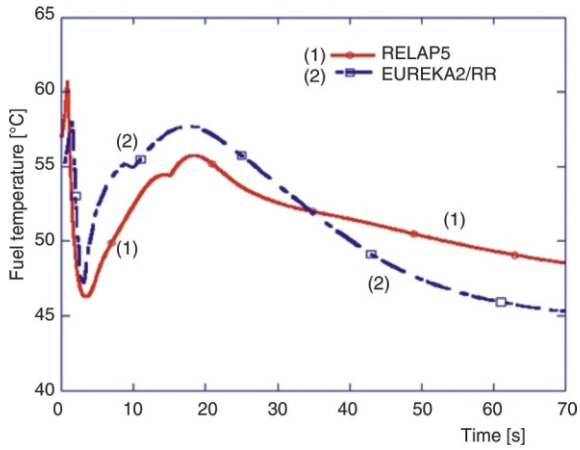

Figure 12. Maximum fuel temperature profile during LOFA transient

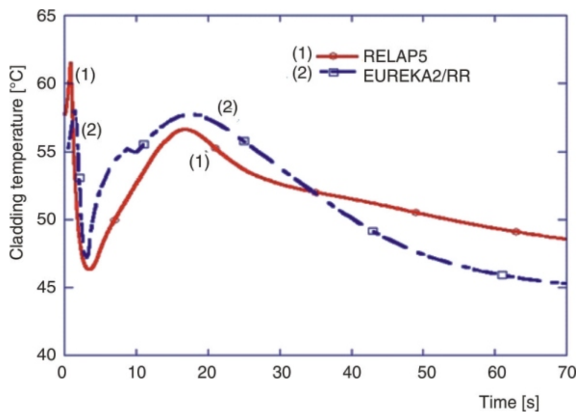

Figure 13. Maximum cladding temperature profile during LOFA transient

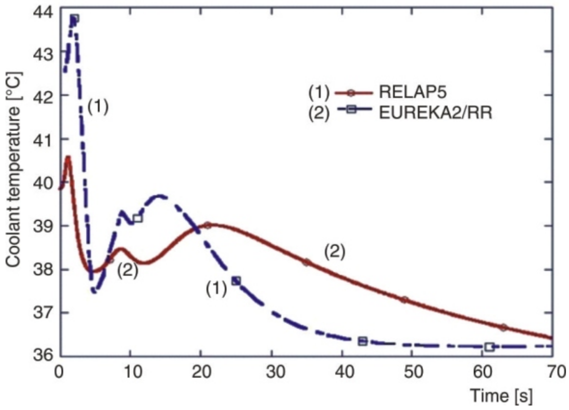

Figure 14. Outlet coolant flow temperature during the LOFA transient

Table 5. Maximum temperature at hottest channel under LOFA transient

Parameters	EUREKA2/RR	RELAP5	Difference [%]
Fuel temperature [°C]	58.97	61.48	4.0
Cladding temperature [°C]	58.74	60.64	3.1
Outlet coolant temperature [°C]	44.78	45.18	0.8

The maximum temperature at the hottest channel under LOFA transient could be seen in tab. 5. The maximum difference between EUREKA2/RR and RELAP5 is 4.0 %. There is no boiling on the hottest channel position, in which the coolant temperature and cladding temperatures are far below the temperature of onset nucleate boiling of 116.12 °C or even the saturation temperature of 114.16 °C. In other words, damage in the fuel elements caused by the melting of fuel cladding could be avoided.

Based on the consistency of the results from RELAP5, EUREKA2/RR, and MTR-DYN codes, the transient state for both RIA and LOFA scenarios is validated to be within the safety margin on TRIGA 2000. It shows an appropriate transient pattern, as well as a good agreement for all parameters of reactor power, cladding temperature, fuel temperature, and coolant temperatures. In general, at 1 MW power and mass flow rate of 50.0 kgs^{-1}, the calculation results show that reactor operation regarding the core modification to facilitate its conversion to plate-type fuel was ensured within the safety limits.

CONCLUSION

The RIA has been calculated by comparing the result of EUREKA2/RR with MTR-DYN and the LOFA has been compared between EUREKA2/RR and RELAP5. Regarding the modification of the reactor core, using a plate-type of U_3Si_2-Al silicide fuel, from the safety point of view, all mentioned codes were capable of performing the transient calculations with appropriate results. In general, the differences in the result from those codes are caused by several reasons such as nodalization effect, and numerical solution. The reactor is safely operated at 1 MW thermal power and 50 kgs^{-1} mass flow rate using the primary coolant pump. The calculation results showed that the transient state of both LOFA and RIA does not exceed the allowable safety limits.

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AUTHORS' CONTRIBUTIONS

S. Dibyo is the first author, main implementer, and contributor in the application of the EUREKA2/RR code for the research. S. Pinem is the main contributor who conducted the calculation of the MTR-DYN Code, gave the main idea for the research, and carried out the review. S. Widodo is a contributor to the research and supplied calculations using the RELAP5 code. The editing was carried out equally by all authors.

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Сукманто ДИБЈО, Суријан ПИНЕМ, Сурип ВИДОДО

ПРОРАЧУН ПРЕЛАЗНИХ СТАЊА РЕАКТОРА TRIGA 2000 СА ГОРИВОМ У ВИДУ ПЛОЧА КОРИШЋЕЊЕМ RELAP5, EUREKA2/RR И MTR-DYN ПРОГРАМА

Како у свету нема произвођача који још увек производе гориво у виду шипке, предложено је да се реактор TRIGA 2000 Бандунг са горивном шипком преведе у реактор са горивом у виду плоче. Прорачун сигурносних параметара и њихове поузданости у вези са радом реактора постао је важан задатак. Циљ овог рада је да се прорачунају прелазна стања реактора TRIGA 2000 који користи гориво у виду плоче. Модификација језгра реактора заснована је на могућностима постојећег система примарног хладиоца, без промене његове брзине протока. Термохидраулички прорачуни који се односе на акциденте уношења реактивности и губитка протока анализирани су коришћењем кодова EUREKA2/RR, MTR-DYN и RELAP5. Одабрани сценарио акцидента губитка протока је опадајући проток хладиоца изазван изненадним прекидом напајања пумпе, док акцидент унете реактивности настаје извлачењем контролних шипки са максималном унетом реактивношћу од 32,33 10^{-5} s^{-1}. Рачунати су параметри реактивности, снаге реактора и температуре расхладне течности, кошуљице горива и горива у положају најтоплијег канала. У погледу сигурности, ови рачунарски кодови били су способни да изврше транзиционе прорачуне са одговарајућим резултатима. На основу прорачуна, током прелазног стања услед акцидената уношења реактивности и сценарија губитка протока, параметри рада реактора не прелазе дозвољену границу сигурности.

Кључне речи: реактор TRIGA 2000, плочасто гориво, прорачун прелазних стања, сигурност рада