



## Analysis on The Performance of The Bandung Conversion Fuel-Plate TRIGA Reactor in Steady State with Constant Coolant Flow Rate

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### ABSTRACT

Bandung TRIGA2000 Reactor, a General Atomic (GA)-made research reactor used for training, research and isotope production, has been upgraded to operate at power of 2000 kW using TRIGA fuel rod type. Recently, the TRIGA reactor fuel element producers are going to discontinue the production of TRIGA fuel element. To overcome the unavailability of TRIGA fuel element, BATAN planned to modify TRIGA2000 fuel type from rod-type to  $U_3Si_2$ -Al plate-type fuel with 19.75% enrichment, similar to the domestically fabricated one used in RSG-GAS. The carried out design emphasized on the determination of operation condition limits for setting the reactor protection system in accordance to the reactor safety calculation results. The conceptual design of the innovative fuel plate TRIGA reactor cooling system is expected to remove heat generated by fuels with nominal power of 1 MW up to 2 MW. The design is developed through modelling and safety analysis using COOLOD-N2 validated code. The safety margin is set to its flow instability at transient condition of the fuel plate, which is  $\geq 2.38$ ; departure from nucleate boiling ratio  $\geq 1.50$ ; and no onset of nucleate boiling,  $\Delta T_{ONB} \geq 0^\circ C$ . The primary coolant flow rate accommodating the existing Bandung TRIGA reactor capability is as high as 50 kg/s. The analysis results show that at power of 1 MW, the reactor can safely operate, while at power of 2 MW the safety margin is exceeded. In other words, the plate TRIGA reactor that employs forced convection mode operates safely at 1 MW with excess power 120% of its nominal power.

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## 1. INTRODUCTION

According to the publication released by the IAEA, the number of TRIGA reactors in the world reaches 68 units: 38 units in operation, 19 units not in operation, and 11 units decommissioned. Some of the TRIGA reactors have been operated since 1958 and the newest units have been operated since 2007 [1]. TRIGA 2000 reactor located in Bandung, used for Training, Research, and Isotope production of General Atomic (GA), has been upgraded to

operate at 2000 kW using TRIGA cylindrical fuel type. However, presently, it is difficult to obtain TRIGA fuel as it is no longer manufactured. This condition made TRIGA operators decide to convert the cylindrical-type fuel into plate-type fuel. The conversion is supported by production capability of  $U_3Si_2$ -Al fuel plate with 19.75% enrichment, as acquired by Indonesia. Another country that is able to convert TRIGA fuel is Vietnam. The fuel of TRIGA-Dalat has been converted from fuel rod to double fuel plate with Russian assistance [2].

BATAN has planned to perform TRIGA fuel modification from cylindrical type to  $U_3Si_2$ -Al plate type with 19.75% enrichment, as the ones produced

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by Indonesia for RSG-GAS research reactor. Research and development of the plate-fuel TRIGA reactor has been carried out since 2005. The preliminary design of the thermalhydraulic aspect of plate fuel TRIGA and 2 MW core physics has been initiated [3-6]. Sujatmi et al. have conducted free convection cooling mode analysis [7]. In 2016, this research and development was continued with the emphasis on the thermalhydraulic and reactor core design using various existing reactor calculation codes.

To support this program, analysis on many aspects, starting from reactor physics calculation to structure, system, and component design, are required. This research will complete the design developed from the thermalhydraulic safety aspect to determine the setting of reactor protection system based on reactor safety calculation. The analysis and determination of operating limits condition (OLC) are carried out using validated codes. The postulated initiating events (PIE) are selected based on safety requirements in the Safety Analysis Report of research reactor and BAPETEN Chairman Regulation as well as the IAEA Safety Requirement [8-9].

The design of reactor core thermalhydraulic was performed as it is to develop a new core, since the core geometry and fuel are completely different. The rod-type TRIGA reactor employs natural convection mode, while the plate-type TRIGA reactor uses force convection mode for the cooling system, in order to maximize power and flux. It is essential to take into account core conversion policies, such as maintaining the existing cooling system design or determining the conversion reactor core power by modifying the cooling system. Subekti et al. have performed analysis of coolant velocity in plate-type fuel element using CFD method for RSG-GAS [10]. Meanwhile, Endiah et al. also have carried out an analysis on flow rate distribution in the plate-type TRIGA reactor core using Caudvap code, of which one of the results is that the coolant flow rate through the fuel plate is 88.2% [11].

This paper describes a thermalhydraulic analysis based on neutronic calculation result. The analysis is carried out with two options: maintaining the existing system design or determining the reactor powers, in this case at the nominal power of 1 MW and 2 MW. The purpose of selecting these two reactor powers is to maintain the design of the TRIGA Bandung 2000 kW (2MW) reactor that has been achieved previously. Meanwhile, to anticipate the primary coolant flow rate that is maintained at 50 kg/s, which has an impact on the ability to dissipate the heat generated,

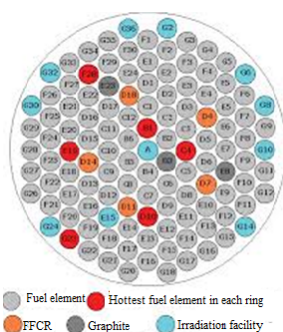
it is important to take into account the safety analysis of the 1 MW reactor power. In addition, the possibility of power surges due to loss of coolant flow accident must be anticipated. For this reason, the safety analysis needs to take into account the increase in reactor power up to 120% of the nominal power. This value will be needed to determine the set point in the reactor protection system. The thermalhydraulic analysis on forced convection is calculated using COOLOD-N2 code with still accommodating the coolant flow rate capability of the Bandung TRIGA reactor, while the neutronic design is performed by the core calculation group [12].

## 2. THEORY

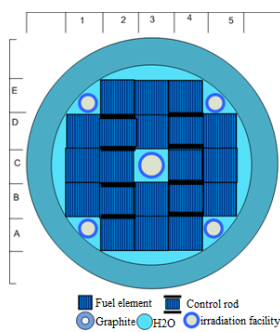
### *The Cooling System of the Innovative Fuel Plate TRIGA Reactor*

The innovative plate-type TRIGA reactor employs forced convection cooling mode to substitute natural convection cooling mode, which has been used in the rod-type TRIGA reactor. The conceptual design of the cooling system of the innovative plate-type TRIGA reactor is developed to remove heat generated by the fuel with nominal power of 2 MW. This system should be maintained to function in any condition. To make forced circulation cooling during normal operation, the primary cooling system is equipped with three centrifugal pumps in downward direction to the core through the hot leg and the delay chamber. The latter is designed to contain N-16 radioisotope in safe margin. The primary coolant leaves the delay chamber and transfer the heat to a heat exchanger and returns to the reactor core. During shutdown, where no fission reaction occurs, the fuel should be cooled by forced convection mode. The thermalhydraulic parameters of the cooling mode are analyzed for steady state and transient states. The objectives of the analysis are to obtain reactor core responses at the most severe postulated operational events or accident condition and to determine safety margin for steady state and transient states.

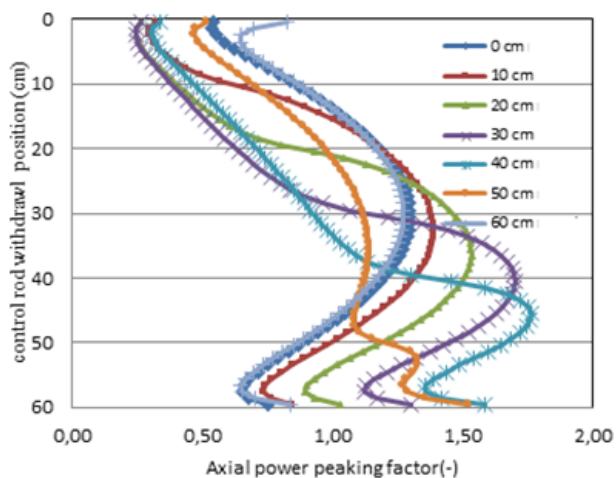
Determination of the fuel plate TRIGA reactor operation limits condition is carried out by calculation based on the results of analysis given by the neutronic/physics group. The fuel used is  $U_3Si_2$ -Al with fuel loading of  $2.96 \text{ gU/cm}^3$ , which dimension is similar to that currently used in the RSG-GAS. The core configuration of the converted TRIGA reactor consists of 16 fuel elements and 4 control rods, with 5 irradiation positions. The core configuration and plate fuel TRIGA reactor conversion are shown in Figs. 1a and 1b.



**Fig. 1a.** TRIGA core configuration [3]



**Fig. 1b.** TRIGA Plate core configuration [12]



**Fig. 2.** The axial PPF as function of control rod position [12]

The calculation is performed at average power channel and the hottest power channel. The calculation for the highest power channel has considered the neutronic calculation results and technical uncertainties. For heat transfer of forced convection mode, the calculation is done at nominal power of 1 MW and 2 MW, with the operation limit is set at maximum 120% of each nominal power. The calculation and analysis can be performed using several codes of heat transfer of forced convection mode at the square channel to obtain optimum degree of certainty. The results shown are obtained from COOLOD-N2 code.

**Safety Margin Determination**

The basic criteria applied to the thermalhydraulic design of fuel plate TRIGA reactor are assurance towards sufficient safety margin at normal operation. The first criterion applied is no onset of nucleate boiling of the coolant in order to prevent the occurrence of burnout of the fuel plate at or any other spots in the reactor core, so that flow instability induced by nucleate boiling in core does not occur and to obtain flux neutron stability for

experiment. Meanwhile, determination of the minimum coolant flow rate is an operation condition limit used in all reactor safety calculations.

Therefore, the minimum coolant flow rate should be determined based on the following technical requirements of many various aspects:

- Flow instability at transient state at fuel plate is  $\geq 2.38$ ;
- Departure from nucleate boiling ratio is  $\geq 1.50$ ;
- No onset of nucleate boiling,  $\Delta T_{ONB}$  is  $\geq 0^\circ\text{C}$ .

**3. METHODOLOGY**

The steps carried out including the thermalhydraulic calculation at steady state using various calculation variables to obtain particular degree of certainty of the results. For this calculation, COOLOD-N2 code is used. COOLOD-N2 code is a calculation code used to analyze thermalhydraulic characteristics of research reactor at steady state. This code is further development of COOLOD-N, which is used to compute thermalhydraulic parameters of either rod or plate-type fuel. The calculation results are then employed to model and determine operation condition limits of accident types as a part of the Safety Analysis Report.

**Input data**

The data for the thermalhydraulic calculation input of the innovative fuel plate TRIGA reactor is obtained from the available data of the existing cooling system. Table 1 shows the core physics parameters, fuel dimension, reactor core dimension, and thermalhydraulic parameters.

**Table 1.** Main data on TRIGA fuel plates conversion Bandung

Parameters	Value
Reactor power, MW	1 and 2
Neutron flux of equilibrium core	$6.040 \times 10^{13}$
	4/1, n/cm <sup>2</sup> .s
Power density (W/cc)	0.3822
Average radial power peaking factor	1.2971
Maximum burn-up, %	1.442
Coolant flow rate, kg/s	50
The flowrate of water through fuel channels, %	88.2
<i>Standard fuel element</i>	
Material	U <sub>3</sub> Si <sub>2</sub> -Al
Low Enrichment, %	19.75
fuel mass, gr	250
Cladding material	AlMg <sub>2</sub>
Number of standard fuel element	16

Parameters	Value
Number of plate	21
Number of coolant channel	20
Fuel element cross section geometry, mm	75.7x67.1x51.5
Coolant channel gap, mm	2.55
Plate geometry, length x width x thick, mm	625x70.75x1.3
Meat geometry, length x width x thick, mm	600x62.75x0.54
<i>Control Element</i>	
Material	AgInCd
Number of control elements	4
Number of plates	15
Number of coolant channel	14
Coolant geometry, length x width x thick, mm	625x70.75x2.55
Absorber material	Ag-In-Cd

**Table 2.** Input data for thermalhydraulics calculation of TRIGA Plate reactor

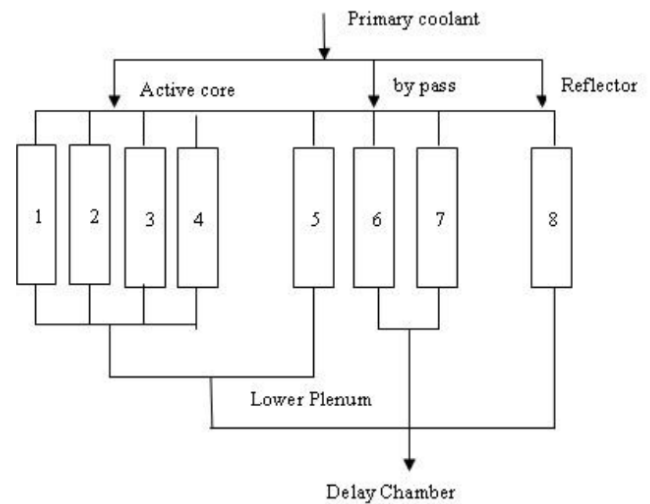
No.	Parameters	Average channel	Highest channel
1.	Reactor power, MW	2.0	2.2
2.	Inlet Temperature, °C	35	35
3.	Primary coolant flowrate 85%, kg/s	50	50
4.	FRATE, core flow rate, %	90	88.2
5.	PPF axial, FA	FA x 1.0	FA x 1.1
6.	Inlet pressure, bar	1.583	1.583
7.	PPF radial, FR	2.0721	2.0721 x 1.35x 1.2
8.	Fcool	1.000	1.167
9.	Ffilm	1.000	1.260
10.	Fhflx	1.000	1.200
11.	F clad, F bond, Fmeat, Floc	1.000	1.000

The axial power peaking factor (PPF) as a function of control rod positions is shown in Fig. 2.

#### 4. RESULTS AND DISCUSSION

Calculation of the thermalhydraulic safety of the conversion fuel plate TRIGA reactor is analyzed at operation power level and anticipated excess power of 120% of nominal power, i.e. 1.0 MW, 1.1 MW, 1.2 MW, and 2.0 MW, 2.1 MW, and 2.2 MW. The primary coolant flow rate into the reactor core is divided to transfer heat generated by the active core, which consists of fuel and control elements. In addition, the primary coolant also transfers heat from the irradiation facility and the

gap between the fuel, and reflector, as depicted in Fig. 3. The primary coolant flow rate is, based on the available pumps, set 50 kg/s, 88.2% of which flows through fuel plate gap.



**Fig. 3.** The coolant flow distribution model in the modified TRIGA plate reactor

Flow in the active core indicate by number 1, 2, 3 and 4 each are: coolant channel in the fuel elements, in the control element, outer channel of fuel element and channel in side blade of control element, respectively. Meanwhile, coolant through the bypass flow are 5, 6 and 7, each are coolant channel between two fuel elements, in the endfitting of IP and in the endfitting of the CIP, respectively. Coolant channel in the reflector is indicated by no 8.

The maximum inlet coolant temperature is set at 35°C. Meanwhile, the calculation of the core physics group results in radial and axial power peaking factor (PPF). The axial PPF reaches its maximum value when control rods are withdrawn as high as 30 cm from the reactor core. Calculation has been performed at the average channel and the hottest channel, each of which represents fuel positions having average heat flux and the highest heat flux. The calculation results of forced convection mode at the average channel and hottest channel are shown in Table 3 and Table 4. Table 3 shows the calculations results of the average channel. To anticipate the occurrence of reactor power surges in the event of loss flow accident, the calculation analysis are performed on the reactor's power of 1 MW, 1.1 MW and 1.2 MW, respectively. Table 4 shows the results of the calculation of the thermalhydraulic parameters on the hottest channel, where this channel represents the position of the fuel channel with the maximum axial and radial power peaking factor. The difference in the generation of heat flux between the average and the hottest channel is shown by differences in cladding

and meat temperature and  $\Delta T$  core. Using the DNBR value limit of 1.5, and  $\Delta T$  ONB  $> 0^\circ\text{C}$ , the safety analysis at the reactor power of 1 MW still meets the specified safety margin.

**Table 3.** Thermalhydraulics characteristic in average channel, 1 MW

Parameter	Reactor power (MW)		
	1.0	1.1	1.2
T in, °C	35.0	35.0	35.0
T out, °C	40.64	41.20	41.76
$\Delta T$ core	5.664	6.2	6.76
T cladding, °C	51.30	52.88	54.45
T meat, °C	51.52	53.3	54.72
heat flux, W/cm <sup>3</sup>	231.68	254.85	278.02
velocity, m/s	0.6873	0.6875	0.6877

**Table 4.** Thermalhydraulics characteristic in hottest channel, 1 MW

Parameter	Reactor power (MW)		
	1.0	1.1	1.2
T in, °C	35.0	35.0	35.0
T out, °C	52.84	54.62	56.40
$\Delta T$ core	17.84	19.62	21.4
T cladding, °C	87.00	91.79	96.51
T meat, °C	87.61	92.46	97.24
heat flux, W/cm <sup>3</sup>	791.74	870.91	950.09
TONB	118.24	118.47	118.69
$\Delta T$ ONB	35.02	26.68	22.19
DNBR	2.47	2.25	2.06
OFIR	2.01	1.83	1.68

Furthermore, to determine the effect of the coolant flow rate of 50 kg/s and the coolant inlet temperature of  $35^\circ\text{C}$  against the reactor thermalhydraulics and safety parameters, the analysis was carried out on the reactor power of 2 MW, 2.2 MW and 2.4 MW, respectively, as shown in Table 5 and Table 6. Table 5 shows the parameters on the average channel, while Table 6 on the hottest channel. It appears that the onset of nucleate boiling has occurred at the 2 MW, likewise the safety margin against DNBR is insufficient. Safety limit values also do not meet the requirements for over power. The primary coolant flow rate of 50 kg/s and an initial inlet temperature of  $35^\circ\text{C}$  are not sufficient for 2 MW safety requirements reactor operation.

**Table 5.** Thermalhydraulics characteristic in average channel, 2 MW

Parameter	Reactor power (MW)		
	2.0	2.2	2.4
T in, °C	35.0	35.0	35.0
T out, °C	44.57	45.53	46.48
$\Delta T$ core	9.57	10.53	11.48
T cladding, °C	66.81	69.82	72.81
T meat, °C	67.15	70.2	73.21
heat flux, W/cm <sup>3</sup>	248.38	273.0	298.05
velocity, cm/s	68.95	69.0	69.05

**Table 6.** Thermalhydraulics characteristic in hottest channel, 2 MW

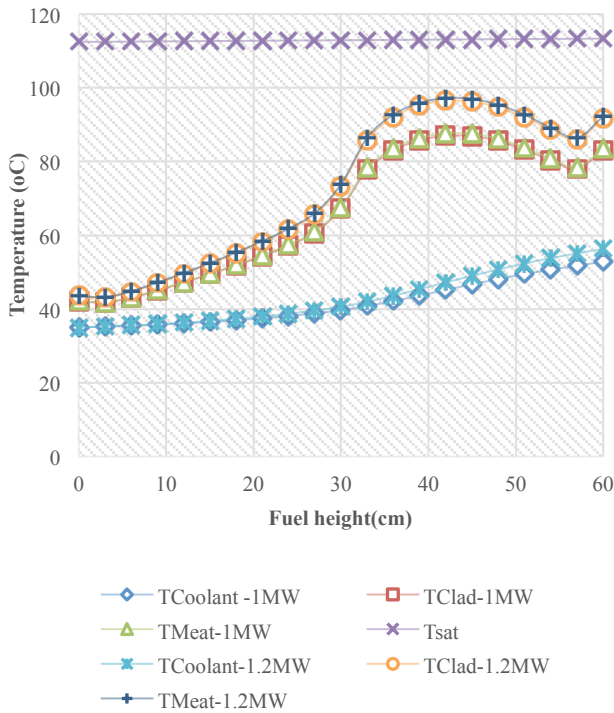
Parameter	Reactor power (MW)		
	2.0	2.2	2.4
T in, °C	35.0	35.0	35.0
T out, °C	70.64	74.2	77.75
$\Delta T$ core	35.64	39.2	42.75
T cladding, °C	121.55	123.68	125.45
T meat, °C	122.45	124.66	126.53
heat flux, W/cm <sup>3</sup>	1583.48	1741.83	1900.18
TONB	119.72	119.78	119.82
$\Delta T$ ONB	-1.83	-3.91	-5.65
DNBR	1.23	1.12	1.03
OFIR	1.6	0.91	0.84

The comparison of safety margins on reactor power of 1 MW and 2 MW is summarized in Table 7. The limits are analyzed against  $\Delta T$  ONB, DNBR, and OFIR. From the table, it can be seen that at power of 1 MW still meets all the specified safety margins, while the coolant flow rate of 50 kg/s and initial coolant temperature of  $35^\circ\text{C}$  is not able to dissipate heat at 2 MW.

**Table 7.** Safety margin characteristic

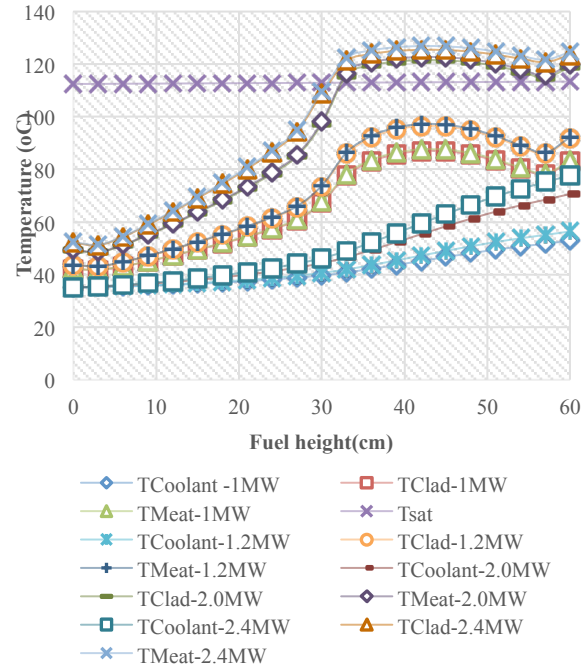
Power, MW	1.0	1.1	1.2	2.0	2.2	2.4
TONB	118.2	118.5	118.7	119.7	118.8	119.8
$\Delta T$ ONB	35.02	26.68	22.19	-1.83	-3.91	-5.65
DNBR	2.47	2.25	2.06	1.23	1.12	1.03
OFIR	2.01	1.83	1.68	1.01	0.91	0.84

The characteristics of the coolant, cladding and fuel temperatures at the reactor power of 1 MW, with a fixed flow rate of 50 kg/s are shown in Figure 4. The figure shows that the coolant, cladding and fuel temperatures, both on the average and the hottest channels, are still under saturated temperature. This shows that the power surge due to loss of coolant flow is able to be overcome before the protection system turns off the reactor.



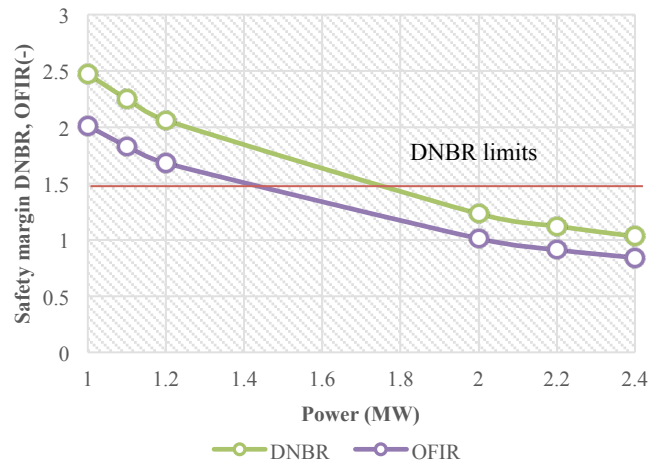
**Fig. 4.** Thermal hydraulic characteristic in the modified TRIGA plate reactor, 1 MW

The coolant and fuel temperature characteristics of the saturation temperature are shown in Figure 5. The saturated temperature of the coolant under these conditions is  $\pm 113^{\circ}\text{C}$ . The figure shows that the coolant temperature for all reactor power levels in this analysis are below of the saturation temperature. Both of the cladding and fuel temperatures at the reactor power of 1 MW also. Whereas at power of 2 MW, the saturation temperature has been exceeded, which is occurred in the fuel position with the highest power peaking factor.



**Fig. 5.** Comparison of thermohydraulic characteristic in the modified TRIGA plate reactor, 1 MW and 2 MW

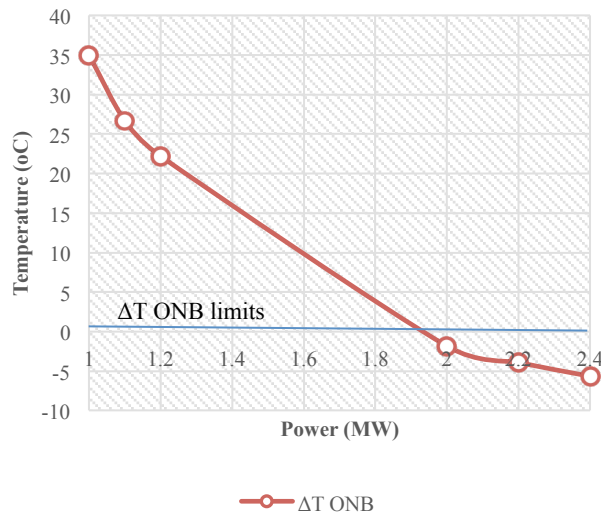
The safety margin limits for departure from nucleate boiling ratio and the onset of flow instability at the reactor power level of 1 MW to 2.4 MW are shown in Figure 6. The minimum DNBR safety margin applied is 1.5. From the figure, it appears that DNBR limits is fulfilled at 1 MW.



**Fig 6.** Safety margins for 1 MW and 2 MW of modified TRIGA plate reactor

Figure 7 shows the results of the safety limit for the onset of nucleate boiling calculation. Nucleate boiling should not occur, as indicated by the value of  $\Delta T_{ONB}$  may not be less than  $0^{\circ}\text{C}$ . From this figure, it is implied that the nucleate boiling has occurred at 2 MW.





**Fig 7.** Onset of nucleate boiling limits for 1 MW and 2 MW of modified TRIGA plate reactor

The results of the most severe condition analysis can be summarized as follows. At nominal power 1 MW, the excess power of 110% (1.1 MW) and 120% (1.2 MW) has sufficient safety margin of initial temperature and saturated temperature for onset of nucleate boiling. Meanwhile, the related DNBRs are 2.47; 2.25; and 2.06, respectively. The higher the power, the DNBR becomes lower. The initial ratios of flow instability are 2.01; 1.83; and 1.68, respectively. The calculation results show that, at power of 1 MW up to 120% of nominal power, the difference of the onset of nucleate boiling ( $\Delta T$  ONB), the DNBR, and OFIR do not occur. The reactor can, therefore, be operated safely.

To identify coolant ability in removing heat of the conversion fuel plate TRIGA reactor, thermalhydraulic safety analysis has been conducted at nominal power of 2 MW up to 120% of nominal power (2.4 MW). The cladding and fuel temperatures are approaching the saturated temperature. The safety indicators,  $\Delta T$  ONB, DNBR and OFIR, at nominal power of 2 MW, are 1.83; 1.23; and 1.01, respectively. Meanwhile, at power above 120% of nominal power, they are -5.65; 1.03; and 0.84. These values show that the reactor operation at 2 MW with primary coolant flow rate as high as 50 kg/s has exceeded the safety margin.

## 5. CONCLUSION

Based on the analysis carried out on the plate-type TRIGA reactor core at power of 1 MW and 2 MW and excess power of 120% with primary

coolant flow rate of 50 kg/s, in accordance with the capability of the Bandung TRIGA reactor pumps, it can be concluded that, at power of 1 MW up to excess power of 120%, there is sufficient margin of safety on temperature of onset of nucleate boiling. In other words, the reactor can be operated safely. Meanwhile, at power of 2 MW, all safety margins have been exceeded. By maintaining the coolant flow rate as high as 50 kg/s, the plate-type TRIGA reactor can only be operated at 1 MW power with excess power up to 120% of its nominal power. If the TRIGA reactor needs to operate at 2 MW power, then its coolant flow rate should be increased to meet the required safety margin.

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