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Transient Analysis of Simultaneous LOFA and RIA in RSG-GAS Reactor after 32 Years Operation

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During the operation of the research reactor RSG-GAS, there are many design parameters should be verified based on postulated accidents. Several design basis accidents (DBA) such as loss of flow accident (LOFA) and reactivity-initiated accident (RIA) also have been conducted separately. This paper discusses about possibility of simultaneous accidents of LOFA and RIA. The accident analyses carry out calculation for transient condition during RIA, LOFA, and postulated accident of simultaneous LOFA-RIA. This study aims to conduct a safety analysis on simultaneous LOFA and RIA, and investigate the impact on safety margins. The calculations are conducted by using the PARET code. The maximum temperature of the center fuel meat at nominal power of 30 MW and steady state conditions is 126.10°C and MDNBR of 2.94. At transients condition, the maximum center fuel meat temperature for LOFA, RIA and simultaneous LOFA-RIA are consecutively 132.99°C, 135.67°C and 138.21°C, and the time of reactor trip are 3.2593s, 3.6494s and 2.7118s, respectively. While the MDNBR for LOFA, RIA and simultaneous LOFA-RIA are respectively at transient condition are 2.88, 2.58 and 2.63, respectively. It is shown that, simultaneous LOFA-RIA has the fastest trip time. In this case, the low flow trip occurs first in advance to over power trip. From these results, it can be concluded that the RSG-GAS has adequate safety margin against transient of simultaneous LOFA-RIA.

1. INTRODUCTION

During the operation of research reactor RSG-GAS [1], there are many design parameters should be verified, particularly after 32 years of operation and another 10 years of extension of operation. Several investigation covering whole system function tests such as instrumentation system, primary cooling system, secondary cooling system and auxiliary system that support to RSG-GAS reactor operation of 30 MW have been conducted. Several accident which can be happened during reactor operation, also have been conducted, such as decrease in heat removal by the reactor cooling system, reactivity insertion and power distribution anomalies, decrease in reactor coolant inventory and loss of primary electric power, etc [1]. All of those have been analyzed separately. However, there is a possibility that two accidents can be happened simultaneously i.e., loss of flow accident (LOFA) and reactivity initiated accident (RIA) due to the initiating events for both accidents could be happened in once. Moreover, the scenario of those simultaneous accidents could be possible due to more than one failure cause and it could be considered as design extension condition. Those conditions have been discussed with BAPETEN to

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identify additional accident scenarios. Therefore, this paper presents the analysis of additional accident based on simultaneous LOFA and RIA for enhancing the safety of the reactor during reactor operation more than 32 years.

LOFA occurs in a reactor due to some causes, such as pump failure, loss of off-site power, pipe blockage, heat exchanger blockage, valve closure, etc. LOFA could destroy fuel integrity due to overheating that arises from a low heat transfer coefficient in the reactor core. Therefore LOFA is classified as a design-based accident (DBA) [1] and an analysis is needed to be taken during the operation stage to ensure that the primary coolant system has adequate safety margins against LOFA [2]. Several analyses under LOFA on research reactor RSG-GAS have been conducted such as analysis for optimization of uranium foil target in RSG-GAS core for the case when the primary flow rate decreased by 15% from its nominal value using MTR-DYN code [3]. Another LOFA analyses for RSG-GAS have been conducted by using PARET [4-5] and RELAP5 [6, 7]. The PARET code was also used for conducting LOFA in NUR reactor [8] and analyzing core flow bypass [9]. Whereas RELAP5 code is also used for IAEA 10MW [10]. As comparison, analysis of LOFA on research reactor have been conducted for IEA-R1 and TRIGA reactors by using EUREKA-2/RR [2, 11].

Reactivity Insertion Accident (RIA) occurs in a reactor due to some causes, such as an abnormal withdrawal of a control rod at start-up condition, an abnormal withdrawal of a control rod at full power operation, or an erroneous large ramp insertion of reactivity at full power operation [12]. RIA is also classified as a DBA [1]. Therefore, an analysis of RIA is needed to be taken well to ensure adequate safety margins against RIA. Several analysis under RIA on RSG-GAS research reactor have been conducted such as in safety analysis of RSG-GAS core conversion from oxide to silicide by using PARET code [5] in analysis for innovative research reactor [13].

The importance of LOFA and RIA analysis are for safety precaution during operation of research reactor as well as nuclear power plant. Several researches related to flow analysis, LOFA or reactivity in research reactor and nuclear power plant that supporting to this research such as preliminary accident analysis for a conceptual design a 10 MW research reactor [12], dynamic analysis for conceptual core design [14], thermal hydraulic analysis improvement for IEA-R1 reactor [15], characterization of oxide fuel element of RSG-GAS [16], accident safety analysis in JRR-3M [17], analysis of temperature effect on control rod worth in TRR [18], and transient analysis in a downward cooling pool-type material testing reactor [19] reactivity feedback effect on LOFA in PWR [20] and validation using standard code on reactor transient condition [21].

This study is aimed to analyze simultaneous LOFA and RIA at full power operation after 32 years operation of the research reactor RSG-GAS. The analysis will be carried out by PARET (**P**rogram **A**nalysis of **Re**actor **T**ransients) code integrated in MTR_PC3.0 package [22]. This code is used to conduct the thermal hydraulics and transient analysis. It is a combination of hydrodynamics, neutronics and heat transfer code employing point kinetics, one-dimensional hydrodynamics, and one-dimensional heat transfer technique. The code is also used for conducting LOFA in NUR reactor [8], whereas other analyses [4-5, 9, 12-13] used PARET code of PC version. Before applying PARET code to analyze the transient condition of LOFA and RIA separately, it will be validated to COOLOD-N2 code for thermal hydraulics on steady state, to ensure that the calculation model of PARET conditions is justified. Previously, the COOLOD-N2 code has been used to analyze thermal hydraulics in reactor TRIGA Mark II [23] on conversion of fuel plat in Bandung TRIGA reactor [24]. The calculation results are fuel meat and cladding temperature are less than the ones of previous research. This result is very important to complete a technical justification for the RSG-GAS analysis as required by regulatory body (BAPETEN) in prolongation of operation license.

2. REACTOR CORE DESCRIPTIONS

The reactor RSG-GAS consists of 40 standard fuel elements (FE) and 8 control fuel elements (CE), operates at a nominal thermal power of 30 MW. Currently, the fuel element is based on silicide fuel, converted from oxide fuel with density of 2.96 g U/cc. The reactor has excess reactivity of 9.2% $\Delta k/k$ and the shutdown margin reactivity of -2.2% $\Delta k/k$ [1,4-6].

The reactor is a pool type reactor, which is moderated and cooled by using light water. The nominal flow is 860 kg/s, downward flow with forced convection that circulated in the primary cooling system by two primary pumps which work parallel [1,5,6]. The main thermal features of RSG-GAS reactor are shown in Table 1.

Table 1. The main features of RSG-GAS reactor [1,5,6]

Parameter	Value
Number of fuel elements	40
Number of control elements	8
Nominal thermal power	30 MW
Nominal flow rate	860 kg/s
Maximum inlet coolant temperature	42.0°C
Maximum cladding surface temperature	150.0°C
Maximum center meat temperature	157.0°C

3. METHODOLOGY

The methodology to achieve the objective of this research could be divided into four types of calculations, namely steady state calculation, LOFA calculation, RIA calculation and simultaneous LOFA – RIA calculation. The calculations are done by using PARET code that installed in MTR_PC3.0. The calculation will give results of thermal-hydraulics values of average core and hot channel such as the distribution of power, energy, reactivity, flow, coolant, cladding and fuel meat temperatures and the safety margin of MDNBR (the Minimum of Departure of Nucleate Boiling Ratio).

All of calculations are done based on the axial power distribution at beginning of cycle (BOC), which all control rods (CR) are on 30 cm withdrawal, with the axial peaking factor F_{ax} of 1.77. The core is divided into 2 channels i.e., one fuel as a hot channel which has the allowable radial peaking factor in operation F_{rad} of 2.22 [1, 5], and the others as average channel which has radial peaking factor of 1.00. In channel model, the total heat channel factor, F_Q *[-]*, is defined by Eq. (1).

$$F_Q = F_{rad} \times F_{ax} \tag{1}$$

The value of the total heat channel factors for hot channel that used in the calculation is 3.9294. Whereas, for the average channel, the total heat average channel factor is equal to the axial peaking factor F_{ax} *[-]* of 1.77.

In the reactor operation analysis, it used the flow rate based on measurement of 3100 m^3/h or 854 kg/s slightly less than nominal flow, and the maximum primary inlet temperature of 42.0°C.

Steady State calculation

For steady state reactor operation, the calculation is conducted for nominal power condition of 30 MW, the flow rate of 3100 m^3/h, and the maximum primary inlet of 42.0°C. The calculation is done base on specification data of RSG-GAS reactor. For steady state analysis is carried out using COOLOD-N2 and PARET codes. While for LOFA analysis is only carried out by using PARET code. Both in COOLOD-N2 and PARET, for heat transfer coefficients of single-phase flow, the Dittus-Boelter correlation is used for the forced convection mode, for heat transfer coefficients of two-phase flow, the Bergles-Rohsenow correlation is used and for DNB heat flux correlation, the Mirshak correlation is used. However, the models in COOLOD-N2 and PARET are different in number of nodes; the COOLOD-N2's model uses 21 nodes, whereas the PARET's model uses 11 nodes.

For ensuring the core reactor safety, the PARET and COOLOD-N2 codes use the criteria of minimum departure from nucleate boiling (MDNBR). The critical value of MDNBR is 1.5 used in Japan [12] or 2.0 used in IEA-R1 [15].

LOFA calculation

In calculation model of LOFA, it is assumed that the reactor is operated at nominal power of 30 MW, steady state condition for 24 h. Two primary pumps stop due loss of power at t = 10 s. The coast down of core coolant flow as function time after the primary pump stop is shown in Figure 1.

In this model, the coast down of flow-1[4] is chosen in the analysis, because the time of coast down is shorter, its mean more conservative than the coast down of flow-2[6]. The sequence model of LOFA events are as follows:

- From t = 0.0 to t = 10.0 s, reactor is operated at steady state conditions.
- At t = 10.0 s the primary cooling pumps are manually stopped.
- At t = 13.42 s, 85 % of nominal flow cause the reactor to trip.
- At t = 86.78 s the flapper valves open (76.78 s after pumps stop due loss of power).

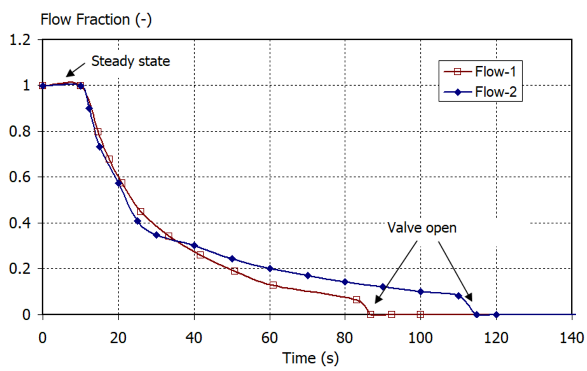


Fig 1. The coast down of core coolant flow as function of time. Flow-1 [4] and flow-2 [6].

RIA calculation

In calculation model of RIA, it is assumed that the reactor is operated at full power of 30 MW, steady state condition for 24 h. At t = 10 s, an operator makes a mistake intuitively or inadvertently, causes all control rods withdrawal at maximum speed of 0.0564 cm/s, continually. The accident will give positive reactivity insertion rate of 2.2×10^{-4} /s or 0.030598$/s. The reactor transient starts at t = 10 s. When the reactor power rises till the reactor protection system by over power of 34.2 MW, the reactor will trip. The sequence of reactivity insertion as function time is shown in Table 2.

Table 2. The sequence of reactivity insertion as a function of transient time.

Time (s)	Reactivity ($)
0	0
10	0
10.01	0.0003598
15	0.1530
25	0.4590
35	0.7650
45	1.0709
55	1.3769
59	1.4993
60	1.5000
100	1.5000
120	1.5000

Calculation of Simultaneous LOFA and RIA

In the scenario model of simultaneous LOFA – RIA, it is assumed that the reactor is operated at full power of 30 MW, steady state condition for 24 h. At t = 10 s, an operator makes a mistake intuitively or inadvertently, causes all control rods withdrawal at maximum speed of 0.0564 cm/s, continually. The accident will give positive reactivity insertion rate of 2.2×10^{-4} /s or 0.030598$/s. The transient starts at t = 10 s. At the same time, two primary pumps stop due to loss of their electric power. While the reactor power rises to the reactor protection system by over power of 34.2 MW, the core coolant flow decreases to zero flow through the reactor protection system by core flow of 85%. Rising power or decreasing flow make the reactor trip. The sequence model of LOFA and RIA events above are used in this calculation.

4. RESULTS AND DISCUSSION

Steady State Analysis

The thermal hydraulics core calculation results for steady state conditions at nominal power of 30 MW, based on hot and averaged channel for BOC is presented in Table 3.

Table 3. Calculation results based on hot and average channel, steady state condition, at nominal power of 30 MW at BOC, comparison between PARET and COOLOD-N2 codes.

Parameter	Calculation Model	
	Paret	Coolod-N2
1. Hot Channel		
Maximum temperature [ºC]		
Outlet coolant - T_{of}	69.30	69.68
Cladding surface - T_c	120.51	120.44
Outer meat -T_{om}	124.08	124.76
Center meat - T_{cm}	126.10	126.82
Max. heat flux, q” [W/cm^2]	159.61	163.07
S minimum	6.33	6.14
MDNBR	2.94	2.78
2. Average Channel		
Maximum temperature [ºC]		
Outlet coolant - T_{of}	54.27	54.48
Cladding surface - T_c	80.60	81.41
Outer meat -T_{om}	82.21	83.43
Center meat - T_{cm}	83.11	84.36
Max. heat flux, q” [W/cm^2]	71.90	73.46
S minimum	N.A.	15.67
MDNBR	6.87	6.49

From Table 3, it is shown that the maximum cladding outer and inner surface temperatures are 120.51°C and 124.08°C by using PARET, and 120.44°C and 124.76°C by using COOLOD-N2. The deviations are 0.06% and 0.55%. The cladding inner surface temperature is equal to the outer meat temperature, because the cladding adheres on meat. It is also shown that the maximum center meat temperature is 126.10°C by using PARET, and 126.82°C by using COOLOD-N2. The deviation of maximum center meat temperature between PARET and COOLOD-N2 is 0.57%. Although, the fuel length is divided into 11 nodes in PARET model, while in the COOLOD-N2 model the fuel length is divided into 21 nodes, the codes give small deviation.

Table 3 also shows that the outlet coolant temperatures is 69.30°C by using PARET, and 69.68°C by using COOLOD-N2. The deviation between PARET and COOLOD-N2 is 0.55%. Whereas, the MDNBR are 2.94 and 2.78 by using PARET and COOLOD-N2, respectively, greater than MDNBR design criteria of 1.5 [12]. It means, has adequate safety margins.

From Table 3, the average channel shows the cladding surface temperature on the channel with position 120 mm below fuel plate mid-height of 80.60°C, by using PARET. When we compare the measured data of cladding surface temperature at T4 position of 76.61°C [7] with the results of RELAP calculation of 77.45°C [7], it can be found that there are difference of 5.21% and 4.07%.

By comparing the result of analysis for optimization of uranium foil target in RSG-GAS core for steady state condition by using MTR-DYN code, it is found that the maximum temperatures of the outlet coolant, cladding and fuel meat are 68.2°C, 125.6°C and 126.6°C [3], whereas PARET code gives result of 69.30°C, 124.08°C and 126.10°C. There are deviation of 1.61%, 1.21% and 0.40%.

From above comparisons between PARET and COOLOD-N2, RELAP and MTR-DYN, it is shown that there are good comparable results to apply PARET for continuing the transient analysis of LOFA, RIA and simultaneous LOFA-RIA.

LOFA Analysis

The calculation of RSG-GAS transients of LOFA conditions is conducted by using PARET. The results are illustrated in Figure 3, 4 and 5.

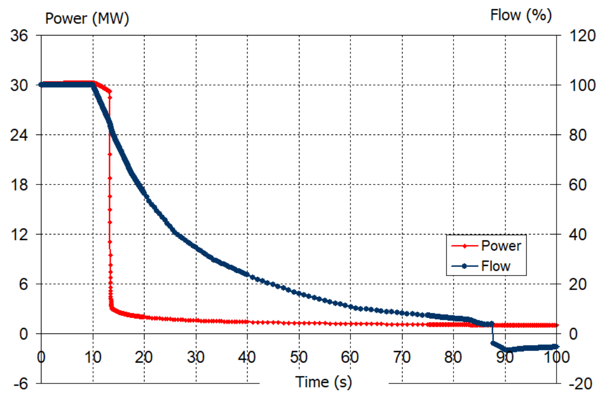


Fig 3. Reactor power and primary flow rate versus time during LOFA.

Figure 3 shows the graphics of reactor power and primary flow rate versus time during LOFA. The figure shows that the transient condition start at t = 10s cause of primary pump failure. Due to the reactor flow rate decreases, the control rod will compensate the reactor by giving little negative reactivity, so the reactor power also will decrease till 29.215 MW. When the flow rate decrease about 15%, the low flow trip happened at t = 3.2593s of transient time, and the reactor scram.

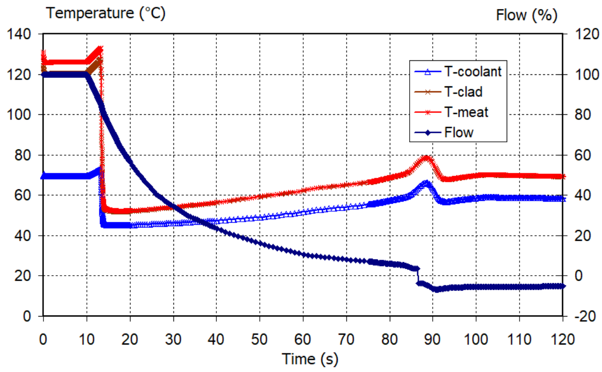


Fig 4. Coolant, cladding, center meat temperatures and flow versus time during LOFA.

Figure 4 shows the graphics of coolant, cladding, center meat temperatures and flow versus time during LOFA. When the transient of flow was happened, the temperatures of coolant, cladding and meat will increase, because the reactor still in operation of about 30 MW. The reactor scram at t = 3.2593s. The temperature still increase, and reach peak at t = 3.282s for outlet coolant temperature of 73.00°C, cladding temperature of 127.62°C and 132.99°C. Compare to the result of analysis for optimization of uranium foil target in RSG-GAS core for 0.5s after reactor scram by using MTR-DYN code, gave the coolant, cladding surface and fuel meat maximum temperatures are 69.5°C, 127.9°C and 128.9°C [3], there are deviation of 5.04%, 0.22% and 3.17%. The comparison shows that the result of PARET is in a good agreement. After scram, decay heat generated in the fuel decreased drastically, whereas the flow rate decreased exponentially, so it produced effective heat transfer and the outlet coolant, the cladding surface and the center meat temperatures will reach minimum of 45.12°C, 51.85°C and 52.26°C, respectively, at t = 6.867s after transient. The flow rate will decrease continuously, it will make the coolant, cladding surface and meat temperatures increase. At about 76.78s after pump failure, the fly wheel will stop rotated and the flapper valve will open, so the flow rate will change from forced convection to natural convection. In transition condition, the outlet coolant, the cladding surface and the center meat temperatures will reach the peak of 66.18°C, 78.49°C and 78.62°C at t = 78.60s.

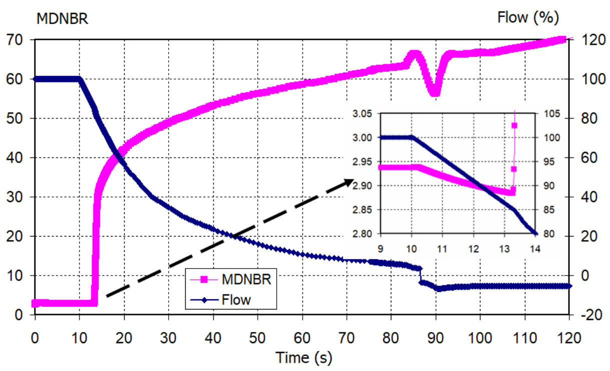


Fig 5. MDNBR and flow versus time, during LOFA in RSG-GAS.

Figure 5 shows the graphic of the MDNBR and flow versus time during LOFA in RSG-GAS. At nominal power and steady state condition, the MDNBR is 2.94. When reactor scram, the MDNBR will decrease and reach the worst condition of 2.88. Then the MDBR will increase again. For all conditions of LOFA, the MDNBR is always greater than critical value of 1.5 [12].

RIA Analysis

The calculation of RSG-GAS transients of RIA conditions is conducted by using PARET. The results are illustrated in Figure 6, 7 and 8.

Figure 6 shows the graphics of reactor power and reactivity versus time during RIA. The figure shows that the transient condition start at t = 10s due to the assuming control rod withdrawal at maximum speed of 0.0564 cm/s to give positive reactivity to the core. In the aftermath, the reactor power will increase. Since there is a reactor protection system, the reactor will reach the over power trip of 34.2 MW at 3.6494s. By reason of the delay time of 0.0286s, the reactor power will reach the peak power of 34.24 MW and scram at 3.678s.

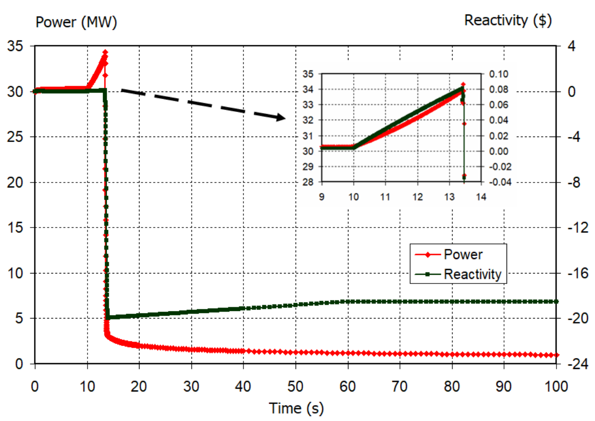


Fig 6. Reactor power and reactivity versus time during RIA.

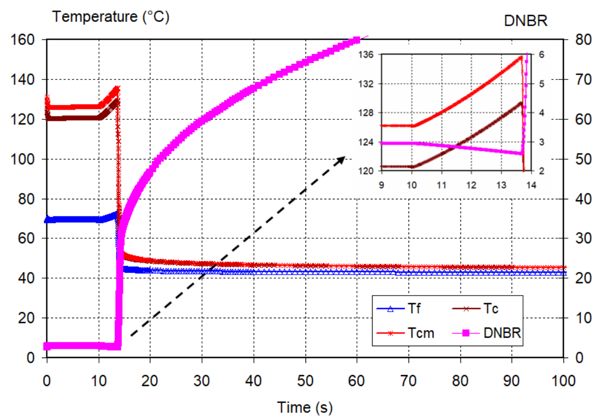


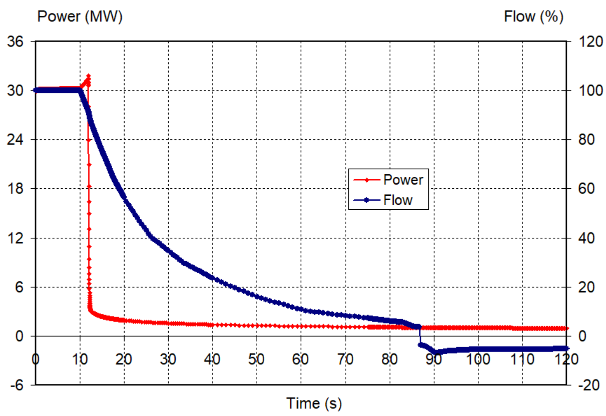
Fig 7. Outlet coolant, cladding surface, center meat temperatures, and MDNBR versus time during RIA.

Figure 7 shows the graphics of outlet coolant, cladding surface, center meat temperatures and MDNBR versus time during RIA. When the transient of reactivity initiated happened, the power of reactor will increase. It makes the temperatures of outlet coolant, cladding surface and center meat will increase, and reach the peak temperatures of 72.58°C, 129.37°C and 135.67°C, respectively. Because the primary pump still in operation, the decay heat generated in the fuel could be well transferred by the coolant flow. Hence, the coolant, cladding and center meat temperatures will decrease and reach the minimum temperatures of 42.91°C, 45.13°C and 45.31°C, respectively. Whereas, the MDNBR is 2.98 at the steady state condition, will decrease to worst of MDNBR of 2.58 when reactor scram, and furthermore, the MDNBR will increase. For all conditions of RIA, the MDNBR is always greater than critical value of 1.5 [12].

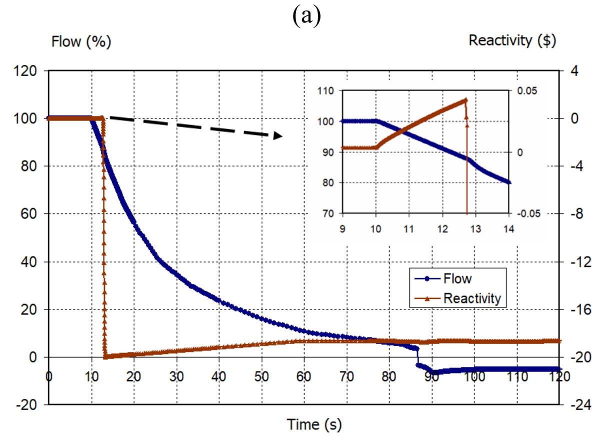
Simultaneous LOFA and RIA Analysis

The calculation of RSG-GAS transients of simultaneous LOFA and RIA is conducted by using PARET. The results are illustrated in Figure 8 and 9.

Figure 8(a) shows the graphics of reactor power and primary flow rate versus time during simultaneous LOFA-RIA. The figure shows that reactor transient start at t=10s after the primary pump is failure that causes the coolant flow rate decrease. At the same time, a human error happened, by the control rod withdrawal. It means the positive reactivity inserted to the core (see Fig. 8(b)), and the reactor power will increase. There are two factors will make reactor trip, i.e., reactor flow decreases and reactor power increases. The calculation result show that, the reactor trip at 2.7118s after transient started, caused by low flow rate of 87.87% of nominal flow rate (the flow decreases about 12.13%) at the reactor power of 31.266 MW, while the reactor was inserted by reactivity of 0.02841$. However, after low flow rate trip, the reactor power still increases till 32.393 MW at 2.729s, and then the reactor scram. The trip time is faster then the trip time of LOFA and also the trip time of RIA. It is different with the LOFA transient that the low flow trip is happened when the flow decrease less than 15%. It is also different with RIA transient, that the reactor power doesn't reach the over power trip of 34.2 MW.



(a)



(b)

Fig 8. Graphics of (a) reactor power and flow rate versus time, and (b) reactivity and flow rate versus time, during simultaneous LOFA and RIA.

Figure 9 shows the graphics of coolant, cladding, center meat temperatures and MDNBR versus time during simultaneous LOFA and RIA. When the transient of flow and reactivity are happened at the same time, the temperatures of coolant, cladding and meat will increase, because the reactor power increase and flow decrease. The temperature of coolant, cladding and center meat increase, and reach peak at t = 2.729s for outlet coolant temperature of 74.79°C, maximum cladding surface temperature of 132.34°C and maximum center meat temperature of 138.21°C, whereas the MDNBR is 2.63. The maximum temperature and the MDNBR mean the maximum and the minimum ones along the fuel channels at that time. As the LOFA case, after scram, decay heat generated in the fuel decreased drastically, whereas the flow rate decreased exponentially. The outlet coolant, the cladding surface and the center meat temperatures will reach minimum of 45.05°C, 51.63°C and 52.04°C, respectively, at t = 6.860s. The flow rate will decrease continuously, it will make the coolant, cladding surface and meat temperatures increase. In transition condition from force to natural convection, the outlet coolant, the cladding surface and the center meat temperatures will reach the peak of 66.20°C, 78.54°C and 78.68°C at t = 78.471s.

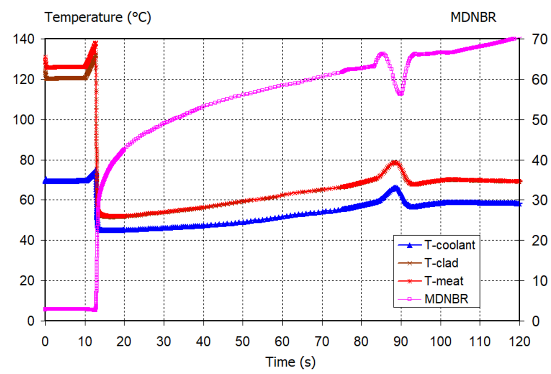


Fig 9. Graphics of coolant, cladding, center meat temperatures and MDNBR versus time during simultaneous LOFA and RIA.

Table 4. Comparison among LOFA, RIA and Simultaneous LOFA-RIA in RSG-GAS

	Case 1	Case 2	Case 3
Reactor trip (s)	3.2593	3.6494	2.7118
Causal factor	Low flow	Over power	Low flow
Max. Temp (°C)			
▪ Outlet coolant	73.00	72.58	74.79
▪ Clad surface	127.62	129.37	132.34
▪ Center meat	132.99	135.67	138.21
MDNBR	2.88	2.58	2.63
After scram			
Min. Temp (°C)			
▪ Outlet coolant	45.12	42.91	45.05
▪ Clad surface	51.85	45.13	51.63
▪ Center meat	52.26	45.31	52.04
Max. Temp (°C)			
▪ Outlet coolant	66.18	N.A	66.20
▪ Clad surface	78.49	N.A	78.54
▪ Center meat	78.62	N.A	78.68

Case 1: LOFA
Case 2: RIA
Case 3: Simultaneous LOFA and RIA

Comparison of LOFA (case 1), RIA (case 2) and simultaneous LOFA – RIA (case 3) analysis is shown in Table 4. Table 4 shows that the reactor trip time of case 3 is the fastest as compared with the time of case 1 and case 2. The outlet coolant temperature of case 3 is the highest among case 1 and case 2. However, the maximum cladding surface and the center meat temperatures of case 3 are the highest. Whereas, MDNBR of case 3 is higher than case 2 and lower than case 1. The condition after scram, the maximum outlet coolant, cladding surface and center meat temperatures of case 3 are lower than case 1. For all conditions, the MDNBR of all cases are always greater than critical value of 1.5 [12].

5. CONCLUSION

The comparison of thermal-hydraulics calculation of RSG-GAS reactor for LOFA (case 1), RIA (case 2) and simultaneous LOFA-RIA (case 3) condition indicates that the reactor trip of the case 3 is the fastest. In this case, the low flow trip occurs first than over power trip. Comparing the outer coolant, cladding surface and the center meat temperatures of transient of case 3 are the highest. Whereas the MDNBR indicates that the safety margin of transient of case 3 is in the middle, between the ones of case 1 and case 2. It can be concluded that the RSG-GAS has adequate safety margin against transient of simultaneous LOFA-RIA.

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AUTHOR CONTRIBUTION

Muhammad Darwis Isnaini, Iman Kuntoro and Muh. Subekti equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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