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Study on Safety Shutdown after LOFA in Downward Flow RR with Plate-Type Fuel

Dayong Kim*, Cheol Park and Kyoungwoo Seo
Research Reactor System Design Division, Research Reactor Development, KAERI, Daejeon
** Corresponding author: dayong@kaeri.re.kr*

1. Introduction

In the Research Reactor (RR) with core downward flow, it is important to maintain the safety margin in core flow stagnant condition during the flow reversal from the downward forced flow to upward flow for core cooling by natural circulation. Especially, it is more difficult to maintain the safety margin after abnormal reactor shutdown by Loos of Flow Accident (LOFA) due to failure of two Primary Cooling System (PCS) pumps. The accident generates the occurrence time of flow reversal is moved more forward than normal reactor shutdown.

For downward flow RR with low core power, the occurrence time of flow reversal is not important consideration to achieve the safety shutdown because core decay heat can be sufficiently removed before flow reversal after LOFA. However, for a downward flow RR with high core power, the decay power is still high for fuel cooling in core flow stagnant condition after LOFA. Therefore, special way is employed to maintain the downward flow at core. The most widely used method is installation on the emergency pump or PCS pumps attached flywheel.

The pumps are designed as safety class, safety class emergency power is supplied to the pumps, and various qualification tests for pumps are performed if installation on the emergency pumps is selected. Thus, the design cost will go up. If the PCS pumps attached flywheel is selected, safety will be enhanced because it is passive method and design cost does not increase significantly. But it is impossible to remove the very high core decay heat. Installation on the emergency pumps can be maintained the long time core downward flow.

Therefore, this study is carried out the safety shutdown of downward flow RRs with plate-type fuel after LOFA. Also, this study present proper safety shutdown method the RRs among the both, pump attached flywheel or emergency pump

2. Evaluation Method

2.1 Critical Heat Flux Ratio

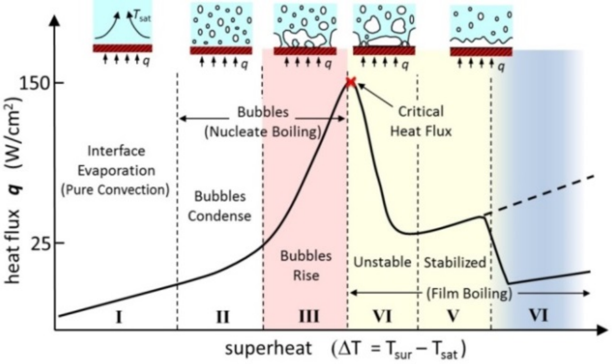

Fig. 1 Typical Boling Curve [1]

The Critical Heat Flux (CHF) describes the thermal limits of a phenomenon where phase change occurs during heating, which suddenly decrease the efficiency of heat transfer as shown Figure 1. At the Critical Heat Flux (CHF) point, a large amount of vapor forming as a thin film covers the cladding surface. Decreasing the heat transfer coefficient by the thin vapor film leads to very high cladding temperature. The safety margin shall be ensured that the Minimum Critical Heat Flux Ratio (MCHFR) is satisfied at least 1.5 under the all operating conditions. The MCHFR is defined as following equation

$$\mathrm{MCHFR} = \frac{q_{CHF}}{q_{local}} = \frac{q_{CHF}}{q_{avg} \times F_q \times F_q^E} \tag{1}$$

If MCHFR is higher than 1.5 in core flow stagnant condition, safety shutdown is guaranteed after LOFA.

2.2 CHF correlation and allowable core decay heat

The following dimensionless CHF correlation proposed by M.Kaminaga [2] used to predict CHF during the flow reversal after LOFA generally.

$$q^*_{CHF} = 0.7 \times \frac{A_f}{A_h} \times \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\rho_g/\rho_f\right)^{1/4}\right\}^2} \times \left(1 + 3 \times \Delta T^*_{sub,in}\right) \tag{2}$$

where, the $\Delta T^*_{sub,in}$ and λ are defined as follows

$$\Delta T^*_{sub,in} = \left(\frac{c_p \Delta T_{sub,in}}{h_{fg}}\right) \tag{3}$$

$$\lambda = \left(\frac{\sigma}{\left(\rho_f - \rho_g\right)g}\right)^{1/2} \tag{4}$$

The "$\Delta T_{sub,in}$ = 0 (subcooling temeperature =0)" is applied in eq. (2) to calculate more conservative dimensionless CHF. Thus, the following dimensionless CHF correlation proposed by Mishima is used in this study.

$$q^*_{CHF} = 0.7 \times \frac{A_f}{A_h} \times \frac{\sqrt{W/\lambda}}{\left\{1 + \left(\rho_g/\rho_f\right)^{1/4}\right\}^2} \quad (5)$$

The critical heat flux, average heat flux and allowable core decay heat are expressed as follows

$$q_{CHF} = q^*_{CHF} \times h_{fg}\sqrt{\lambda\left(\rho_f - \rho_g\right)\rho_g g} \quad (6)$$

$$q_{avg} = \frac{q_{CHF}}{MCHFR \times F} \quad (7)$$

$$Q_{allow} = q_{avg} A_h \quad (9)$$

2.3 Core Decay Heat

The ANS-5.1-1971(R1973)[3] decay power with a multiplication factor 1.2 is used for the calculation of core decay heat. This study considers the reactor operating time, the fraction of operating power due to fission-production decay shall be obtained from the infinite operation curve. Core decay heat are calculated as below

$$Q_{decay} = 1.2 \times \frac{P}{P_0}\left(t_0, t_s\right) \times Q_{Power} \quad (10)$$

$$\frac{P}{P_0}\left(t_0, t_s\right) = \frac{P}{P_0}\left(\infty, t_s\right) - \frac{P}{P_0}\left(\infty, t_0 + t_s\right) \quad (11)$$

The fraction of operating power, P/P_0, attributable to fission products is given by curve in Figure 1. If core decay heat at occurrence time of flow reversal after LOFA, Q_{decay}, calculated by Eq. (10) is lower than allowable core decay heat, Q_{allow}, calculated by Eq. (9), the reactor can be achieved and maintained the safety shutdown after LOFA.

2.4 Virtual Research Reactors

This study assumes three virtual RRs with the core power of 5 MW, 10 MW and 15 MW, respectively. The fuel design and thermal hydraulic parameters for three virtual RR used in this study show the Table 1. The plate-type fuel used in the many RRs worldwide is adopted for the virtual RR. The design parameters of fuel are slightly modified from the standardized values.

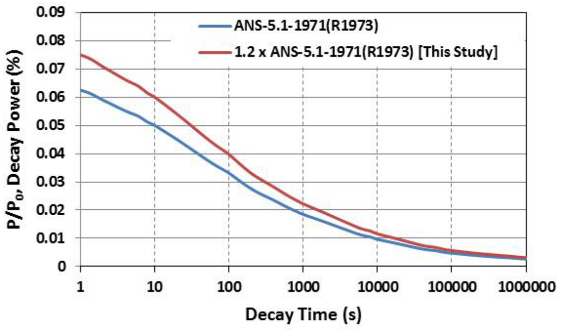

Fig. 1 Standard Fission-Product Decay Heat Curve [3]

Table 1 Fuel design and thermal hydraulic data for three virtual RRs

Input Data			RR-1 (5MW)	RR-2 (10MW)	RR-3 (15MW)
Fuel Design Parameter	Fuel Meat	Width (m)	0.061		
		Length (m)	0.65		
	Fuel Plate	Gap (m)	0.00234		
		Width (m)	0.069		
	No. of fuel assembly (EA)		18	24	30
	No. of fuel plate (EA)		22	22	24
	Average fuel plate heat flux (MW/m^2)		0.152	0.228	0.250
Thermal Hydraulic Parameter	peaking factor		3.6		
	Inlet pressure (kPa)		180		
	Inlet temp. (℃)		37		

To calculate more conservative results, The 3.6 is used for peaking factor. The value is higher than general RRs peaking factor [5, 6, 7]. The inlet pressure and temperature are assumed to be constant regardless of the core power for convenience of calculation.

3. Evaluation Result

3.1 Infinite reactor operating time ($t_0 = \infty$)

Table 2 shows the evaluation results on time that downward flow shall be maintained to safety shutdown after LOFA for virtual RRs in infinite reactor operating time. To achieve and maintain the safety shutdown for RR-1, more than 7 seconds downward flow shall be maintained after LOFA. The time is possible to install the PCS pumps attached flywheel although the coastdown time varies depending on the system.

Table 2 Time that downward flow shall be maintained for safety shutdown after LOFA in infinite reactor operating time

Model	RR-1	RR-2	RR-3
Operating Time	∞		
Q_{allow}	320 kW	427 kW	585 kW
Time (s) ($Q_{decay} < Q_{allow}$)	7 s (Q_{decay}: 319)	70 s (Q_{decay}: 426)	115 s (Q_{decay}: 584)

To achieve and maintain the safety shutdown for RR-2 and RR-3, more than 70 and 115 seconds downward flow shall be maintained after LOFA, respectively. It is very difficult to manufacture a pump attached flywheel having coastdown time more than 60 seconds. Therefore, emergency pump shall be installed for safety shutdown after LOFA.

3.2 finite reactor operating time (t_0 = 20 days, 30 days, 40 days, 50 days, 60 days)

The shorter reactor operating time, core decay heat decreases. So, this section is studied the relationship between the RR operating time and time that downward flow shall be maintained for safety shutdown. In general, RR has shutdown period of 30 to 60 days. Then, 20, 30, 40, 50 and 60 days RR operating times are considered in this section.

Table 3 shows the evaluation results on time that downward flow shall be maintained to safety shutdown after LOFA for RR-2 in finite reactor operating time. To achieve and maintain the safety shutdown, the downward flow shall be continued about 60 seconds after LOFA, if the operating time is limited to within 60 days. Therefore, if PCS pumps attached flywheel having coastdown time more than 60 seconds are installed in RR-2, the safety shutdown is possible after LOFA without emergency pumps.

Table 3 Time that downward flow shall be maintained for safety shutdown after LOFA in finite reactor operating time

Model	RR-2 (10 MW)		
Q_{allow}	427 kW		
Operating Time	20 days	30 days	40 days
Time (s) ($Q_{decay} < Q_{allow}$)	50 s (Q_{decay}: 426)	52 s (Q_{decay}: 426)	53 s (Q_{decay}: 426)
Operating Time	50 days	60 days	∞
Time (s) ($Q_{decay} < Q_{allow}$)	55 s (Q_{decay}: 426)	56 s (Q_{decay}: 426)	70 s (Q_{decay}: 426)

Table 4 Time that downward flow shall be maintained for safety shutdown after LOFA in finite reactor operating time

Model	RR-3 (15 MW)		
Q_{allow}	584 kW		
Operating Time	20 days	30 days	40 days
Time (s) ($Q_{decay} < Q_{allow}$)	80 s (Q_{decay}: 584)	83 s (Q_{decay}: 584)	85 s (Q_{decay}: 584)
Operating Time	50 days	60 days	∞
Time (s) ($Q_{decay} < Q_{allow}$)	88 s (Q_{decay}: 584)	90 s (Q_{decay}: 584)	115 s (Q_{decay}: 584)

Table 4 shows the evaluation results on time that downward flow shall be maintained to safety shutdown after LOFA for RR-3 in finite reactor operating time. To achieve and maintain the safety shutdown, the downward flow shall be continued more than 80 seconds after LOFA even in the shortest operating time, 20 days. Therefore, emergency pump shall be installed for safety shutdown after LOFA for RR-3.

4. Conclusion

This study is carried out the safety shutdown of assumed virtual RRs with core downward flow. The virtual RRs assumed the core power of 5 MW, 10MW and 15 MW, respectively, and adopt the plate-type fuel. The fuel design parameters are slightly modified from the standardized.

The RR-1(5MW), more than 7 seconds downward flow shall be maintained after LOFA to achieve and maintain the safety shutdown in infinite reactor operating time. Therefore, safety shutdown after LOFA is possible to attach the flywheel the PCS pumps.

The RR-2(10MW), about 60 seconds downward flow shall be maintained after LOFA to achieve and maintain the safety shutdown within 60 days reactor operating time. Therefore, safety shutdown after LOFA is possible to attach the flywheel the PCS pumps having coastdown time more than 60 seconds. If costdown time does not satisfy, Emergency pump shall be installed.

The RR-3(15MW), more than 80 seconds downward flow shall be maintained after LOFA to achieve and maintain the safety shutdown even in the shortest operating time, 20 days. Therefore, safety shutdown after LOFA is possible to installed the emergency pumps.

NOMENCLATURE

A_f: Flow area (m^2)
A_h: Heated area (m^2)
F: Peaking factor (the ratio of maximum local power density to the core average power density)
g: Acceleration of gravity (m^2)
h_{fg}: Latent heat of evaporation (kJ/kg)
Q_{allow} Allow core decay heat after LOFA (kW)
Q_{decay} Core decay heat at flow reversal (kW)
Q_{power} Core Power during full power operation (MW)
q_{CHF}: Critical heat flux (CHF) (kW/m^2)
q^*_{CHF}: Dimensionless CHF
$\Delta T_{sub,in}$: Inlet subcooling (K)
$\Delta T^*_{sub,in}$: Inlet dimensionless subcooling
t_0: Reactor operating time
W: Channel width of rectangular channel (m)
ρ_g: Density of gas (kg/m^3)
ρ_f: Density of liquid (kg/m^3)
σ: Surface tension (N/m)
λ: Critical wave length (m)

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