Safety analysis on large partial inlet flow blockage in PGSFR

J. Yoo*, W. P Chang, J. H. Jeong, K. S Ha
Korea Atomic Energy Research Institute
P.O.Box 105, Yuseong, Daejeon, 305-600, Korea
**Corresponding author: yoojin@kaeri.re.kr*

1. Introduction

The flow blockage has been considered one of the main issues to be addressed in SFR since the Ferim-1 suffered a partial fuel meltdown. The flow blockage causes an insufficient amount of coolant to enter the fuel assembly. Large Partial Inlet flow blockage is classified as DEC (Design Extension Condition) for PGSFR[1]. There are several flow paths at lower plenum and possibility of occurrence of inlet flow blockage is estimated to be about 1×10^{-8} which is very remote. However, it should be dealt with in PGSFR because it is a BE (Bounding Event). There are no known sources for inlet flow blockage but one could postulate that a large object might be gotten down to lower plenum during normal operation[2]. Then it leads to not only reduced flow rate that flows into assemblies but also temperature increase within fuel assembly.

The objective of the present study is to predict cladding temperature for the hot assembly by postulating flow blockage accident occurring side orifice nozzles at lower plenum.

2. Accident Analysis

2.1 Geometry at lower plenum and Assumption of inlet blockage

The geometry at lower plenum is presented in Figure 1. The receptacle columns are inserted into lower grid plate and assemblies are located at the top of receptacle. The primary circuit coolant through primary pump flows to the lower plenum and passes through the side orifice nozzle of the receptacle, and then further upward through the fuel assembly. It is heated up the core which has a total of 313 assemblies and exits the core. It then is directed downward into the IHX and entered into the primary system pump to continue the cycle shown in Figure 2. The flow blockage could occur as well only if an object passes through the nozzle flow path with coolant. For the case of large partial inlet flow blockage, it was assumed that, a hypothetical large object would block the inlet orifice nozzle at receptacle which has 6 nozzles located just below the orifice plates. It is an important for safety aspect because blockage of orifice nozzle makes a significant impact on voiding effect of coolant.

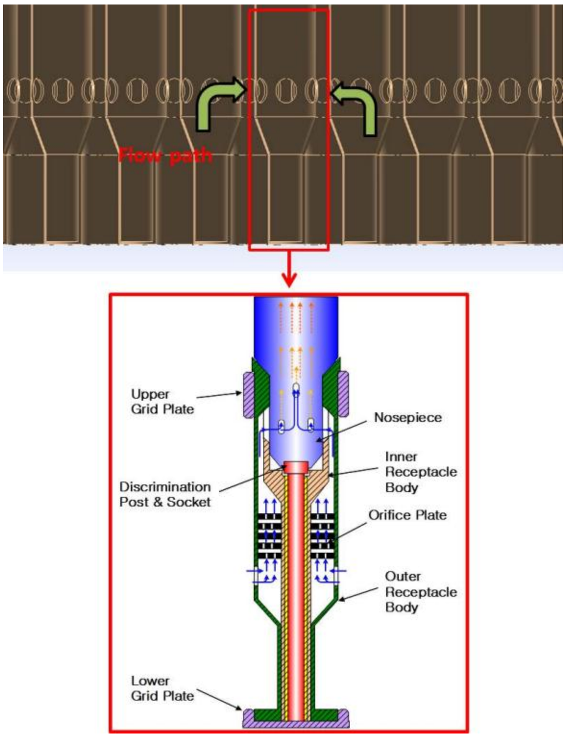

Figure 1. Details at lower plenum in PGSFR

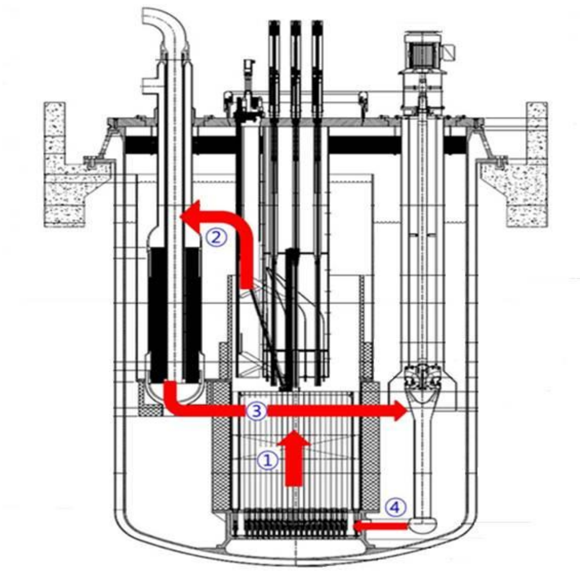

Figure 2. Flow path of coolant in PGSFR

2.2 Reduced flow rate prediction caused by flow blockage

In the event that large partial lnlet flow blockage which blocks entrance of side orifices occurs in a lower plenum, flow rate distributed into the fuel assemblies will be determined by loss coefficient of each assembly. The resistance loss coefficient is expressed as follows [3]

$$k_{loss} = C\,\mathrm{Re}^{n1}\,\beta^{n2}\left(\frac{D_e}{D_2}\right)^{n3}\left(\frac{l_e}{D_2}\right)^{n4}\left(\frac{b}{h}\right)^{n5} \qquad (1)$$

Where Re is dimensionless reynold number at the side-orifice nozzle and β is area ratio(A_1 =cross sectional area of side orifice divided by A_2 =area of downstream section), D_e is the equivalent diameter of the side-orifice, l_e is leading edge, and D_e / D_2 is ratio of equivalent diameter of side-orifice to downstream diameter, l_e / D_2 is ratio of leading edge length of side-orifice to downstream diameter, b/h is ratio of average width to height of side-orifice and C, n_1, n_2, n_3, n_4, n_5 is constant value depending on the reynold number.
For given orifice nozzle geometry shown in Figure 3, loss coefficient can be calculated as below [Table 1],:

Table1. Loss coefficient as a function of orifice nozzle

Number of orifice nozzle	Form loss coefficient	
	IC nozzle	OC nozzle
1	98.98	114.49
2	24.75	28.62
3	11.00	12.72
4	6.19	7.16
5	3.96	4.58

Figure 4 shows inner/outer core hot assembly in PGSFR. In order to find out the flow rate of hottest fuel assembly as a function of number of blockage, we need several assumptions as below:

1. The pressure drop is the same in case of with blockage and without blockage as a boundary condition and the total pressure drop is the sum of the individual pressure drop.
2. The pressure drop at orifice nozzle is due to form loss and friction loss is negligible.
3. The pressure drop at the fuel assembly is due to friction loss and form loss is negligible.

From these assumptions, the total axial pressure drop values in case of no-blockage:

$$\Delta P_x = \Delta P_1 + \Delta P_2 = K_1 \frac{\dot{m}_n^{\,2}}{2\rho A_1^{\,2}} + f_2 \frac{L_2}{D_2}\frac{\dot{m}_n^{\,2}}{2\rho A_2^{\,2}} \qquad (2)$$

For equal axial pressure drop values in case of with-blockage

$$\Delta P_y = \Delta P_3 + \Delta P_4 = K_3 \frac{\dot{m}_b^{\,2}}{2\rho A_3^{\,2}} + f_4 \frac{L_4}{D_4}\frac{\dot{m}_b^{\,2}}{2\rho A_4^{\,2}} \qquad (3)$$

Assuming Equation (2) and (3) is equal as a boundary condition:

$$\Delta P_x \approx \Delta P_y \qquad (4)$$

We can obtain flow rate in case of with-blockage:

$$\dot{m}_b = \sqrt{\frac{\Delta P_y}{\left(K_3 \frac{1}{2\rho A_3^{\,2}} + f_4 \frac{L_4}{D_4}\frac{1}{2\rho A_4^{\,2}}\right)}} \qquad (5)$$

Where ΔP_1 is the pressure drop acting on the orifice nozzle and the pressure drop ΔP_2 acting on assembly without blockage and ΔP_x is the sum of two pressure drop across the total axial length and ΔP_3 is the pressure drop acting on the orifice nozzle and ΔP_4 is the pressure drop acting on assembly with blockage and ΔP_y is the sum of two pressure drop across the total axial length, and $\dot{m}_n$, $\dot{m}_b$ is the flow rate for fuel assembly in case of without no-blockage case and with blockage, respectively. And ρ is density of fluid, f_2 , f_4 is friction factor for the fuel assembly and A_1, A_3 is the flow area of side orifice nozzle in case of without no-blockage case and with blockage, A_2 is the flow area of fuel assembly and K_1 , K_3 is the loss coefficient at orifice nozzle in case of without blockage case and with blockage.

Figure 5 illustrates flow rate variations in a hottest assembly, which is calculated by above equations. The more blockage area at orifice increases, the more flow rate of the hottest assembly decreases. The maximum reduced flow of hottest assembly was predicted to be about 2.7 kg/s for inner core hot assembly and 2.5 kg/s for outer core hot assembly. In the case of 5-orifice nozzle blockage which corresponds to the blockage area of 83.3%, the maximum reduced flow is about 87.2 % for inner core hot assembly and 82.4 % for outer core hot assembly compared to no-blockage case, respectively.

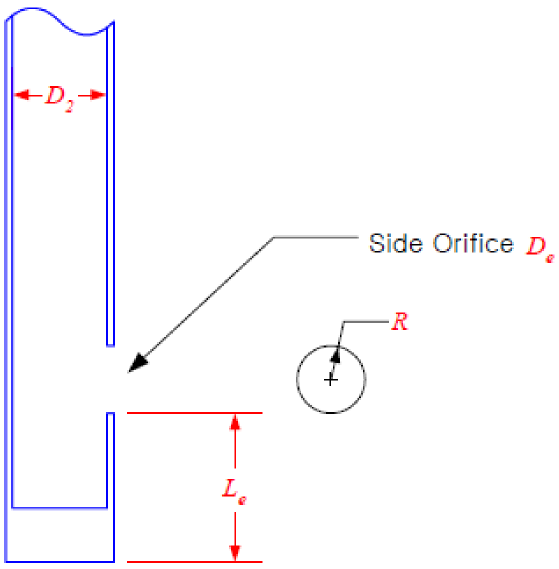

Figure 3 Geometry of side-orifice in a lower plenum

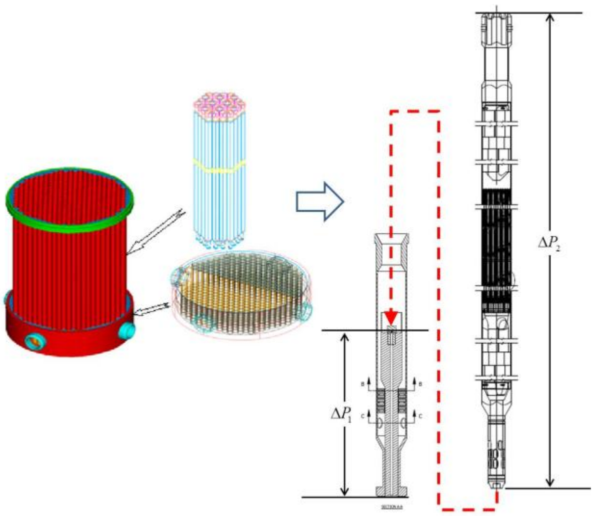

Figure 4. Inner/Outer core hot assembly in PGSFR

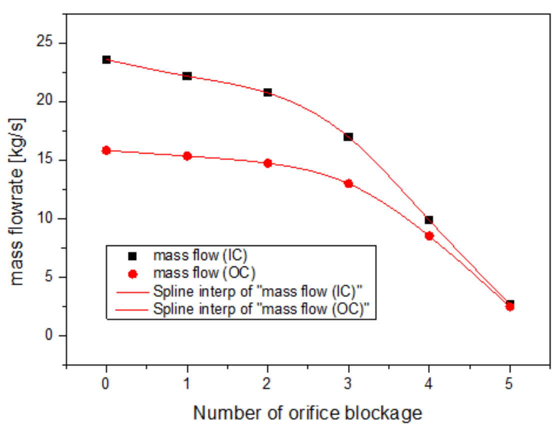

Figure 5. flow rate variations as a function of number of blocked nozzle in a hottest assembly

2.3 Inputs for analysis

Flow blockage accident has been investigated by Korea Atomic Energy Research Institute (KAERI) with MATRA-LMR/FB code which has been used as fuel assembly analysis tool[5]. MATRA-LMR/FB code was applied to the analysis of large partial Inlet flow blockage. Table 2 shows operating conditions and core design parameters in PGSFR. The core is consisted of 112 inner/outer fuel assemblies. The number of new (fresh) fuel assemblies have to be reloaded every Effective Full Power Day (EFPD) which are 4 for inner core/ 5 for outer core, respectively. The hot assembly which represents the lowest flow among the core assemblies with the maximum power and initial cycle condition out of 4/5 cycle was chosen for conservative analysis. And reduced flow rate in the event of flow blockage accident was used as input deck. A node size was roughly divided into a length (3.1 cm) of 1/6 wire-wrap pitch to keep a periodic wire-wrap degree along the axial direction.

Table 2. Operating Conditions and Core Design parameters in PGSFR

Operating Conditions	
Effective Full Power Day (EFPD) [day]	290
Number of Batches (Inner Core/Outer Core)	4 / 5
Core Design Parameters	**U Core**
Number of fuel pins	217
Flow Area of assembly	0.00431 m^2
Number of Assemblies	
Inner Driver Fuel	52
Outer Driver Fuel	60
Flow Rate [kg/sec]	
Inner Driver Fuel Assembly	23.57
Outer Driver Fuel Assembly	15.82
Number of reloaded Fuel Assembly per Batch (Inner Core/Outer Core)	13 / 12

3. Results

Figure 6 illustrates coolant temperature contours of Inner core assembly in the end of the active region without blockage. It is found that the temperature distribution is uniform and maximized around the center of channel with wire wrapped because of fuel rod's heat flux. The maximum coolant temperature is about 590 ℃.

Figure 7 and 8 show that streamwise coolant temperature contours of inner core assembly in the end of the active region with 2, 3-blocked side-orifice nozzle, respectively. The more flow rate decreases, the more cladding temperature increases. Reduced flow rate influenced the average coolant temperatures depending on law of energy conservation. The maximum coolant temperature is predicted to be about 670 ℃ in case that 3-orifice nozzle at receptacle is blocked.

Figure 9 shows the streamwise coolant temperature contours of outer core assembly in the end of the active region without blockage. It shows that temperature distribution is somewhat distorted from around the center of channel because of biased radial fuel pin power, but the maximum coolant temperature is approximately predicted to be around the center of channel such as inner core assembly. The maximum coolant temperature is about 580 ℃.

Figure 10 and 11 show that streamwise coolant temperature contours of outer core assembly in the end of the active region with 2, 3-blocked side-orifice nozzle, respectively. It has a similar tendency to increase the coolant temperature as the flow rate flowing into the fuel assembly decreases. For the case of outer core assembly, the maximum coolant temperature is predicted to be about 630 ℃ in case that 3-orifice nozzle at receptacle is blocked, which is lower compared to maximum coolant temperature of inner core assembly.

Figure 12 shows empirical correlation for eutectic penetration rate which was created using uranium melt tests in 1962[4]. The eutectic penetration rate increases in an Arrhenius manner with increasing temperature between 725 ℃ and 1080 ℃ ($9.9\times10^{-4}K^{-1}$ and $7.4\times10^{-4}K^{-1}$). It is confirmed that penetration rate reaches in a 10 μm/s at 1080 ℃ starting from at 725 ℃. It means that in case of 3-side orifice nozzle blockage, safety margin is ensured against eutectic temperature as well as sodium boiling limits. On the other hand, the maximum cladding temperature of both inner and outer core fuel assembly reaches at about 806℃/739℃, respectively, which goes beyond eutectic temperature. Thus, there is a possibility that fuel pin has been damaged in case that more than 3-orifice nozzle is blocked.

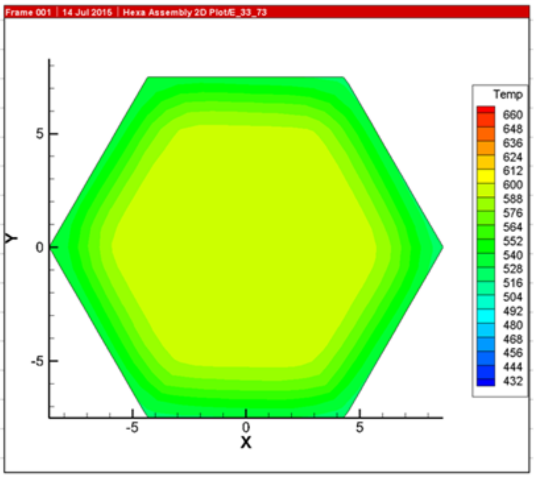

Figure 6. Streamwise coolant temperature contours of inner core assembly in the end of the active region without blockage

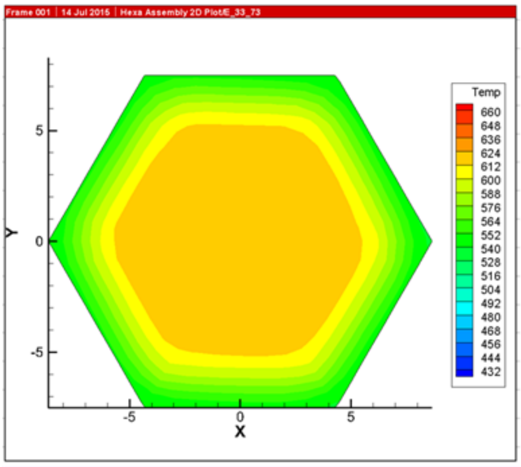

Figure 7. Streamwise coolant temperature contours of inner core assembly in the end of the active region with 2 blocked side-orifice nozzle

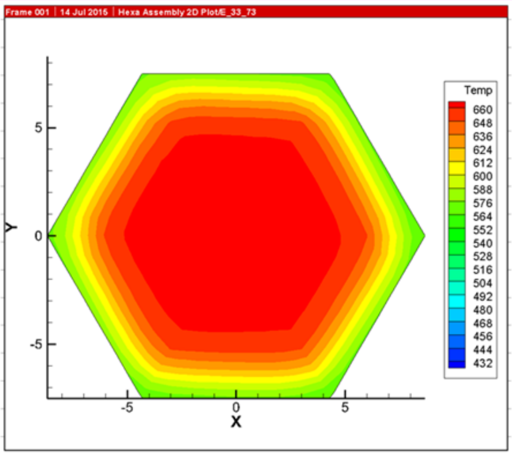

Figure 8. Streamwise coolant temperature contours of inner core assembly in the end of the active region with 3 blocked side-orifice nozzle

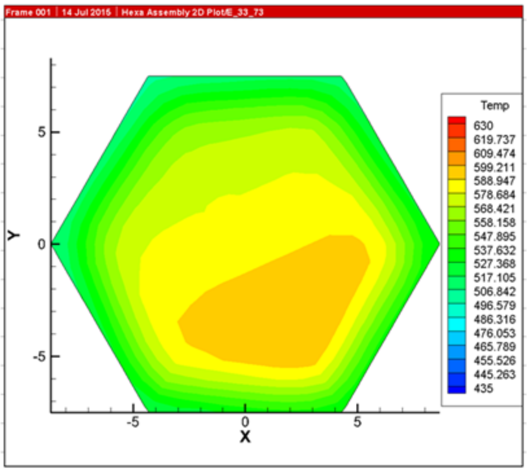

Figure 9. Streamwise coolant temperature contours of outer core assembly in the end of the active region without blockage

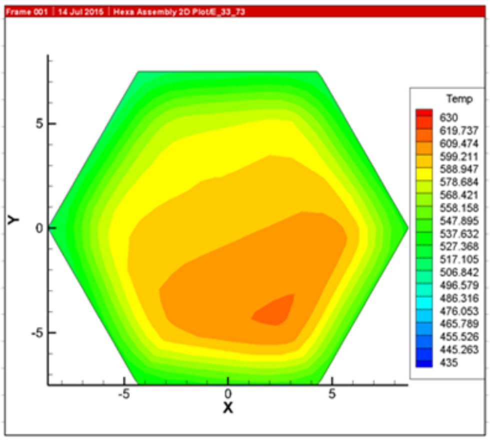

Figure 10. Streamwise coolant temperature contours of outer core assembly in the end of the active region with 2 blocked side-orifice nozzle

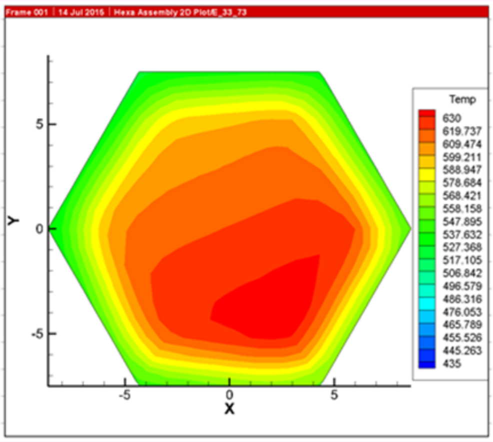

Figure 11. Streamwise coolant temperature contours of outer core assembly in the end of the active region with 3 blocked side-orifice nozzle

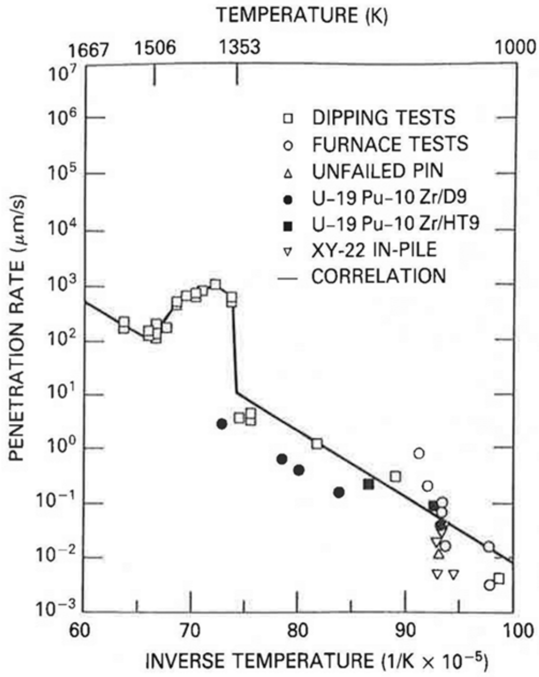

Figure 12. Empirical correlation for eutectic penetration rate

4. Conclusions

The large partial inlet flow blockage occurring orifice nozzles of receptacle was estimated by MATRA-LMR/FB. It is hypothesized that a large object has gotten down to lower plenum during normal operation and blocked side orifice nozzles at lower plenum.

The results indicate that 3-orifice nozzles blockage (50% of blockage area) lead to a maximum clad temperature of inner/outer core assembly around 670 ℃/580 ℃. This is guaranteed that safety margin is enough considering the eutectic temperature. On the other hand, for more than 4-orifice nozzles blockage (67% of blockage area), the maximum clad temperature of both inner/outer core assembly reaches around 806 ℃/739 ℃, respectively, which go beyond eutectic temperature. It means that there is a possibility that cladding could be damaged by eutectic penetration rate in case that more than 4-orifice nozzle is blocked.

REFERENCES

[1] Kwi-Seok Ha, "Safety Analysis Methodology for Design Basis and Transient Accident in SFR", SFR-900-DS-474-001

[2] Clinch River Breeder Reactor Project, "Preliminary Safety Analysis Report," Volume 9, June, 1975.

[3] Moon. Hynu. Chun et al., "An Experimental Investigation of the Effects of the sudden Contraction on Single- and Two-Phase Pressure Drop," Journal of the Korean Nuclear Society, Volume 21, June, 1989

[4] Matthew R. Denman et al., "Probabilistic Transient Analysis of Fuel Choices for Sodium Fast Reactors", Massachusetts Institute of Technology, June, 2011.

[5] Ha, K. S., Jeong, H. Y., Chang, W. P., Kwon, Y. M., Cho, C.H., and Lee, Y. B., "Development of the MATRALMR-FB for Flow Blockage Analysis in a LMR", Nuclear Engineering Technology,797-806, 2009.
[6] R.W. Lyczkowski et al., "Analysis OF a PWR Downcomer and Lower Plenum Under Asymmetric Loop Flow Conditions", June, 1985
[7] C. H. Shin et al., "Assessment of Inner Channel Blockage on the Annular Fuel Rod", October, 2010