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Cumulative Damage Fraction Evaluation for the Sub-channel Blockage Accident in PGSFR

Jin Yoo*, Won-Pyo Chang, Ki-Suk Ha
Korea Atomic Energy Research Institute
P.O.Box 105, Yuseong, Daejeon, 305-600, Korea
[*]Corresponding author: yoojin@kaeri.re.kr

1. Introduction

In determining a safety concern of sub-assembly, the CDF or life fraction, is very useful for predicting pins failure within sub-assembly that are subjected to creep damage at elevated temperatures and has been accepted as a means for predicting fuel pin failure in SFR.

In particular, the sub-channels inside a fuel assembly in Sodium cooled Fast Reactor (SFR) may partially be blocked by an ingression of damaged fuel debris or foreign obstacles into fuel assembly due to the geometrically compact design of the core fuel pin arrangement. When the partial blockage occurs, sodium coolant flow would be disturbed in the vicinity of the blockage, and the affected flow could lead to a high local coolant temperature [1, 2, 3]. And peak coolant temperature would end up rupturing the cladding by increasing the internal pressure and temperature of the fuel pins due to fission gas released from fuels into their gas plenums, which is a primary cause of creep damage to the cladding. The cladding breaching is assumed to occur when the CDF exceeds 1.0 and it is required that the CDF be below 1.0 to avoid the creep rupture of the cladding tube in fuel pin design. It is, therefore, important to evaluate the CDF of the fuel pins in an assembly of the 150MWe Prototype SFR. The objective of this paper is to predict the CDF of fuel pin within the hottest assembly which is designed in KAERI when the sub-channel blockage accident occurs. For the preliminary analysis, the CDF was calculated in the nominal condition without the hot channel factor.

2. Analysis

2. 1 MATRA-LMR-FB code for the CDF calculation

The Multichannel Analyzer for Transient and steady-state in Rod Array - Liquid Metal Reactor for Flow Blockage analysis (MATRA-LMR-FB) code for the analysis of a sub-channel blockage has been developed and evaluated through several experiments. The MATRA-LMR-FB solves the governing equations for mass, momentum, and energy as a boundary problem in space and as an initial value problem in time. It assumes that the axial velocity component is dominant, compared to the components in the transverse direction. For the analysis, we added the new subroutine in the MATRA-LMR/FB code for calculating the CDF under the steady state operation.

The CDF is not a directly measurable quantity. It is a function of time applied stress, temperature and material strength. These are closely related to linear power, burnup, wastage thickness, and fission gas fraction, all of which effects are combined into a single parameter. Cumulative damage fraction is given as follows

$$\int_0^{*} \frac{dt}{t_r(\sigma, T)} = 1$$

where T is the temperature, σ is the hoop stress and t_r is the rupture time at constant temperature and stress. The CDF value approaching unity means less margins to the creep rupture. In this approach, it is assumed that the time to rupture t_r has previously been determined for constant stress σ and constant temperature T conditions out of fuel pin. The fractional damage which occurs in time interval dt is simply dt/t_r. It is assumed that damage accumulates linearly so that rupture will occur when CDF is 1. However, CDF =1 does not mean that failure indeed would occur at this value. Virtually it indicates the most probable failure point

2. 2 Input for the sub-channel blockage

Figure 1 shows a schematic of the fuel assembly for 150MWe Prototype Sodium cooled Fast Reactor (PGSFR). The assembly was modeled with 438 sub-channels, 654 gaps and a total length of 2187.22 mm. Each of the 217 fuel rods has a diameter of 7.4 mm and all the rods are arranged in a triangular pitch within a hexagonal duct. Spacing between the rods is maintained by a wire wrapped helically around each rod. The wire spacers have a diameter of 0.95 mm and the wire spacer around the rod counter-clockwise as it moves up the rod and its pitch is 199.6 mm. A node size was divided into a length (2.5 cm) along the axial direction. The form loss coefficient and the flow area were reasonably adjusted to estimate the reduced flow rate arising from the blockage effect.

The hot assembly which represents the lowest flow among the core assemblies with the maximum power was chosen for the analysis. The calculation region was chosen from active core to gas plenum which is wounded with the wire wrap. The blockage sizes were represented with 6 sub-channel, i.e. all sub-channels surrounding a particular pin are blocked. The radial blockage position was located in the center of the subassembly. The blockage position was assumed near the axial position with the highest heat flux due to the background that the coolant temperature would be large at that position. The axial distributions of the relative heat generation in the fuel rod were considered for input.

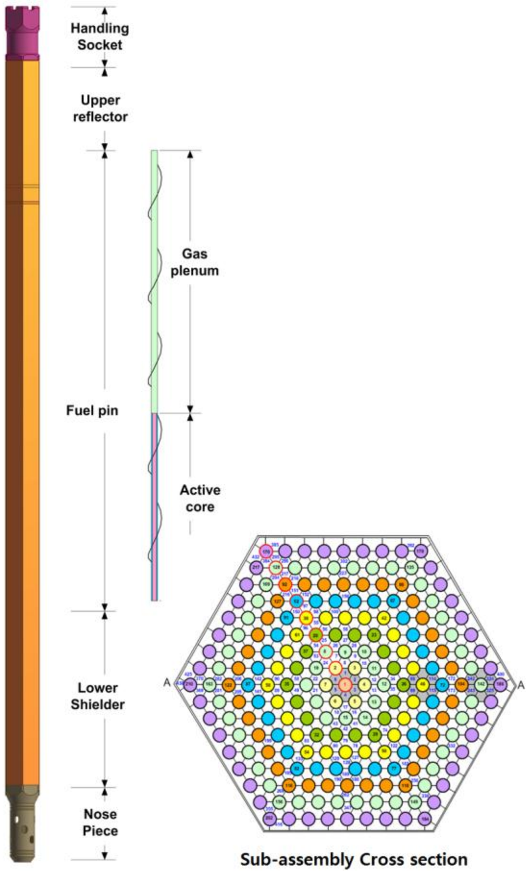

Figure 1. Fuel assembly for 150 MWe PGSFR

Table 1. PGSFR design parameter

Operating Conditions	
Effective Full Power Day (EFPD) [day]	290
Number of Batches (Inner Core/Outer Core)	4 / 5
Core Design Parameters	**U Core**
Fuel type Cladding Material Number of fuel pins Number of Assemblies Inner Driver Fuel Outer Driver Fuel Flow Rate [kg/sec] Inner Driver Fuel Assembly Outer Driver Fuel Assembly	U-10Zr HT9M 217 52 60 23.86 16.02
Number of reloaded Fuel Assembly per Batch (Inner Core/Outer Core)	13 / 12

Table 1 summarizes the key design parameters of 150MWe Prototype Sodium cooled Fast Reactor. The reactor fuel for core design is made of Uranium metal or U-10Zr metals. The fuel slug is immersed in sodium inside the pin for thermal bonding with the cladding. The fission gas plenum is located above the fuel slug and sodium bond, while a lower shielder is located at the bottom of the fuel pin for axial shielding. In all subassemblies, the pins are arranged in a triangular pitch array with the wire-wrap spacer. Fig. 1 illustrates key parts of the fuel pin and the fuel subassembly.

Table 2 shows BOC/EOC condition of the effective volume of gas plenum, pressure and temperature at gas plenum, and burn-up, cladding inner radius, cladding thickness etc. Calculations were used with BOC condition for 1160 effective full power days (EFPDs) of operation with a total assembly power of 5.1071 MWt because the inner core assembly for the PGSFR is designed as 52 fuel assemblies and 13 fuel assemblies during effective full power day (EFPD) each year would be reloaded.

Table 2. BOC/EOC condition

Item	BOC	EOC	Unit
Hottest assembly power	5.1071	5.1089	MWt
Effective volume of gas plenum	2.97×10^{-5}	7.93×10^{-5}	m^3
Pressure at gas plenum	0.21×10^{-6}	7.93×10^{-6}	Pa
Temperature at gas plenum	913	873	K
Burn-up	1.02	11.97	at %
Cladding inner radius	3.29	3.49	mm
Cladding thickness	0.395	0.169	mm

3. Results

3.1 6 channel blockage analysis

Fig. 2 represents the axial distribution of coolant, cladding, fuel temperature in the hottest assembly for 6 channel blockages. The highest coolant temperature appears near the fuel slug end position which is located at the 1065 mm. The maximum cladding temperature was about 605 ℃, which was found at 965.9 mm length. Coolant temperature was heated up above the blockage due to the flow reduction shown in Fig 3.

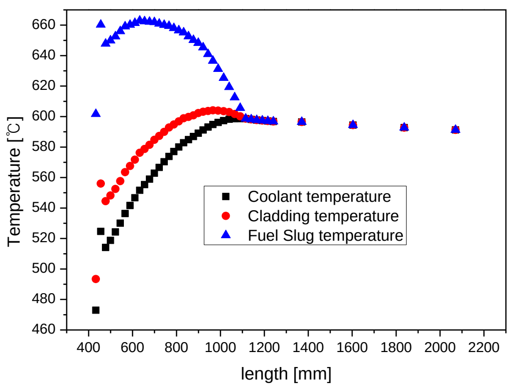

Figure 2. Coolant temperature distribution for 6-central blockage in a axial direction

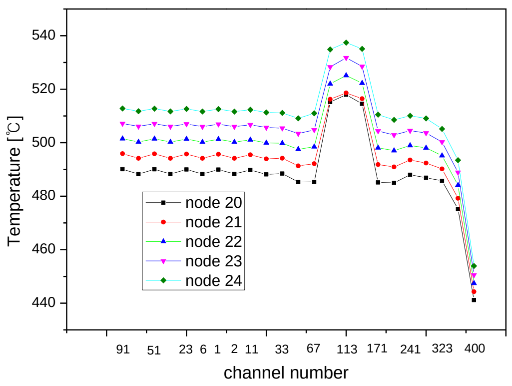

Figure 3. Coolant temperature distribution for 6-central blockage in a radial direction

3.2 CDF analysis

Cladding temperature calculated by 6 channel blockage accident estimated about 605 ℃ was used for the CDF prediction, and cladding thickness was applied with end of cycle condition which is conservative.

Figure 4 shows the fractional fission gas release as a function of burnup for prediction which is based on the ANL U-10Zr irradiation data [4]. Fractional fission gas release increases to 70 % when the burnup reaches 4-5 at % burnup and levels off at about 80 %.

Figure 5 shows the CDF as a function of burnup. The CDF after 1160 effective full power days (EFPDs) was 0.006, indicating a low probability of breach. The calculated CDF increased rapidly from a point that fraction levels off. This shows that burnup more than 6 % gives a strong influence on the CDF evaluation.

Figure 6 shows pressure behavior within fuel pin. The fuel pressure increases linearly with the time. The maximum pressure within the hottest fuel pin was estimated to be about 5.72 MPa after 1160 effective full power days (EFPDs) of operation. It is because the pressure in the fuel pin is governed by fission gas release which is proportional to fission rate in the fuel. Therefore, the pressure in the fuel pin increased as a function of time. When the fission gases in the fuel pin provide the loading on the cladding, the cladding may be conveniently approximated by a thin-walled tube closed at both ends. Therefore, the hoop stress, σ_θ is obtained from thin-walled vessel theory as below

$$\sigma_\theta = \left(P_g - P_{ch}\right)\frac{r_{ci}}{t_{clad}}$$

Where P_g is the internal pressure, P_{ch} is the coolant channel pressure, r_{ci} is the inner radius of the fuel pin and t_{clad} is the cladding thickness. This means that the increase of the pressure difference between the internal of the fuel and the coolant channel makes an effect on hoop stress of the fuel pin. Figure 7 shows the hoop stress as a function of time. The hoop stress increases linearly with the time because the fission gas release increases the internal pressure of the fuel pin. Figure 8 shows the CDF as a function of time. This shows that the CDF following 25000 hour which is about 1040 effective full power days of operation increases rapidly. However, CDF value of the hottest pin in PGSFR is below 1.0. It appears that safety margins are obtained for 6 channel blockage case.

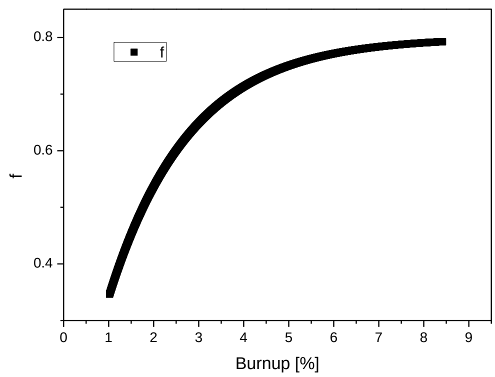

Figure 4. Calculated fission gas fraction with time

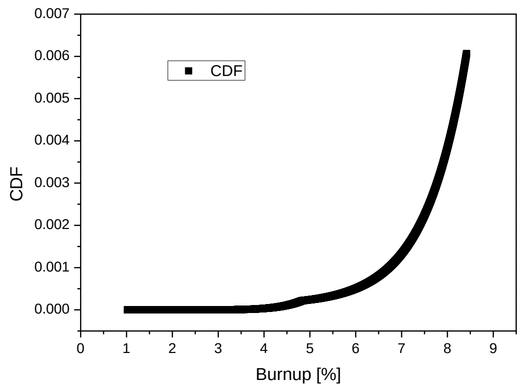

Figure 5. Calculated CDF with burnup (%)

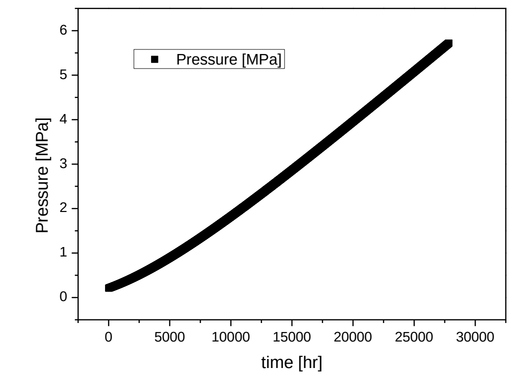

Figure 6. Calculated pressure in the fuel pin with time

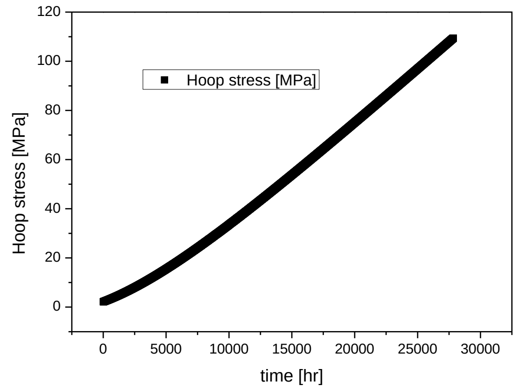

Figure 7. Calculated hoop stress in the fuel pin with time

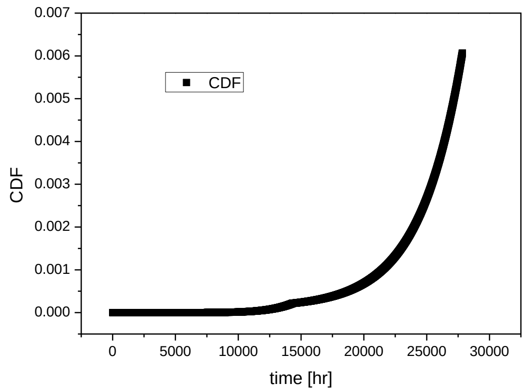

Figure 8. Calculated CDF with time

4. Conclusions

The evaluation of cumulative damage fraction was carried out for 6 sub-channel blockages in 150MWe Prototype Sodium cooled Fast Reactor (PGSFR) using the MATRA-LMR-FB code. The fuel peak temperature of the hottest pin was about 605 ℃ and the CDF value obtained from the hottest pin during 1160 effective full power days (EFPDs) is 0.006, which means that fuel pins have large safety margins against breaching. Therefore, it is assumed that 150MWe Prototype Sodium cooled Fast Reactor (PGSFR) would be safe although 6 sub-channel blockages accident occurs in an assembly.

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