Effect of burnup on molten fuel behavior under hypothetical core disruptive accident (HCDA) condition in PGSFR

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1. Introduction

Sodium-cooled fast reactor (SFR) has inherent safety features arising from high thermal conductivity, low corrosiveness, and high boiling temperature of liquid sodium. Nevertheless, severe accident that core disruption occurs should be studied to prevent devastating event. The accident able to cause core disruption is called as hypothetical core disruptive accident (HCDA) [1].

As the temperature of fuel pin increases during the HCDA condition, the cladding ruptures because of metallurgical reaction between uranic fuel and ironic cladding and creep damage. After the cladding failure, molten fuel is ejected to sodium channel by internal pressure. Post-ejection sequences such as channel blockage and recriticality varies with molten fuel behavior.

In this research, effect of burnup on molten fuel behavior under HCDA condition in Korean prototype gen IV SFR (PGSFR) is studied using computational analysis codes: MARS-LMR, FEAST [2], ABAQUS (commercial FEA software) [3], and MESFRAC.

Table I: Condition of normal operation and fuel configuration for MARS-LMR simulation

Content	Value
Fuel radius	2.77×10^{-3} m
Cladding inner radius	3.2×10^{-3} m
Cladding outer radius	3.7×10^{-3} m
Porosity	75 %
Fuel length	0.97 m
Plenum-to-fuel ratio	1.89
Fuel constituent	U-10Zr
Wire-wrap radius	4.75×10^{-4} m
Sodium bond height	2.5×10^{-2} m
Peak linear power	343 W/cm
Coolant inlet temperature	390 ºC
Coolant outlet temperature	583 ºC

2. Methods

2.1. Analysis of Beyond Design Basis Accident (BDBA) using MARS-LMR Code

In order to determine the hypothetical severe accident where the nuclear fuel would be melt, the unprotected transient scenarios were simulated and analyzed using MARS-LMR code. The MARS-LMR code, the system code for SFR safety analysis, was generally used to simulate Design Basis Accident (DBA) scenarios such as Transient Over-Power (TOP), Loss of Flow (LOF), and Loss of Heat Sink (LOHS). However, we simulated BDBA scenarios by turning off the Reactor Protection System (RPS) and Diverse Protection System (DPS) of DBAs. Moreover, in order to compare the development of severe accident in different burn-up fuels, MARS-LMR inputs for Beginning of Equilibrium Cycle (BOEC) and End of Equilibrium Cycle (EOEC) were provided. Table I shows the condition of normal operation and fuel configuration.

2.2. Analysis of Cladding Failure using FEM

Details of cladding failure simulation method are described in reference [4] and brief description is given here.

Cladding failure simulation is conducted using commercial finite element analysis software, ABAQUS with user subroutines. Mesh modelling and boundary conditions are given in Figure 1. Axial element size is 1 mm and radial element size is 0.01 mm. In heat transfer analysis, heat generation of fuel and heat removal calculated by MARS-LMR are applied. For heat transfer analysis, axisymmetric 8-node element, DAX8 is used. In structural analysis, calculated temperature distribution by heat transfer analysis and plenum pressure derived from fuel peak temperature are applied. For structural analysis, axisymmetric 8-node reduced-integration element, CAX8R is used. Material properties of U-Zr fuel and HT9 cladding are given in references [5-8].

In structural analysis, to simulate cladding failure, stiffness-reduction technique that reduces stiffness of damaged element is implemented. Two damage criteria, cumulative damage fraction (CDF) and eutectic penetration fraction, are used. CDF implies the level of creep damage, which is calculated from stress and temperature using following equation:

$$CDF == \sum \frac{\Delta t}{t_{rup}(\sigma, T)} \quad \ldots \text{ Eq. (1)}$$

Δt is the step time, σ is equivalent stress, T is temperature and t_{rup} is creep rupture time of HT9 cladding. Eutectic penetration fraction of element is calculated from element coordinate and penetration depth. If the penetration is deeper than an element coordinate, the element is considered as damaged. Penetration rate is calculated using equations from SAS4A-FPIN2 [5, 9].

When cladding ruptures, failure time, failure size, failure site, molten fuel mass, and ejection pressure are derived for MESFRAC analysis. Molten fuel mass is calculated considering temperature and zirconium distribution calculated by FEAST code [2]. Melting temperature is calculated using equation below [10]:

$$T_{melt} = -3648U_{at}^4 + 8087U_{at}^3 - 4900U_{at}^2 - 616U_{at} + 2380 \quad \ldots \text{ Eq. (2)}$$

T_{melt} is melting temperature of fuel in K and U_{at} is uranium atom fraction. Plenum pressure at failure is considered as ejection pressure.

2.3. Analysis of In-channel Molten Fuel Behavior using MESFRAC Code

To calculate the behavior and distribution of molten fuel after molten fuel is injected to the coolant channel, thermohydraulic analysis is needed. To do this, MESFRAC (MEtal-fueled SFR Accident analysis Code) is being developed. The MESFRAC is in-house code to analyze in-channel molten fuel behavior written in FORTRAN. This code covers phenomena from injection of molten fuel, interaction with coolant, heat transfer to/from cladding and solidification. And final goal of this code is to calculate the reactivity to determine whether accident is stopped (enough minus reactivity) or not. In this study, cladding failure simulation results are used as input of MESFRAC code.

This code calculates the behavior with implicit method to find a solution of mass, energy and momentum equations. Only voided channel (no liquid sodium coolant) is considered when molten fuel is ejected from pressurized cavity inside nuclear fuel cladding. The reason void channel is considered is that liquid sodium would boil when the heat generation of fuel increase or cooling is degraded. This makes void region expand immediately in the narrow channel. In the momentum equation, only velocity of molten fuel is considered. If molten metal mixture (fuel + cladding) is solidified, lumps of solidified metal mixture are assumed to stay in the sell where they made. Sodium gas is assumed to stop; more gas drag results in conservative results in mass distribution. Those assumptions lead to the condition of the velocity of gas and solid equals zero. Only liquid metal velocity is calculated in momentum equation.

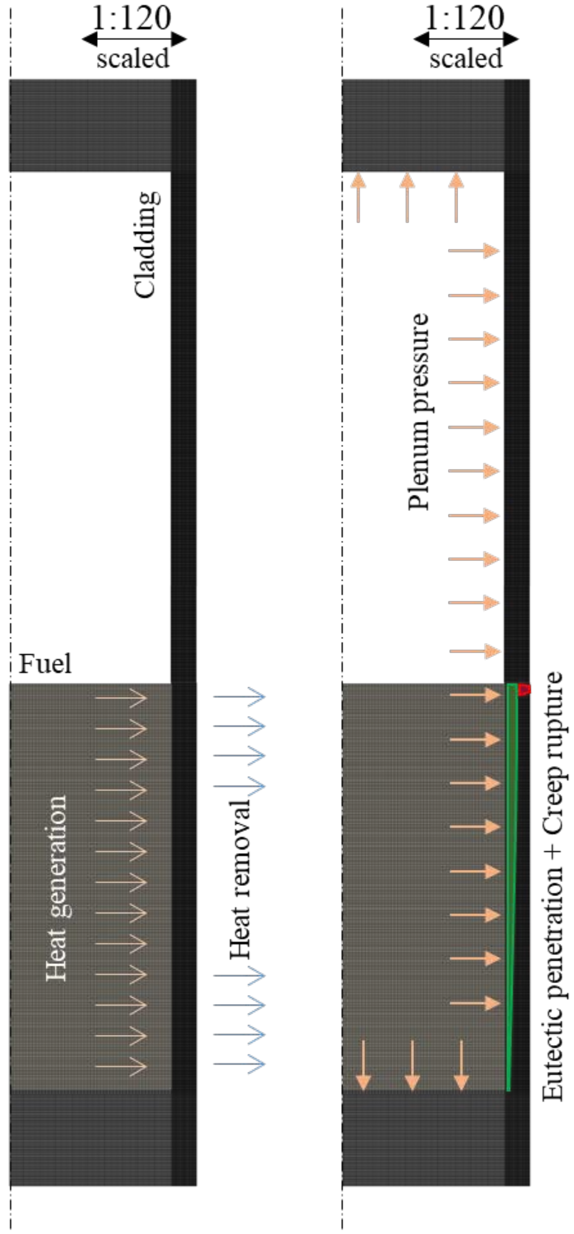


Fig. 1. Modelling and boundary conditions: (a) thermal boundary condition and (b) structural boundary condition

3. Results

One of the hypothetical severe accidents is unprotected Primary Pump Coast-down (PPC) accident that caused coolant boiling. PPC scenario is an accident in which the mass flow of one of primary pumps is drastically reduced and then moves by the inertia. Since RPS and DPS have been ceased at this time, the coolant failed to core cooling and the fuel temperature increases. The coolant temperature also increases, and the coolant starts to boil from 13 seconds.

Cladding failure simulation results of BOEC (burnup 0.94 at %) and EOEC (7.05 at %) pins on PPC event are given in Table II. Clad outer surface temperature distributions are described in Fig. 2. Because of high plenum pressure, failure time of EOEC pin (21.09 s) is earlier than that of BOEC pin (16.15 s). Dominant failure mechanism of BOEC pin and EOEC pin are eutectic reaction and creep damage, respectively. Failure size of EOEC pin (14 mm) is far larger than that of BOEC pin (68 mm). Failure site of both pins is fuel top, but failure site of EOEC pin (90.8 %) is a little higher than that of BOEC pin (88.6 %). Molten fuel mass of BOEC pin and EOEC pin is 54.4 g and 49.0 g, respectively. Ejection pressure of EOEC pin is 5.5 MPa, which is much higher than 0.6 MPa, that of BOEC pin.

The cladding failure simulation results are used as the boundary and initial condition of MESFRAC thermohydraulic calculation. Molten fuel ejection velocity is calculated to determine convective momentum flux into a cell beside failure point. Ejection velocity of EOEC pin (29.74 m/s) is much faster than that of BOEC pin (10.33 m/s) because of higher pressure. Fig. 3 shows in-channel fuel mass distributions of BOEC pin and EOEC pin after ejection. EOEC pin shows much lower elevation of molten fuel than that of BOEC pin because of high wall friction inside narrow coolant channel with high ejection velocity of EOEC pin.

Table II: Cladding failure simulation results

	BOEC (0.94 at%)	EOEC (7.05 at%)
Failure time	21.09 s	16.15 s
Failure size	14 mm	68 mm
Failure site (Axial position/fuel length)	Fuel top (88.6 %)	Fuel top (90.8 %)
Eutectic penetration depth	99.8 %	65.5 %
Molten fuel mass	54.4 g	49.0 g
Ejection pressure	0.6 MPa	5.5 MPa
Molten fuel temperature	1506 K	1516 K

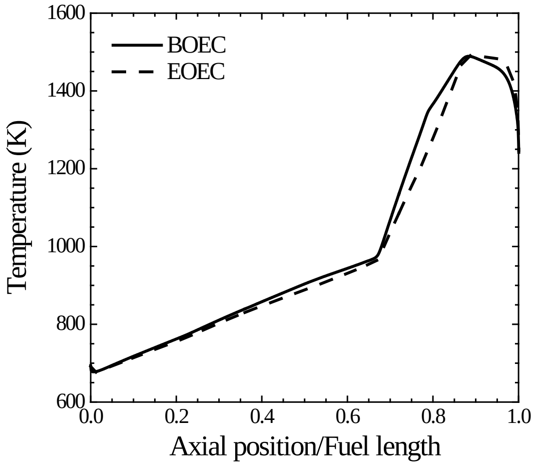
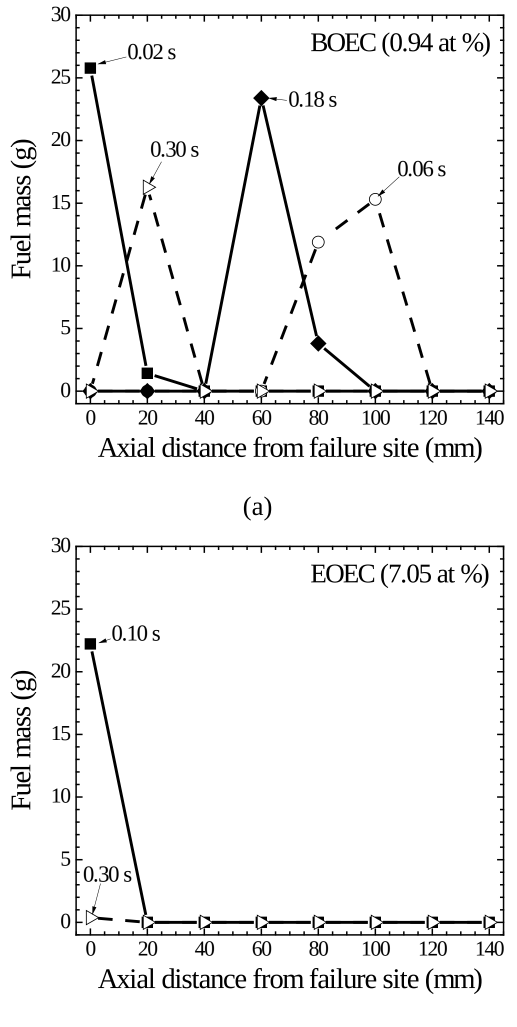


Fig. 2. Clad outer surface temperature distributions



(b)

Fig. 3. In-channel fuel mass distribution after ejection: (a) BOEC pin and (b) EOEC pin

4. Conclusion

In this study, the effect of burnup on molten fuel behavior under HCDA condition in PGSFR is studied. BOEC and EOEC pins are analyzed under PPC accident without reactor protection systems using MARS-LMR, ABAQUS and MESFRAC computational analysis codes. Through this study, following conclusions are derived:

(1) There are large differences in failure analysis results between low burnup (BOEC) and high burnup (EOEC) pins. In particular, the failure size of EOEC pin (68 mm) is much larger than that of BOEC pin (14 mm) and the ejection pressure of EOEC pin (5.5 MPa) is far higher than that of BOEC pin (0.6 MPa). It makes large difference in molten fuel behavior in sodium channel.

(2) Low burnup (BOEC) pin shows higher elevation of molten fuel than high burnup (EOEC) pin because of low ejection velocity. It implies low burnup pin has higher possibility that ejected fuel is discharged into upper plenum than high burnup pin. Note that the solidification is not considered yet and plenum pressure is considered as ejection pressure. To enhance the accuracy, basic foundation of MESFRAC and method of molten fuel pressure calculation will be improved.

In a future study, effect of accident scenario will be studied. ULOF, UTOP, ULOHS, and complex accident cases will be considered.

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