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Sensitivity Tests for Cumulative Damage Function (CDF) for the PGSFR

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has designed a Gen-IV Prototype Sodium cooled Fast Reactor (PGSFR), which is a metallic fueled pool type SFR. A safety analysis including the design basis and beyond design basis events has been conducted using MARS-LMR. Previous safety limits were based on temperature and the duration time. However, the cumulative damage function (CDF) will be used as the safety limit to evaluate the fuel cladding integrity. Recently, a 4S reactor developed by Toshiba used the same approach for a safety analysis [1]. Therefore, the development of a CDF is necessary to evaluate the safety limit for the PGSFR safety analyses. The major keys in the CDF model are behavior of fuel and cladding. It is not easy to obtain a metallic fuel database for a CDF model including the cladding materials. Argonne National Laboratory (ANL) in the United States is the only major leading group for metallic fuel experiments. They conducted various experiments with various facilities and experimental reactors, for example, EBR-II, FFTF, and TREAT. In addition, they have recently been trying to extend their oxide fuel based a severe accident code, SAS4A/SASSYS, to a metallic fuel version using their metallic fuel database.

In this study, the preliminary CDF model was supplemented in the MARS-LMR code. The major source was the SAS4A/SASSYS modules related to fuel and cladding transient behaviors. In addition, a sensitivity test for some parameters in the CDF model was conducted to evaluate the capability of these models and to find the major parameter of fuel failure.

2. Cumulative Damage Function (CDF)

The Cumulative Damage Function (CDF) or life fraction is a widely used method for predicting the failure of components that are subjected to creep damage at elevated temperatures, and has been accepted as a means for predicting a fuel pin failure in LMR systems [2]. The CDF method allows rupture time data from creep tests at constant stress and temperature to be used to predict a failure under similar loading conditions, but with time-varying stress and temperature. The basic assumption is that creep damage is linearly additive so that the damage over a given time interval is proportional to the ratio of the time interval, dt, to the rupture time, t_r, which would cause a failure at instantaneous stress and temperature levels. The CDF is then defined as the sum of these fractions, or

$$CDF = \int_{t=0}^{t=t} \frac{1}{t_r} dt \tag{1}$$

The expected value of the CDF at failure should equal 1.0 in order to be consistent with the database for t_r. However, in practice, the allowable CDF is usually chosen to be smaller than 1.0 to account for differences in the loading conditions from those assumed, uncertainties in the applied temperature and stress histories, and scatter in the creep-rupture database.

2.1 Rupture Time

For HT9 cladding, the rupture time is proposed as correlation in the SAS4A/SASSYS Code [3], which was function of hoop stress, cladding temperature, etc.

2.2 Hoop Stress

A hoop stress is the force exerted circumferentially in both directions on every particle in the cylinder wall. The hoop stress in the cladding, σ_θ, is determined for a thin shell under internal pressure loading:

$$\sigma_\theta = \left(P_g - P_{ch}\right)\frac{r_{ci}}{t_{clad}} \tag{2}$$

where P_g is the internal pressure, P_{ch} is the coolant channel pressure, r_{ci} is the inner cladding radius, and t_{clad} is the cladding thickness. Hoop stress is correlated with the pressure in the coolant channel. In the SAS4A-SASSYS code, they defined minimum and maximum hoop stresses. In MARS-LMR also defined the maximum and minimum hoop stresses. In other words, if P_{ch} is greater than the P_g, stress has a negative direction, in this condition, 1 MPa of the minimum hoop stress will be applied. The cladding thickness and cladding inner radius are assigned as input variable.

As the cladding temperature is increased, the penetration of cladding is increased. The correlation is developed for the eutectic penetration rate as a function of absolute temperature is used [4]. Fig. 1 shows the eutectic penetration rate for different cladding temperatures. This correlation is based on three tests: tests in which iron capsules were dipped into molten

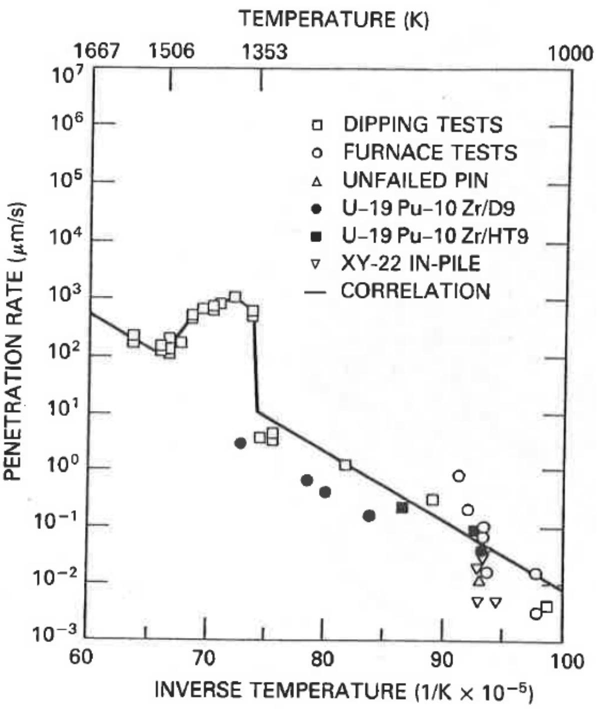

Fig. 1 Rates of cladding penetration by uranium-based melts as compiled from various sources [5].

uranium and uranium/iron alloy baths [6], tests of EBR-II Mark-II driver fuel [7, 8, 9] and test of ternary alloy fuel (U-19Pu-10Zr) clad with stainless steel D9 [4]. Waltar and Kelman associated the rate increase in a range from 1353 K to 1506 K with the formation characteristics of the compound UFe_2 [7]. The model based on these experiments is supplemented in MARS-LMR to calculate the cladding penetration as a function of time and the effective cladding thickness at each axial location and in each SAS4A/SASSYS channel.

2.3 Pressure in Gas Plenum

The pressure in the gas plenum in Eq. (3) is governed by fission gas release, which is proportional to fission rate in the fuel. The major fission gases are Xe and Kr. The sum of the yields of the stable Xenon and Krypton isotopes is between 0.23 and 0.25 [10]. The more recent summary of fission-product yields presented by Meek and Rider [11] also shows that the total yield of the stable fission gases is about 0.25 for both uranium and plutonium. In addition, the fission rate can be evaluated from following simple relation, because the fission rate is directly related to the fission power. Initially, gas state in the gas plenum can be assumed ideal gas. Therefore, the initial the number of gas molecules can be defined as follows:

$$N_{ini} = \frac{P_{ini} V_{ini}}{R T_{ini}} \cdot N_A \qquad (6)$$

And this parameter will be initial condition for a transient analysis.

And the molecules of fission gas generated by fission in the fuel can be defined as follows:

$$\begin{aligned} N_{fission} &= R_f \cdot Y_{gas} \cdot C_{convert} \cdot q_{fission} \cdot dt \\ &= 0.25 \cdot 3.12 \times 10^{10} \cdot R_f \cdot q_{fission} \cdot dt \end{aligned} \qquad (7)$$

Where, $N_{fission}$ is the number of fission gas released to a gas plenum, Y_{gas} is a yield of fission gas, $C_{convert}$ is a conversion constant for power to fission, $q_{fission}$ is a fission power, and dt is a certain time span. Thus, during a transient, the fission gas will be increased by the fission gas release. And fission gas release fraction is depends on a fuel volume expansion. The gas release data for swelling can be obtained from SAS4A/SASSYS [12, 13]. However, in current CDF model, it is assumed that all generated fission gases is released to the gas plenum to get conservatism. In other words, the R_f is assumed to 1.

3. Sensitivity Test of CDF for the PGSFR

3.1 Fuel conditions for the PGSFR

The inner core has higher power to flow condition. However, outer core has higher gas pressure in the pin. In addition, the fuel pin condition can be changed during the cycle. Therefore, for the safety analysis for the PGSFR, the fuel conditions can be defined with four statuses, as summarized in Table I.

Table I: Design Parameters for Fuel Pin

Parameters	BOC	EOC
Hot Pin in the IC (inner core)		
Burnup [at%]	1.02	11.97
Volume of gas plenum, V_{GP} [m^3]	2.97e-5	2.97e-5
Pressure at gas plenum, P_{GP} [Pa]	2.1e5	7.93e6
Cladding inner radius, R_{clad} [mm]	3.29	3.49
Cladding thickness, δ_{clad} [mm]	0.395	0.169
Hot Pin in the OC (outer core)		
Burnup [at%]	1.04	11.79
Volume of gas plenum, V_{GP} [m^3]	2.97e-5	2.97e-5
Pressure at gas plenum, P_{GP} [Pa]	2.1e5	7.84e6
Cladding inner radius, R_{clad} [mm]	3.29	3.5
Cladding thickness, δ_{clad} [mm]	0.39	0.161

3.2 Sensitivity Test

Based on the Table I, the sensitivity parameters are selected. Additionally, cladding and fuel temperatures and fission power are considered as sensitivity parameter. Based on those parameters' range, sensitivity test conducted with five cases for each parameter as shown in Table II. The Case 1 is reference. A sensitivity test is assumed under steady-state condition. To indicate

Table II: Sensitivity Test Cases

Parameters	Cases				
	1	2	3	4	5
V_{GP} [×1e-5 m^3]	2.97	2.82	2.67	2.52	2.38
P_{GP} [×1e6 Pa]	0.2	0.5	1.0	4.0	8.0
δ_{clad} [mm]	0.4	0.35	0.25	0.15	0.1
T_{clad} [×100 K]	9	10	10.1	10.2	10.3
T_{fuel} [×100 K]	10	10.5	11	11.5	12
Q_{pin} [kW]	22	23.1	24.2	25.3	26.4

$$S_{CDF} = \frac{\dfrac{\Delta t_r}{t_{r,ref}}}{\dfrac{\Delta v}{v_{,ref}}} \quad (7)$$

the sensitivity of parameters, a sensitivity factor for the CDF, S_{CDF} is defined as the ratio of the rupture time change due to change of the test parameter.

Fig. 2 shows final results of the sensitivity test. The cladding temperature shows the highest sensitivity. And cladding thickness and pressure in the gas plenum are sensitive parameters in the CDF comparing the rest parameters. The cladding temperature has influence on the cladding penetration as shown in Fig.1.

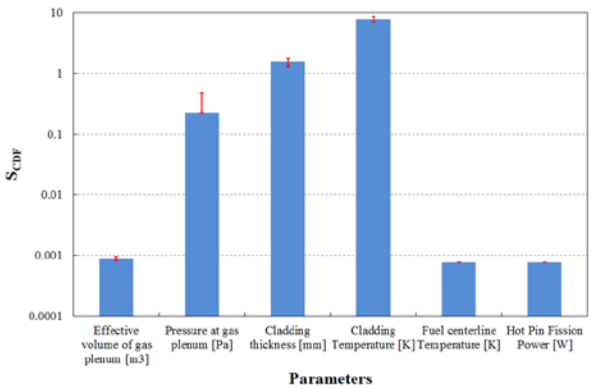

Fig. 2 Sensitivities for different parameters in the CDF model

3.3 Cladding temperature

The cladding temperatures are changed from 900 K to 1030 K. As increasing the cladding temperature, cladding penetration rate is increased as shown in Fig. 1. Therefore, cladding thickness is decreased as shown in Fig. 3. At the T_{clad} of 900K there is no penetration, however, at the T_{clad} of 1030K, whole clad thickness is penetrated for 2×10^4 seconds. The released fission gas amount is same due to no fission power change, which indicates that gas pressure in the gas plenum is the same. Fig. 4 shows hoop stress for different cladding temperature. Obviously, the hoop stress is drastically increased as the cladding thickness is reduced. And the rupture time is also drastically decreased as shown in Fig. 5.

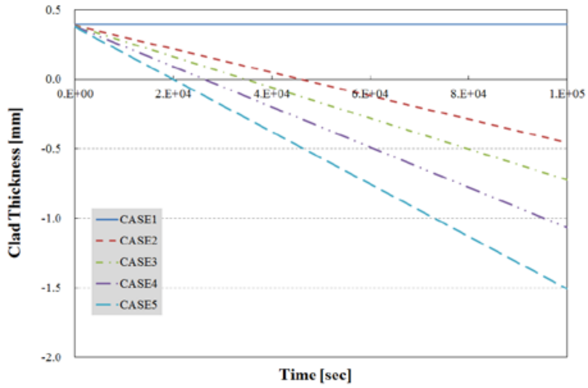

Fig. 3 Cladding thickness for different cladding temperatures

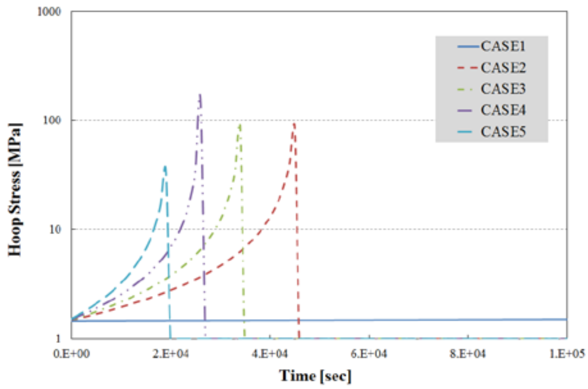

Fig. 4 Hoop stress for different cladding temperatures

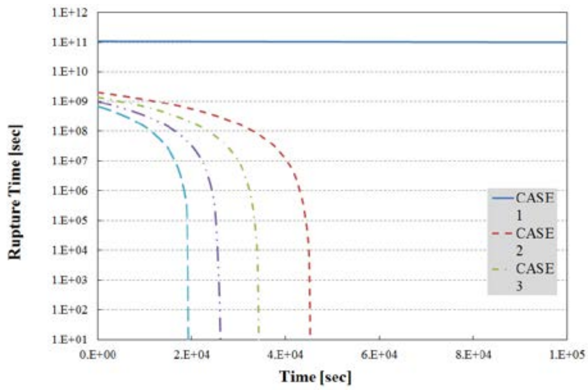

Fig. 5 Rupture time for different cladding temperatures

3.4 Cladding thickness

As discuss in the cladding temperature effect, the cladding thickness is sensitive parameter in the hoop stress. The cladding thickness is changed from 0.4 mm to 0.1 mm as shown in Table II. Fig. 6 shows the rupture time for different cladding thickness. With same reason of the cladding temperature effect, the rupture time is decreased as the cladding thickness reduced. There is little decreasing during the transient because of the fission gas release.

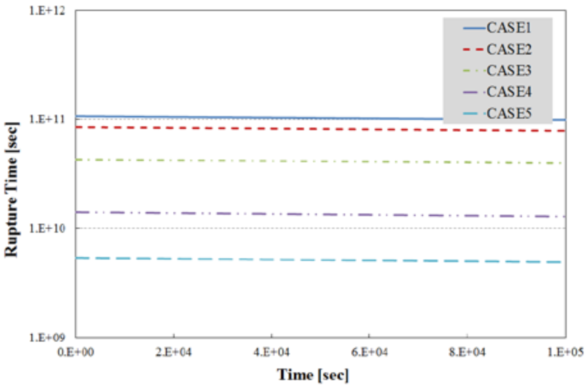

Fig. 6 Rupture time for different cladding thickness

3.3 Pressure in the gas plenum

The initial pressure in the gas plenum is changed from 0.2 MPa to 8 MPa. Fig. 7 shows hoop stress for different initial gas pressure in the fuel pin, which indicates the initial pressure directly proportional to the hoop stress as defined in Eq. (2).

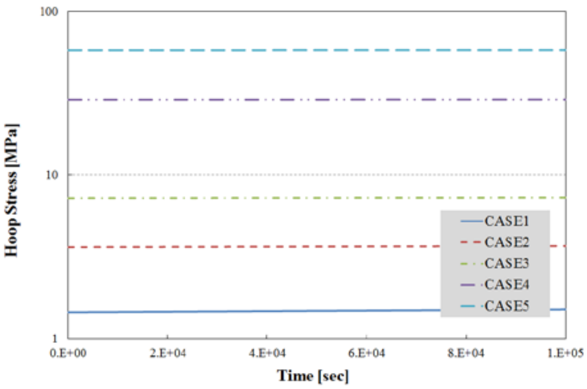

Fig. 7 Hoop stress for different initial pressure in the fuel pin

3.3 The rest of parameters

The rest of parameters, i.e. volume of gas plenum, fuel temperature, and pin power were relatively insensitive. The pin power is increased to 120%. The pin power can affect to the fission gas generation, however, the amount of the fission gas was not effective as shown in Fig. 8.

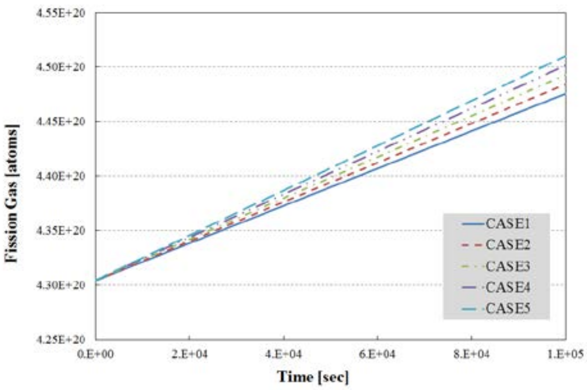

Fig. 8 Fission gas for different fuel pin power

And the fuel temperature and volume of gas plenum can affect the only state of the fission gas in the plenum as shown in Eq. (6). Thus, they are not influential parameter on the CDF.

4. Conclusions

The Cumulative Damage Function is a good indicator for a fuel failure. And this parameter will be used to evaluate the safety analysis result of the PGSFR. Therefore, the preliminary CDF model based on the metallic fuel based SAS4A/SASSYS code developed by Argonne National Laboratory is developed and supplemented in the MARS-LMR code. In addition, sensitivity test for the developed CDF model are carried out with fuel conditions for the PGSFR. The major parameters for the CDF model are selected including cladding and fuel temperatures, initial pressure and volume in the gas plenum, clad thickness, and fission power in the fuel pin. The most sensitive parameter is the cladding temperature. Also, cladding thickness and gas pressure in the fuel pin are effective parameters on the CDF.

During an actual transient, various parameter including sensitivity test parameters in this study will be changed simultaneously. This study can give the phenomenological understanding for the CDF change. In addition, sense for dominant parameter for safety in the fuel pin failure, which can be useful for design feedback.

REFERENCES

[1] 4S Safety Analysis, AFT-2009-000155 Rev.000, Toshiba Corporation, 2009.

[2] A. E. Waltar and A. B. Reynolds, Fast Breeder Reactors, Pergamon Press, 1981.

[3] M. L. Hamilton and N. S. Cannon, HT-9 Transient Data Base and Failure Correlation, Hanford Engineering Development Laboratory, 1985 (Unpublished).

[4] T. H. Bauer, G. R. Fenske, and J. M. Kramer, Cladding Failure Margins for Metallic Fuel in the Integral Fast Reactor, Transaction of the 9th International Conference on Structural Mechanics in Reactor Technology, Vol. C, p.31, Lausanne, Switzerland, August 17-21, 1987.

[5] T. H. Bauer, A. E. Wright, W. R. Robinson, J. W. Holland, and E. A. Rhodes, Behavior of Modern Metallic Fuel in TREAT Transient Overpower Tests, Nuclear Technology, Vol. 92, pp. 325- 352, 1990.

[6] C. M. Walter and L. R. Kelman, The Interaction of Iron with Molten Uranium, J. Nuclear Meaterials, Vol. 20, pp. 314-322, 1966.

[7] P. R. Betten, J. H. Bottcher, and B. R. Seider, Eutectic-Peneatration-Induced Cladding Rupture in EBR-II Driver Fuel Elements, Trans. Am. Nucl. Soc., Vol. 45, p.300, 1983

[8] B. R. Seidel, Metallic Fuel Cladding Eutectic Formation During Post-irradiation Heating, Trans. Am. Nucl. Soc., Vol. 34, p. 210, 1980.

[9] C. E. Lahm, et al. EBR-II Driver Fuel Qualification for Loss-of-Flow and Loss-of-Heat-Sink Tests without Scram, Nucl. Eng. Des., Vol. 101, pp. 25-34, 1987.

[10] D. R. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, Technical Information Center, Office of Public Affairs Energy Research and Development Administration, 1976.
[11] M. E. Meek and B. F. Rider, Summary of Fission Product Yields for U235, U237, Pu239, and Pu241 at Thermal, Fission Spectrum and 14 MeV Neutron Energies, USAEC Report APED-5398-A, General Electric Company, 1968.
[12] L. C. Walters, B. R. Seiderl, and J. H. Kittel, Performance of Metallic Fuels and Blankets in Liquid-Metal Fast Breeder Reactors, Nucle. Tech., Vol. 65, pp. 179-231, 1984
[13] E. E. Gruber and J. M. Kramer, Gas Bubble Mechanisms in the Analysis of Metal Fuel Swelling, Argonne National Laboratory , 1985 (Unpublished).