Simulation of Whole-Pin Furnace (WPF) tests using finite element method with stress-reduction concept

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1. Introduction

Advanced Gen IV sodium fast reactor (SFR) has superior safety features resulting from high thermal conductivity, low corrosiveness, and high boiling temperature of sodium. However, despite extremely low probability, the severe accident that nuclear fuel melts could be caused by multiple accidents. For the safe plant operation, scenario after the severe accident must be studied.

When the temperature of clad increases during the accident, the clad could rupture because of eutectic reaction and creep damage. When clad failure occurs, molten fuel is ejected to sodium channel by internal pressure. There are many post-ejection scenarios such as flow blockage and recriticality. To predict the post-ejection sequences, failure time, failure location and failure size should be determined.

In this study, finite element (FE) analysis method to predict clad failure using stress-reduction concept is suggested. Using the FE analysis method, FM2 and FM4 cases of Whole-Pin Furnace tests (WPF) [1] were simulated and the effect of failure mechanisms on the failure size was analyzed. Unlike previous safety analysis codes, with the use of extremely fine element size, failure size were determined analytically.

2. Methods

2.1. Clad model for FE analysis

The design parameters of the WPF fuel pin used in this study are suggested in Table I. The FE analysis was conducted by using commercial finite element analysis software, ABAQUS 2016. Two dimensional axisymmetric 8-node reduced elements (DCAX8R, CAX8R) are used for the FE analysis. Through clad axial and radial direction, 1 mm and 0.0127 mm of element sizes are used, respectively. Thermal and structural boundary conditions of the FE analysis are suggested in Fig. 1(a) and (b), respectively. *HEAT TRANSFER with user-subroutines, FILM, DFLUX and USDFLD is used for heat transfer analysis. *VISCO with user-subroutines, USDFLD, CREEP, UEXPAN and DLOAD is used for structural analysis. Convective heat transfer coefficient between coolant and clad is calculated by using Schad-Modified Correlation [2]. Heat flux, coolant inlet and outlet temperatures are assumed so that each test conditions are simulated well.

Table I: WPF Fuel Pin Design Parameters

Fuel type	U-10Zr (FM2), U-19Pu-10Zr (FM4)
Clad material	HT9
Fuel slug length	343 mm
Fuel radius	2.2 mm
Clad outer radius	2.92 mm
Clad Inner radius	2.54 mm
Plenum to fuel ratio	1.0 (FM2), 1.5 (FM4)

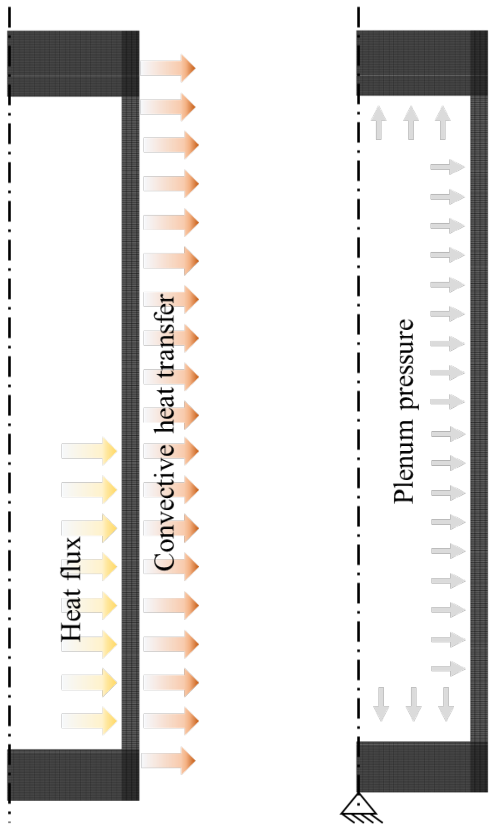

Fig. 1. Mesh and boundary conditions of clad: (a) Thermal boundary condition and (b) Structural boundary condition

2.2. Material properties for FE analysis

Thermal conductivity of HT9 is given in following equation [3]:

$$k_c = \begin{cases} 17.622 + 2.42\times10^{-2}T - 1.696\times10^{-5}T^2 & (T < 1030) \\ 12.027 + 1.218\times10^{-2}T & (T \geq 1030) \end{cases} \quad (1)$$

k_c is thermal conductivity of HT9 in *W/m/K*, and *T* is temperature in *K*. Specific heat of HT9 is suggested in following equation [4]:

$$c_{pc} = \begin{cases} \frac{1}{6}(T-500)+500 & (T<800) \\ \frac{3}{5}(T-800)+550 & (T \geq 800) \end{cases} \quad (2)$$

c_{pc} is specific heat of HT9 in *J/kg/K*, and T is temperature in *K*. Assigned density of HT9 is 8000 kg/m^3.

Young's modulus and Poisson's ratio of HT9 are given in following equations [5]:

$$E_c = (213.28 - 4.799\times10^{-2}T - 4.065\times10^{-6}T^2)\times10^3 \quad (3)$$

$$\nu_c = 0.2762 + 8.9309\times10^{-5}T - 6.262\times10^{-8}T^2 \quad (4)$$

E_c is Young's modulus of HT9 in *MPa*, ν_c is Poisson's ratio of HT9, and T is temperature in ^oF. Thermal expansion strain of HT9 is suggested in following equation [3]:

$$\varepsilon_{tc} = -0.2191\times10^{-2} + 5.678\times10^{-6}T + 8.111\times10^{-9}T^2 - 2.576\times10^{-12}T^3 \quad (5)$$

ε_{tc} is thermal expansion strain, and T is temperature in *K*.

Steady-state creep strain rate and creep rupture time of HT9 are suggested in following equations [6]:

$$\begin{aligned} &\dot{\varepsilon}_{ss} = \dot{\varepsilon}_{oos}(\frac{E}{\sigma_{so}})^n(\frac{\sigma_{eq}}{E})^n \exp(-\frac{Q_c}{kT}) \\ &\dot{\varepsilon}_{oos} = 5.1966\times10^{10} \\ &\sigma_{so}/\mathrm{E} = 3.956\times10^{-3} \\ &E = 2.12\times10^5(1.144 - 4.856\times10^{-4}T) \\ &n = 2.263 \\ &Q_c/k = 36739 \end{aligned} \quad (6)$$

$$\begin{aligned} &t_r = \theta\exp(Q/RT) \\ &\ln\theta = A + B\ln\ln(\frac{\sigma^*}{\sigma}) \\ &A = -34.8 + \tanh(\frac{\sigma-200}{50}) + C \\ &B = \frac{12}{1.5 + 0.5\tanh(\frac{\sigma-200}{50})} \\ &C = -0.5\times[1+\tanh(\frac{\sigma-200}{50})]\times0.75\times[1+\tanh(\frac{\dot{T}-58}{17})] \\ &\sigma^* = 730 \\ &Q/R = 35332 \end{aligned} \quad (7)$$

$\dot{\varepsilon}_{ss}$ is secondary creep strain rate in s^{-1}, σ_{eq} and σ is equivalent stress in *MPa*, T is temperature in *K*, t_r is creep rupture time in *s*, and $\dot{T}$ is heating rate in *K/s*.

Cumulative damage fraction (CDF) suggested in the following equation is used for creep damage criteria [6]:

$$CDF = \sum\frac{\Delta t}{t_r} \quad (8)$$

When the CDF value of an integration point becomes unity, the integration point is regarded as damaged.

When the metallic fuel contacts with ferrous clad at higher temperature than 948 K, eutectic reaction occurs. Eutectic reaction of fuel and clad causes penetration of fuel toward clad so that thickness of clad reduces. Penetration rate used in this study is suggested in following equation [7]:

$$\frac{dX}{dt} = \exp(11.646 - \frac{15865}{T}) \quad (9)$$

In proposed FE analysis method, it is assumed that whole active section beside the fuel contacts with the fuel so that eutectic reaction occurs in whole active section. On each analysis step and at whole axial location in active section, local penetration depth is calculated based on the temperature of clad inner surface. When the penetration depth reaches to the coordinate of an integration point, the integration point is regarded as damaged.

2.3. *Simulation of eutectic penetration and creep rupture with stress-reduction concept*

Stress-reduction concept to mimic the behavior of local damaged section is adopted in this study. The stress-reduction concept is reducing stiffness of damaged element. Element having very low stiffness behaves like void; it cannot resist deformation. It have been used for ductile tearing simulation [8].

2.4. *Whole-Pin Furnace (WPF) test conditions and results*

The WPF tests have been conducted to simulate accident condition such as unprotected loss of flow (ULOF) and derive failure margin of metallic fuel pin by Argonne National Laboratory (ANL). Pre-irradiated fuel pins were heated to temperature above steady-state condition in furnace. In this study, FM2 and FM4 cases were simulated. In FM2 and FM4 cases, which are safety margin tests, temperature was increased and held until failure. Summary of WPF tests is suggested in Table II.

Table II: Summary of WPF tests [1]

Case	FM2	FM4
Burnup	3.0 at%	11.4 at%
Peak temperature	820 °C	770 °C
Peak plenum pressure*	3.43 MPa	9.22 MPa
Duration	112 min	54 min**
Eutectic penetration***	67 %	24 %
Failure	O	O
Failure size****	2.0mm/0.9mm	12.5mm/3.5mm
Failure location	Fuel top	Plenum

* Calculated using FEAST-Metal code [9]
** Delayed failure caused by contact between the clad and the wall
*** At fuel top
**** Axial crack length and width

Table III: Fracture simulation results of WPF tests

	Case	Experiment	FE analysis
Failure time (min)	**FM2**	112	80
	FM4	68	54
Failure site	**FM2**	Fuel top	Fuel top
	FM4	Plenum	Fuel top
Eutectic penetration (%)	**FM2**	67	82
	FM4	24	28
Peak strain (%)	**FM2**	3.3	1.1
	FM4	15	1.2
Failure size (mm)	**FM2**	2.0/0.9	3.0/NA
	FM4	12.5/3.5	5.5/NA

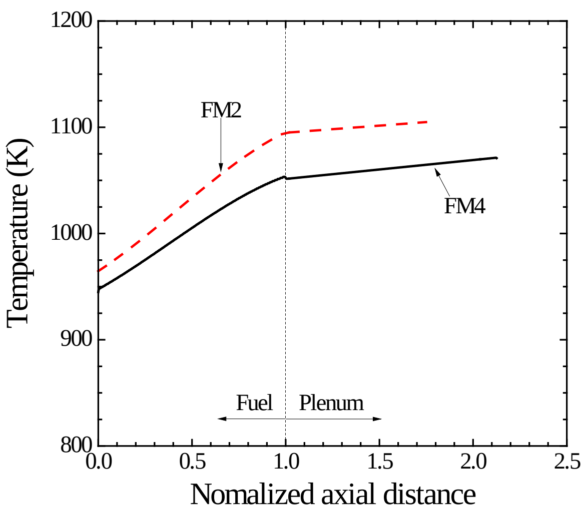

Fig. 2. Temperature distribution of clad

3. Results

Temperature distribution of clad calculated by FE heat transfer analysis is suggested in Fig. 2. Fracture simulation results are summarized in Table III.

FM2 test is low-burnup and high-temperature test. In case of low-burnup fuel pin, eutectic penetration is dominant mechanism of failure because the plenum pressure driving creep damage is low. In the experimental result, most of clad (67 %) was penetrated. In the FE analysis result, most of clad (76 %) was penetrated also. Early failure prediction of FE analysis arises from the overestimate of penetration depth. However, the prediction is still in good agreement with experimental result. Predicted failure size and failure site are also in good agreement with experimental result.

FM4 test is high-burnup test. In case of high-burnup fuel pin, plenum pressure is high. Therefore, creep becomes dominant mechanism of failure. In the experimental result, 24 % of clad was penetrated. In the FE analysis result, 28 % of clad was penetrated. Early failure prediction of FE analysis does not solely result from the overestimation of eutectic penetration rate. Main reason of the error is that the clad expanded by high plenum pressure contacted with the capsule wall so that failure at fuel top section was interrupted [1]. Therefore, the experimental failure site and failure size cannot be directly compared with the FE analysis result. In the FE analysis result, the failure size of FM4 is larger than that of FM2 which is eutectic-penetration-dominant case. The reason is that the penetration depth at failure is shallower, the time that creep damage axially propagates becomes longer.

4. Conclusions

In this study, FM2 and FM4 cases of WPF tests were simulated using finite element method with stress-reduction concept. Through this study, following conclusions are derived:

(1) Using proposed FE analysis method, the failure time, failure site and failure size of FM2 case were predicted well. In FM4 case, the FE result and the experimental result cannot be directly compared with each other, because unexpected error occurred in the experiment. Further simulations are needed to verify proposed method.

(2) It is expected that the failure mechanism affects failure size; when eutectic penetration depth at failure becomes shallower, failure size becomes larger. To convince the effect of failure mechanism, further simulations are needed.

In further study, remain cases of WPF tests (FM1, FM3, FM5, and FM6) [1] and TREAT-M tests [10] will be simulated to verify suggested method and analyze the effect of failure mechanism on failure size. Comparison of our result with the results from other safety analysis codes is needed as well.

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