Determination of Cladding Creep Model Constant Based on Test Database

Yong Sik Yang*, Jong Dae Hong
Korea Atomic Energy Research Institute, (34057), 111, Daedeok-daero, 989beon-Gil, Yuseong-Gu, Daejeon, Korea
**Corresponding author: yys@kaeri.re.kr*

1. Introduction

A cladding's creep phenomena caused by the difference between coolant and fuel rod internal pressure has a significant effect on in-reactor performance of the nuclear fuel.

Because a creep is greatly influenced by temperature, fast neutron fluence and stress of cladding, US NRC's fuel performance codes, FRAPCON[1] and FAST, adopt the Limback and Andersson models[2] to calculate creep behavior during irradiation. The Limback model is a popular creep models for Zircaloy-4 cladding.

In FRAPCON code, the difference in cladding composition, such as Zr-4, Zirlo and M5., is considered by introducing 'alloy factor'. In case of Zirlo creep rate, 'alloy factor' is set to 0.8 and after calculating a creep rate (see Eq. 1) with Zr-4 model as a reference, it is applied by multiplying it by the 'alloy factor'.

$$\dot{\varepsilon}_H = \frac{52\varepsilon_p^s \dot{\varepsilon}_{th+irr}^{1/2}}{2t^{1/2}} \exp\left(-52\sqrt{\dot{\varepsilon}_{th+irr} t}\right) + \dot{\varepsilon}_{th+irr} \quad (1)$$

However this approach can't properly consider the temperature/stress dependence of new alloy's creep characteristics because it is a method to match the final creep displacement only.

To overcome this limitation, we tried to develop new methodology to reflect new cladding alloy's creep characteristics to FRAPCON code.

This paper summarizes a procedure for determining the creep model constants, which faithful to the basic methodology applied to the Limback model and its applicability is confirmed by comparing it with the test data.

2. Creep experiment database

For the evaluation of Zr-4 cladding's creep behavior during dry storage, thermal creep tests had been performed and their results were released.[3] All cladding have a same final heat treatment condition(CWSR, Cold Worked Stress Relief) and test variables are temperature, stress and hydrogen contents.

Because the Limback model does not consider hydrogen content as an independent test variable, we ignored a hydrogen content effect in this modeling.

Table I show a creep test matrix which were used to determined creep model constants and Fig.1 shows a experiment results

Table I: Creep Test Database [3]

Temp. (℃)	Stress (MPa)	Test time (hrs)
400	90	1488
	70	3641
	90	3188
360	120	8537
	90	8537
	70	8537
330	150	5667
	120	5667
	90	5490
	120	5376
	90	5376
	70	5376

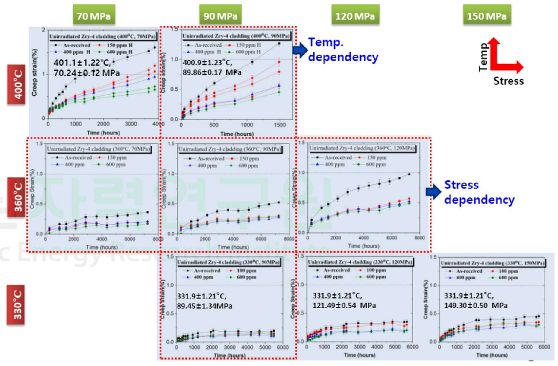

Fig. 1 Zr-4 Creep Test Results [3]

2.1 Reference Model Formula

$$\dot{\varepsilon}_{th} = A\frac{E}{T}\left(\sinh\frac{a_i\sigma_{eff}}{E}\right)^n \exp\left(\frac{-Q}{RT}\right) \quad (2)$$

$$\varepsilon_p^s = 0.0216\cdot\dot{\varepsilon}_{th+irr}^{0.109}\left(2-\tanh(35500\cdot\dot{\varepsilon}_{th+irr})\right)^{-2.05} \quad (3)$$

Table II. Creep model variable definition

Variables	Definition
$\dot{\varepsilon}_H$	Total creep strain rate
ε_p^s	Saturated primary creep strain
$\dot{\varepsilon}_{th+irr} = \dot{\varepsilon}_{th} + \dot{\varepsilon}_{irr}$	Irradiation creep and thermal creep
σ_{eff}	Effective stress in cladding
E	Young's modulus of cladding
R	Gas constant
T	Temperature
t	time
ai, n, Q, A	Model constants to be determined

As can be seen in Eq (1), thermal and irradiation creep are expressed together, however, this study only focuses on the thermal creep model determined through the creep test which had been conducted in out-of-reactor condition. Therefore we use Eq (2) and Eq. (3) as a reference thermal creep model formula. Variables in Eq. (2) and (3) are summarized in Table II

2.2 Model Constants Decision Procedure

- As the first step, the secondary creep strain rate and the saturated primary strain are sequentially determined
- The secondary creep strain rate is determined by linear fitting of the last 3 or more data of the experiment

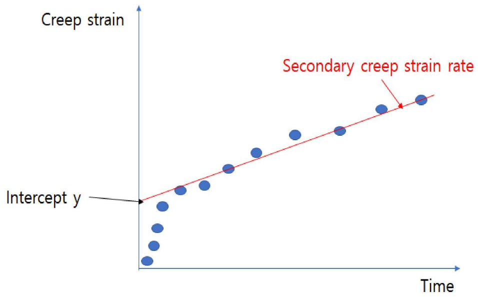

Fig.1 Determination of secondary creep strain rate and saturated primary creep strain

- The value of the intercept where the induced linear fitting equation and y-axis cross point(intercept y) is decided as saturated primary creep strain

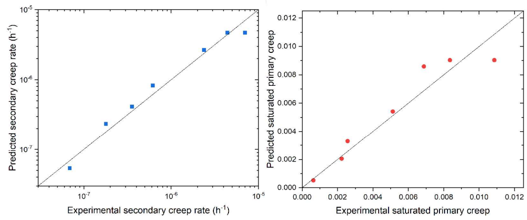

Fig. 2 Creep test results analysis (left: secondary creep strain rate, right: saturated primary creep strain)

- To find the unknown ai and n, one of the two model constants must be fixed, and then, the value of the remaining constants can be determined. In our study, ai is set to 650.0 (Same with Zircaloy4 cladding)
- To find stress dependent model constant(n) is decided using creep test results conducted as a function of stress under same constant stress.
- Along with the ai and n determined earlier, the temperature dependent factor, Q, is determined using creep test results performed as a function of temperature under constant stress condition.
- The last model constant, A, is determined through model tuning after substituting ai, n, and Q into Eq (2)
- After organizing the saturated primary creep strain as a function of secondary creep strain rate, an optimal fitting equation is determined without no restriction in the form of a function. (More simple form compared to original Limback model)

3. Conclusions

Eq. 4 and 5 are the final creep formula which were derived proposed procedure. And Fig. 3 and 4 show the comparison results between predicted creep strain and measured one.

$$\dot{\varepsilon}_{th} = 3.84*10^9 \frac{E}{T}\left(\sinh\frac{650\sigma_{eff}}{E}\right)^{1.95}\exp\left(\frac{-217}{RT}\right) \quad (4)$$

$$\varepsilon_p^s = 0.00909\left(1-\exp\left(1.09155*10^{-6}\cdot\dot{\varepsilon}_{th+irr}\right)\right) \quad (5)$$

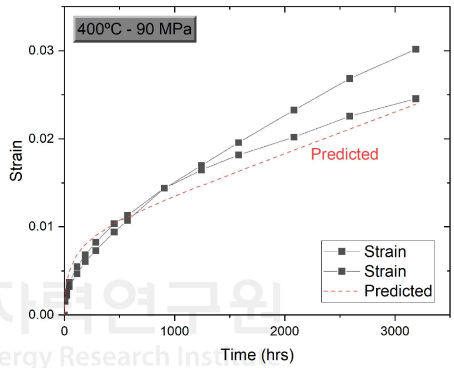

Fig. 3 New model vs Measured strain (400℃, 90MPa)

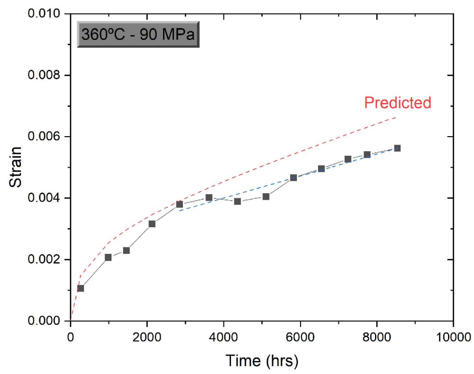

Fig. 4 New model vs Measured strain (360℃, 90MPa)

Although there are little difference, newly proposed model show good agreement with measured data. If more test data added, it is believed that it will be possible to improve a better model formula.

Determined new model constants such as ai, n, Q and A were implemented to FRAPCON code for validation testing with original FRAPCON's creep model.

Currently, we are analyzing HANA cladding's creep test results which were published via paper or report. After this analysis is finished, an evaluation between the model determined through this study and the FRAPCON model will be performed.

REFERENCES

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Acknowledgement

This work has been carried out supported by the Korea Foundation of Nuclear Safety R&D Program (2106002-0222-WT111)