

## **CREEP BEHAVIOR OF ZIRCALOY-4 IN HIGH BURNUP FUEL**

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### **ABSTRACT**

The creep model for Zircaloy-4 incorporated in a KAERI's fuel performance code COSMOS has been improved by including the metallurgical effect of Zircaloy cladding.

Based on the experimental results in which the creep strain rate is highest for stress relief annealed cladding (SRA) and lowest for recrystallized annealed cladding (RXA), the annealing factor was introduced and derived by iterative calculations with trial formulation until the best predictions for all the rods were obtained.

The creep model has been incorporated into the COSMOS and then verified with 3 cladding creep data, of which 2 cases exhibit creepdown and the other one creepout.

The model predicts well the creep behavior obtained from the GROHNDE and KWU database. The prediction for GROHNDE data does not show any discernable difference between the high- and low-Sn claddings.

Although there are controversies over the experimental method and the analysis procedures for clad creepout, COSMOS generally well predicts the creep behavior, even in the case of creepout, if the creepout factor of 1.7 is applied as suggested by HALDEN.

# 1. INTRODUCTION

Creep modeling of Zircaloy cladding is essentially required in fuel performance analysis for the assessment of gap closure that affects the fuel behaviors such as the temperature distribution and fission gas release [1].

The creep deformation behavior of the cladding, if plotted against time to obtain the creep curve, can be categorized into primary, secondary, and tertiary phases. In the initial phase, the creep rate is high and diminishing continuously. For a metallurgically stable material such as Zircaloy cladding, the creep rate would continue to decrease, until the minimum creep rate is reached. In this phase, the creep rate may remain constant for long periods.

Creep of cladding in the hoop (circumferential) direction is of particular interest because it affects the width of the gap between pellet and cladding. Changes in gap size influence fuel temperature, which affects the rate of fission gas release, alters the internal gas pressure within a rod, and thereby the driving force for creep. In effect, there is a coupling mechanism between creep and the driving force for further deformation [2].

Early in life, the reactor coolant pressure exceeds the rod internal gas pressure, and the cladding is subjected to compressive stress, with the results that the fuel to clad gap decreases as creepdown occurs, which in turn reduces the fuel temperature. Overall, creepdown is driven by the reactor coolant overpressure (compressive stress) and is affected by temperature and fast flux. On the other hand, the fuel-cladding gap tends to close at higher burnup. The rod internal pressure rises owing to fission gas release and in principle may exceed the system coolant pressure. Clad creepout can then occur and re-open the fuel-cladding gap, a phenomenon termed clad lift-off. Under these circumstances fuel temperature rises and further fission gas release is possible. Clad lift-off does not arise, however, if the outward creep rate of the cladding remains lower than the fuel swelling rate, because the pellet-cladding gap remains closed. For the high burnup fuel rods, a higher fission gas release is anticipated in the fuel rods by end of life. Thus, the accurate estimation of creep in the cladding subjected to stress reversal, from coolant overpressure (compression) to rod gas

overpressure (tension) becomes more important. Therefore, an understanding of the creep behavior of Zircaloy–4 cladding is required to predict the thermal performance and mechanical integrity of fuel rods.

The purpose of this paper is to develop a creep model of Zircaloy–4 cladding. The developed model is verified for both creepdown and creepout. The database used comes from the GROHNDE and KWU for creepdown, and from HALDEN for creepout.

## 2. DEVELOPMENT OF CREEP MODEL

We revised the COSMOS creep model [3] to accommodate the following creep database:

- GROHNDE (10 rods)
- KWU (10 rods)
- HALDEN (2 rods)

The KWU and GROHNDE database are related to the creepdown, while the HALDEN database is obtained for the creepout experiment.

The creep behavior of a Zircaloy tube has suggested that the creep rates depend on either the mechanical properties (yield strength and ultimate tensile strength) or on the fabrication process (cold working, reduction area, and annealing). Among these parameters, the final annealing parameter was selected to obtain the appropriate predictions since it is the most commonly available data for the cladding manufacturing process and it seems to accommodate the other effects such as yield strength and reduction of area.

Fig. 1 shows the annealing factor dependent on the final annealing parameter, in which the creep strain rate is highest for stress relief annealed cladding (SRA) and lowest for recrystallized annealed cladding (RXA).

The final annealing parameter,  $A_f$  is determined by

$$A_f = t_f \cdot \exp\left(-\frac{Q}{R \cdot T}\right)$$

where  $Q/R$  activation energy divided by the molar gas constant = 40,000 K

The annealing factor was derived by iterative calculation with a trial formulation until the appropriate predictions for all the rods were obtained. The least squares method yields the following dependence of the annealing factor on the final annealing parameter:

$$F_{ann} = -10.482 - 0.537 \times \log(A_f)$$

The inverse dependence of the annealing factor indicates that creep rate decreases with increasing final annealing parameter (increasing degree of recrystallization).

Limback [4] also observed that for moderate hoop stresses (< 120 MPa) the measured hoop creep rates, both out-of-reactor and in-reactor, decrease with increasing final annealing temperature. However, the steady state creep rate has a minimum for partially recrystallized cladding with higher stresses, in which this annealing factor cannot be applied.

Therefore, the annealing factor in Fig. 1 representing the highest creep rate for stress relief annealed cladding is reasonable because the present in-reactor creep database was measured under the steady state condition so the hoop stress is usually less than 120 MPa.

Finally, with the assumption of superposition of thermal creep component and irradiation creep component, KAERI's creep model was established :

$$\mathbf{e}_{cp} = \mathbf{e}_{1,th} + \mathbf{e}_{2,th} + \mathbf{e}_{1,irr} + \mathbf{e}_{2,irr}$$

$$\mathbf{e}_{1,th} = C_1 \cdot \dot{\mathbf{e}}_{2,th} \left(1 - e^{-k \cdot \sqrt{t}}\right) \quad \mathbf{e}_{1,irr} = C_1 \cdot \dot{\mathbf{e}}_{2,irr} \left(1 - e^{-k \cdot \sqrt{t}}\right)$$

$$\mathbf{e}_{2,th} = F_{ann} \cdot C_{2,th} \cdot \exp\left(-\frac{26,116}{TK_c}\right) \cdot \mathbf{s}_K(n_{th}) \cdot t$$

$$\mathbf{e}_{2,irr} = F_{ann} \cdot C_{2,irr} \cdot \mathbf{s}_K(n_{irr}) \cdot \mathbf{f}^{0.85} \cdot t$$

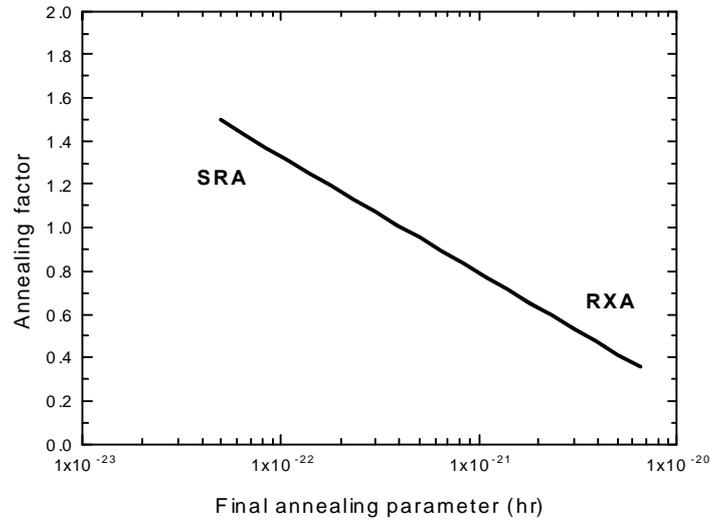


Fig. 1 Annealing factor considering the final annealing effect on the creep

### 3. RESULTS AND DISCUSSION

The creep model is implemented in the fuel performance code, COSMOS [5] for the evaluation of cladding creep behavior in PWRs. The developed creep model is verified by an experimentally measured database from GROHNDE(10 Rods), KWU(10 Rods), and HALDEN(2 Rods).

#### 3.1 CASE 1 (GROHNDE)

The cladding materials irradiated in the GROHNDE reactor were nominally high-tin (HS) and low-tin (LS) Zircaloy-4 with average tin contents of 1.5 and 1.3 wt%, respectively.

The final heat treatment and annealing parameters are listed in Table 1 [6]. The degree of recrystallization estimated from TEM shows that the HS and LS claddings are similar to that in typical stress-relieved fuel. A variation of 2 to 10% is a small difference which is not significant considering the extremely small volume of material examined by TEM.

Table 1 Heat treatment and microstructure of cladding

	Final anneal condition	Annealing parameter	Degree of recrystallization
HS	764K/4hr	580	2 %
LS	764K/4hr	576	10%

### 3.1.1 Measurement and its analysis

The fuel rod diameters were measured by the mechanical displacement of two rubbing shoes located 180° apart around the fuel rod. The mechanical displacement of the rubbing shoes by the fuel rods was converted to an analog voltage by a linear variable differential transformer (LVDT).

The measured diameters were corrected for oxide on the cladding surface. The oxide has a density 1/1.56 times that of the substrate Zircaloy. The diameter data were corrected for the presence of oxide using the following equation:

$$D_c = D_m - 2 \cdot \left( d_{ox} - \frac{d_{ox}}{1.56} \right) = D_m - 0.72 \cdot d_{ox}$$

where  $D_c$  Corrected Diameter  
 $D_m$  Measured Diameter in Span  
 $d_{ox}$  Average Oxide Thickness in Span

The average oxide thickness is multiplied by two in the above equation to account for oxide on the diametrically opposite sides of the fuel rod.

Diametral creepdown was then calculated as follows :

$$CRP = \frac{D_0 - D_c}{D_0} \cdot 100$$

where CRP Diametral Creepdown (%)

### 3.1.2 Comparison with measurement

The creep prediction by adopting the annealing factor in Table 1 has been compared against the measured creepdown at EOL along the axis for low and high Sn cladding irradiated in the GROHNDE PWR.

Fuel rod creepdown was measured on 10 fuel rods of which 4 rods had higher Sn cladding and the others included lower Sn in the cladding.

As shown in Fig. 2, comparison between predicted and measured creepdown indicates the acceptable agreement in the maximum creepdown in the central region of the cladding. The low neutron flux at both ends of a fuel rod results in a low creep rate and a steep gradient in cladding creepdown. Small differences in measured creepdown at the bottom and top are not considered significant.

The axial profile of the cladding diameter is determined by cladding creep (both thermal and irradiation-assisted) and by pellet-cladding contact. After contact is made between the cladding and the fuel pellets in the central region of a fuel rod, creepdown will stop and eventually reverse (creepout). After four irradiation cycles, the cladding has crept down onto the fuel pellets and the measured creepdown generally shows constant in the middle of the axial cladding, which means the occurrence of a gap contact. From the almost constant creepdown in the middle of the cladding, KAERI's fuel performance code, COSMOS well predicts the effect of pellet and cladding gap contact.

It was observed that the lower tin cladding (LS) showed slightly higher creepdown than the cladding (HS) with a higher tin content after four irradiation cycles. However, it is difficult to distinguish the effect of tin contents on creepdown by adopted the annealing factor.

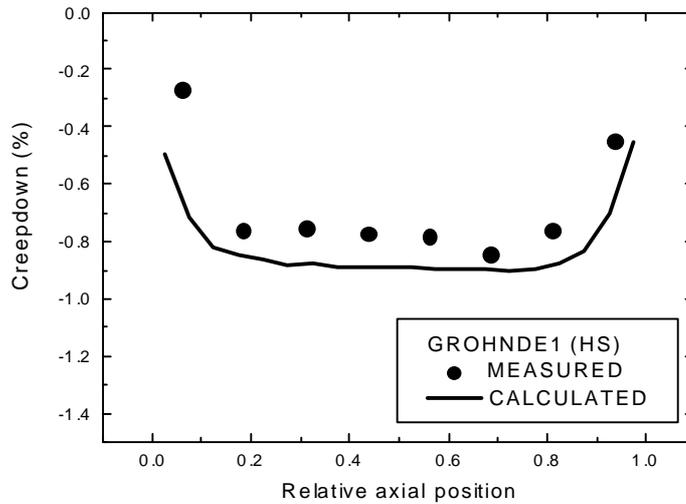


Fig. 2 Creepdown at EOL along relative axial positions for GROHNDE1 (HS).

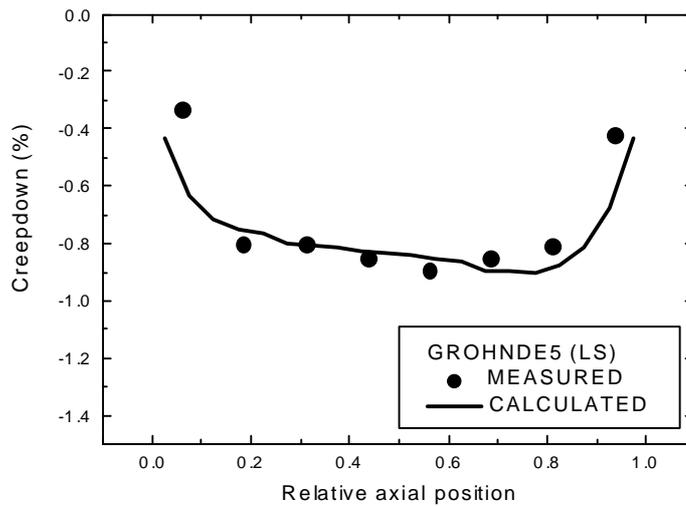


Fig. 3 Creepdown at EOL along relative axial positions for GROHNDE5 (LS).

### 3.2 CASE 2 (KWU)

The creep prediction by adopting the annealing factor has been compared against the measured peak creepdown at EOL. Fuel rod creepdown was measured on 10 fuel rods. However, the heat treatment condition is not available so the annealing factor is assumed to be 1.0 because the cladding manufactured by KWU seems to be the partially recrystallized annealed one.

A comparison between predicted and measured creepdown indicates the acceptable agreement in the peak creepdown in the central region of the cladding. The measured maximum values are extended in the middle region of the cladding because only the peak creepdown has been reported.

As mentioned before, a low creep rate and a steep gradient in cladding creepdown results from a low neutron flux at both ends of a fuel rod.

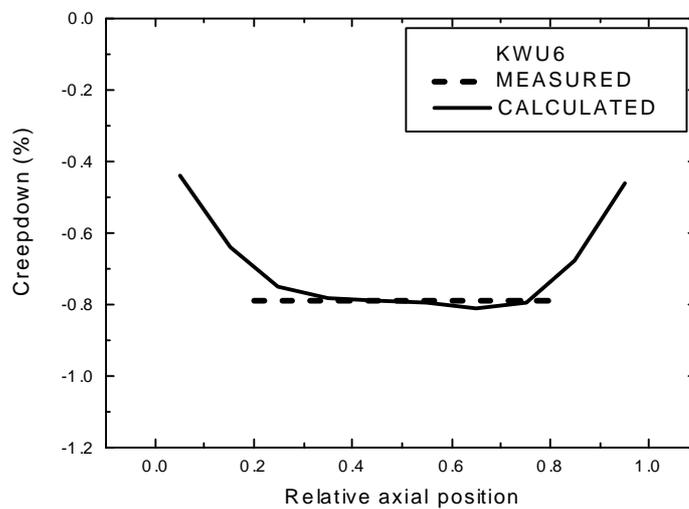


Fig. 4 Creepdown at EOL along relative axial position for KWU6.

### 3.3 CASE 3 (HALDEN, Creep- out)

A creep experiment has been carried out in the HALDEN rods, UP and LOW to investigate the in-reactor creep behavior of Zircaloy-4 pre-irradiated to a fast neutron fluence of  $1.2 \times 10^{22}$  n/cm<sup>2</sup>. The operating conditions were a fast neutron flux of about  $3 \times 10^{13}$  n/cm<sup>2</sup>-s, a mid-wall clad temperature of about 380°C, with a mid-wall hoop stress of either 30 or 85 MPa [7]. The UP and LOW test rods were exposed to these conditions for 3100 full power hours (FPH).

The calculation with a creep model which was applied to creepdown was performed to check

whether the unified creep model is available between creepdown and creepout.

As shown in Fig. 5, the comparison (dash and dot line) between the predicted and measured creepdown indicates the under-prediction with irradiation time for both rods. It is considered that small differences in measured creepout for the lower segment are not substantial.

Although there are many controversies on the accuracy of the experimental method and the analysis procedure, it is considered that KAERI's fuel performance code, COSMOS well predicts the creep behavior in the case of creepout, if it includes the creepout factor of 1.7 suggested by HALDEN, as shown by the solid line in Fig. 5.

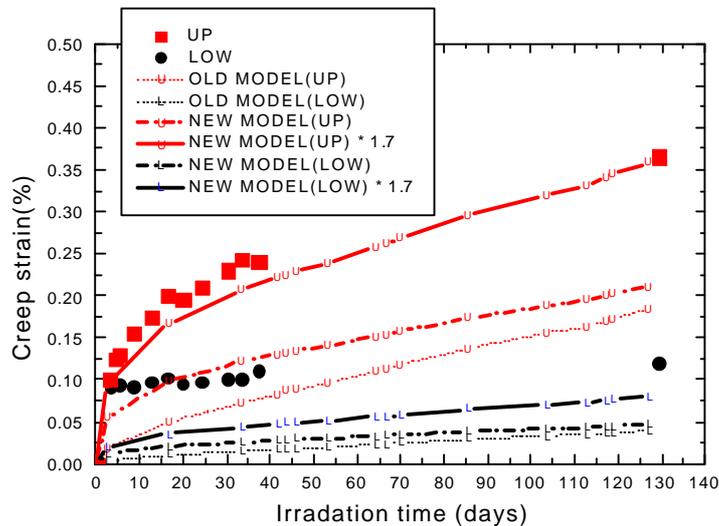


Fig. 5 Creepout as a function of irradiation time for the upper and lower segments.

### 3.4 Summary of Creep Model Verification

Fig. 6 shows the summary of the predicted versus measured data from both the creepdown and creepout experiments. It is well known that a large scattering in the Zircaloy creep strain is obtained not only from one reactor to another, but also within the same reactor with rods manufactured by the same process and experiencing similar irradiation histories. However, it can be considered that the developed creep model implemented in the COSMOS code well predicts the various creep behaviors.

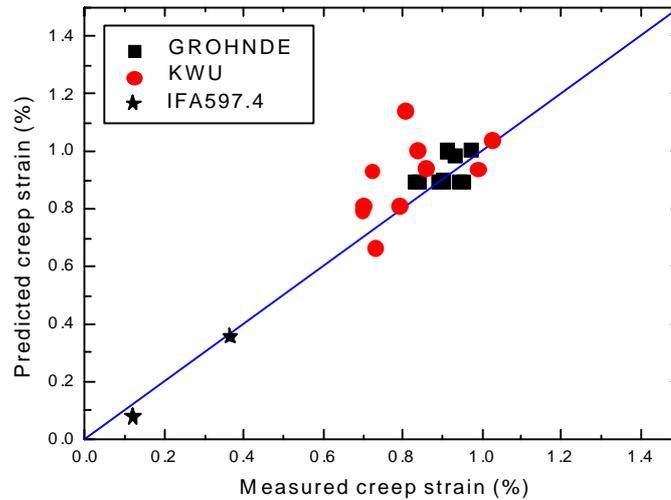


Fig. 6 Comparison of the calculated and measured creep strains.

## 4. CONCLUSION

A creep model combined with the COSMOS model for Zircaloy-4 cladding in PWRs was improved to account for the metallurgical effect of Zircaloy cladding.

Based on the experimental results in which the creep strain rate is highest for stress relief annealed cladding (SRA) and lowest for recrystallized annealed cladding (RXA), an annealing factor was derived by iterative calculations with a trial formulation until the best predictions for all the rods were obtained.

The creep model implemented in KAERI's fuel performance code, COSMOS, was verified with 3 cladding creep data, of which 2 cases exhibit creepdown and the other is related to creepout.

The creep model adopting the annealing effect for the GROHNDE and KWU database well predicts the creep behaviors. The prediction for GROHNDE does not show any discernable difference between the high- and low-Sn claddings

Although there are many controversies on the accuracy on the experimental method and the analysis procedure, it is considered that KAERI's fuel performance code, COSMOS, well predicts the creep behavior, even in the case of creepout if including the creepout factor of 1.7 suggested by HALDEN.

Agreement between predicted creepdown and creepout with the measured data shows the good ability of the COSMOS code to estimate the creep behavior of cladding.

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