Preliminary Burnup Limits Analysis of the Barrier Cladding for KALIMER

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1. Introduction

A metallic fuel is being considered as a fuel for the KALIMER. The eutectic melting between metallic fuels and their claddings has been an issue in the metal fuel development.

However, the formation of the eutectic phase can be eliminated by the use of barrier cladding such as Zr liner. In order to apply the concept of the barrier cladding to the liquid metal fast reactor, it is also needed to analyze the burnup limits of the barrier cladding.

In this paper, the creep rupture strengths for Zr liner and Mod.HT9 were derived. The continuum mechanistic model by Tanaka was inserted into MACSIS[1]. A parametric study for analyzing the design limits of the cumulative damage fraction has been performed by MACSIS. The optimum cladding thicknesses were derived to satisfy the burnup goal.

2. Methods and Results

In this section, a need for the barrier cladding, the creep rupture strength of the barrier cladding, and the burnup limits analysis are described.

2.1 A Need for Barrier Cladding

The eutectic melting between metallic fuels and their claddings has been an issue in the metal fuel development[2].

Fuel/cladding chemical interaction (FCCI) is a multi-component diffusion problem. With stainless steel cladding, even in the simplest fuel alloys such as U-Fs and U-Zr, at least five major constituents participate in the diffusion process.

FCCI causes the weakening of cladding and formation of relatively low-melting-point compositions in the fuel.

Although melting due to FCCI is not expected at normal operating conditions, the fuel can form a mixture of liquid and solid phases that may promote further cladding interaction during transient conditions.

However, the formation of the eutectic phase can be eliminated by the use of barrier cladding. In barrier cladding, a steel cladding tube is lined with a material resistant to attack by the fuel. Use of a cladding resistant to FCCI would contribute to the robust behavior of the fuel at high burnup.

2.2 Creep Rupture Strength of the Barrier Cladding

One of the possible cladding liner material is zirconium, and the cladding material is the modified HT9.

To satisfy cladding stress and strain limits in the fast reactor metallic fuel design, it is required to evaluate the cumulative damage fraction (CDF). The CDF value is determined from the time-to-rupture correlation as a function of the temperature and stress.

So the time-to-rupture correlation for the Zr liner, the Mod.HT9 cladding, and the barrier cladding must be derived to estimate CDF.

The creep rupture strengths for the Zr liner and Mod.HT9 were derived by the available data[3,4].

Figure 1 shows the time to rupture correlation for Zr liner & Mod.HT9 at 650°C. It is estimated that the strength of Zr liner is weaker than that of Mod.HT9 at the high temperature.

The time to rupture correlations of the Zr liner and the Mod.HT9 cladding were modeled into MACSIS.

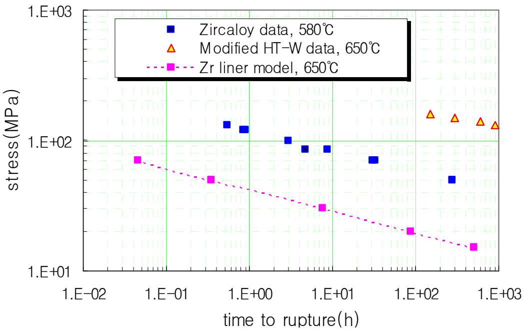

Figure 1. Time to rupture correlation for Zr liner & Mod.HT9

The deformation rate for the barrier cladding can be determined using the Tanaka's equation is given as [5];

$$\varepsilon_{ij} = (1-f)\varepsilon_{ij}^{I} + f\varepsilon_{ij}^{II}$$

where f is the rate of the second phase.

The above equation is applicable to the material in which the volume fraction of the strong phase is large enough to surround the weak phase.

So it is expected that this model is very applicable for the Zr liner cladding, because the creep rupture strength of Zr liner is weaker than that of Mod.HT9.

The creep rupture strength of the barrier cladding was also modeled into MACSIS.

2.3 Burnup Limits Analysis

MACSIS is a metallic fuel performance computer code which calculates the temperature distribution, the mechanical deformations, the fission gas release, and the constituent migrations of the fuel elements during an irradiation. MACSIS also estimates the performance of the metallic fuel pin by analyzing (1) the cladding stress and strain, (2) the slug center-line melting (3) the liquid phase attack to cladding.

The key design parameters for analyzing the metal fuel performance are shown in Table 1.

Table 1. Key design parameter

Fuel Slug Contents (wt%)	U-14TRU-10Zr
Fuel Slug Diameter (mm)	6.44
Smeared Density (%)	75
Pin Outer Diameter (mm)	8.5
Cladding Thickness (mm)	0.53
Zr Liner Thickness (mm)	0.1
Coolant Outlet Temperature (°C)	545
Cladding Material	Mod.HT9

Figure 2 shows CDF vs. cladding thickness according to the burnup for the Mod.HT9 cladding without Zr liner and the Mod.HT9 cladding with Zr liner.

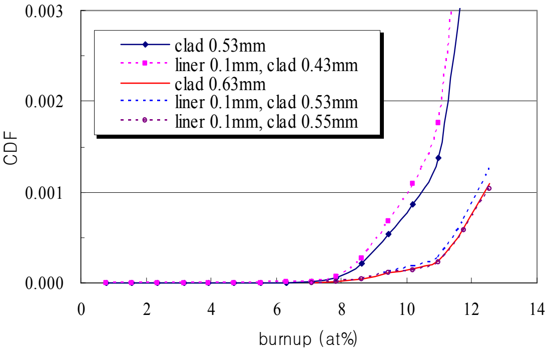

Figure 2. CDF vs. cladding thickness according to the burnup

Generally the limit of CDF on the fuel pin failure rate of the fast reactor core is less than 0.01%.

In the case of 0.53mm of cladding thickness for Mod.HT9 without Zr liner, the calculated CDF limit for the fuel pin during the steady-state was about 10.2 at.% for the 1.75 plenum-to-fuel ratio. However, in the case of Mod.HT9 with Zr liner (0.43mm of cladding thickness and 0.1mm of Zr liner thickness, respectively), the calculated CDF limit was about 9.8 at.%.

When the total thickness of the cladding is same, it was estimated that the burnup limit of Mod.HT9 with Zr liner was lower than that of Mod.HT9 without Zr liner, because the creep rupture strength of Zr liner is weaker than that of Mod.HT9.

In the case of 0.63mm of cladding thickness for Mod.HT9 without Zr liner, the calculated CDF limit for the fuel pin was about 12.1 at.%. So, it was estimated that 0.63mm of thickness was optimum for satisfying 12at.% of the potential burunp goal.

However, in the case of Mod.HT9 with Zr liner (0.53mm of cladding thickness and 0.1mm of Zr liner thickness, respectively), the calculated CDF limit was about 11.9 at.%. So, the burnup limit was recalculated to derive the optimum thickness for the Mod.HT9 with Zr liner.

In the case of Mod.HT9 with Zr liner (0.55mm of cladding thickness and 0.1mm of Zr liner thickness, respectively), the calculated CDF limit was about 12.1 at.%. It was estimated that 0.55mm of cladding thickness and 0.1mm of Zr liner thickness were optimum for satisfying 12at.% of the potential burunp goal.

Table 2 shows the optimum thickness for satisfying 12at.% of the potential burnup goal.

Table 2. Thickness for satisfying 12at.% of burnup goal (mm)

Mod.HT9 without Zr liner	0.63
Mod.HT9 with Zr liner	
Mod.HT9	0.55
Zr liner	0.1

3. Conclusion

The formation of the eutectic phase can be eliminated by the use of barrier cladding such as Zr liner. In order to apply the concept of the barrier cladding to the liquid metal fast reactor, preliminary burnup limits of the barrier cladding were analyzed. The creep rupture strengths for Zr liner and Mod.HT9 were derived. The deformation rate for the barrier cladding was inserted into MACSIS. The burnup limits of the barrier cladding were analyzed by MACSIS. The optimum cladding thicknesses were derived to satisfy the potential burnup goal. As for the Mod.HT9 without Zr liner, it was estimated that 0.63mm of thickness was optimum for satisfying burunp goal. As for Mod.HT9 with Zr liner, it was estimated that 0.55mm of cladding thickness and 0.1mm of Zr liner thickness were optimum.

Acknowledgements

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REFERENCES

[1] B.O.Lee, et al., Analysis on the Temperature Profile and the Thermal Conductivities of the Metalic and the Dispersion Fuel Rods for HYPER, Proceedings of KNS, May (2001).
[2] G. L. Hofman, L. C. Walters and T. H. Bauer, Prog. Nucl. Energy, 31, 83 (1997).
[3] Y.Zhou, et al., Short-Term Rupture Studies of Zircaloy-4 & Nb-Modified Zircaloy-4 Tubing using Closed-End Internal Pressurization, SMiRT16,Washington DC, August (2001)
[4] W.S.Ryu et al., High temperature material characterization and advanced materials development, KAERI/RR-2515(2004).
[5] Tanaka, Prediction of creep deformation in ductile two-phase alloys by a continuum mechanics model, journal of Materials Science, 28 (1993)