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Preliminary Crack Effects Analysis of the Metal Fuel for SFR

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1. Introduction

A metallic fuel is being considered as a fuel for the KALIMER. A metallic fuel shows a rapid swelling with burnup. The swelling fuel contacts the cladding at about 1~2 at% burnup. If a metal fuel includes high TRU contents, the rate of radial swelling is enhanced markedly. High rate of the radial swelling increases the radial anisotropy and creates stresses in the peripheral region of the metallic fuel enough to create the radial crack formation. So evaluation of the effect of the crack is needed to estimate the performance of the metal fuel with high TRU contents.

In this paper, the crack module was installed into MACSIS. The CDF design limits were analyzed considering the crack effects such as the change of the swelling rate and the fission gas release rate.

2. Methods and Results

In this section, the radial crack of a metallic fuel, the crack model and the crack effect analysis are described.

2.1 Radial crack of a metallic fuel

The general swelling behavior for a metallic fuel is a rapid swelling, so the swelling fuel contacts the cladding at about 1~2 at% burnup. In order to allow a metallic fuel swelling (approximately 30%), the smeared density is typically chosen to be 75% [1]. If the swelling of a metal fuel is isotropic, the rate of the axial growth is about 15%. However, the observed rates of the axial growth are consistently smaller. This means the anisotropic swelling characteristics of the metallic fuel for SFR. The main reason of the metallic fuel anisotropy appears to be the difference in swelling behavior between the hotter center of the fuel and the colder periphery [2].

After the fuel slug comes into contact with the cladding, further axial growth is restrained. The metal fuel deformation before the fuel-cladding contact is anisotropic. In the case of the metallic fuel including high TRU contents, the larger anisotropy has been observed and the anisotropic of the metallic fuel can be attributed to large crack formation.

The large crack formation enhances the rate of anisotropy swelling markedly. This high rate of radial crack may affect on the metallic fuel performance.

2.2 Crack model

The cracks increase the strain of a metallic fuel. In order to evaluating the effect of the cracks on the stress-strain state, the concept of the effective hot fuel radius was introduced [3].

In this paper, the hot fuel radius r_f was defined as;

$$r_f = (r_0 + dr_{crack}(\approx f^{crack}) + \Delta D_s) \times (1 + \Delta D / D)$$

where r_0 is the cold fuel radius, dr_{crack} is the radial crack radius, f_{crack} is the anisotropy factor, ΔD_s is the fuel swelling rate, and $\Delta D / D$ is the volumetric average thermal expansion.

f_{crack} was given as;

$$f_{crack} = 1 - \left(\frac{\varepsilon_{iso}}{\varepsilon_{iso} + \varepsilon_{crack}} \right)$$

where ε_{iso} is the isotropic strain, and ε_{crack} is the anisotropic strain.

Figure 1 shows f_{crack} as a function of TRU wt% according to a burnup. It was estimated that maximum value of the f_{crack} was 0.8 at 1at%. If the burnup was over 2 at.%, f_{crack} was ignored because the further radial swelling was restrained after the fuel-cladding contact.

The hot fuel radius and the derived f_{crack} as a function of TRU wt% was modeled into MACSIS.

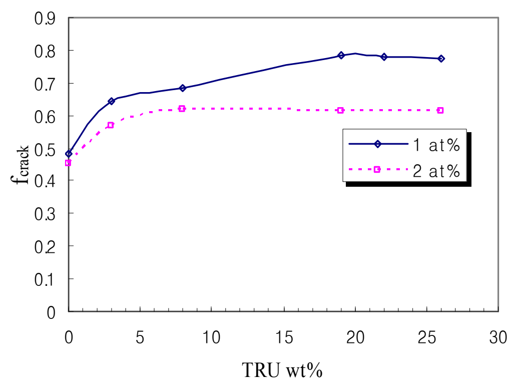

Figure 1. Anisotropy factor, f_{crack},as a function of TRU wt% according to a burnup

2.3 Crack effect Analysis

Figure 2 shows the fission gas release rates without considering the crack effect and with considering the crack effect, which was predicted by the semi-theoretical model in the MACSIS code [4].

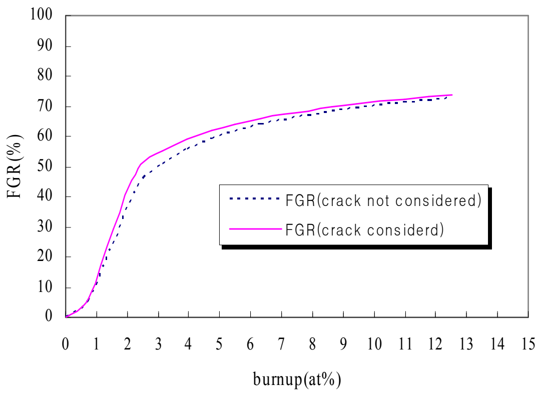

Figure 2. Fission gas release rate according to the crack

According to the calculation, it was estimated that the fission gas release increased considerably at around 1 to 2 at% burnup without regard to the crack.

In the case of ignoring the crack effect, the maximum fission gas release rate was about 71% at 11 at.% burnup. However, in the case of considering the crack effect, the maximum fission gas release rate was about about 72.3%. It was expected that the difference of the fission gas release rate was caused by the difference of the radial anisotropic swelling.

Even though the difference of the fission gas release rate according to the crack was about 1.3%, this difference may affect on the integrity of the cladding at the end of cycle.

Figure 3 shows the CDF (cumulative damage fraction) without considering the crack effect and with considering the crack effect, which was also predicted by the MACSIS code.

The cladding was the modified HT9. The thermal creep strain of the modified HT9 with the He effects was below 1% at 15 at.% for the 1.75 plenum-to-fuel ratio [5]. So in this paper, the CDF was analyzed for the steady-state conditions. It was assumed that the cladding strain of a low-smeared density pin can be analyzed by the plenum pressure stress alone.

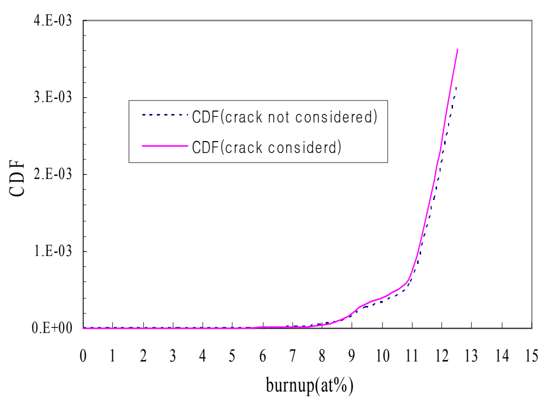

Figure 3. CDF according to the crack

In the case of ignoring the crack effect, the calculated CDF was about 0.006% at 11 at.% burnup. However, in the case of considering the crack effect, the calculated CDF was about 0.007%. It was estimated that the difference of CDF was caused by the difference of the fission gas release rates.

Generally the limit on the fuel pin failure rate of the fast reactor core is less than 0.01%. So it was estimated that burnup limit was affected by the crack, even though the difference of the CDF according to the crack was small.

There were a little fuel characteristics relating to TRU material. There are lots of uncertainties in the modeling such as the crack radius, the swelling rate, etc., so the experimental tests are needed for clarifying the uncertainties of the crack effect.

3. Conclusion

In the case of the metallic fuel including high TRU contents, the larger anisotropy has been observed and the anisotropic of the metallic fuel can be attributed to large crack formation. So evaluation of the effect of the crack is needed to estimate the performance of the metal fuel with high TRU contents. In this paper, the crack model was derived by concept of the hot fuel radius and anisotropy factor. The crack module was installed into MACSIS. The fission gas release rates according the crack effect was estimated by the semi-theoretical model in the MACSIS code. The cumulative damage fractions were analyzed by considering the crack effects. It was estimated that burnup limit was affected by the crack.

Acknowledgements

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