A Corrosion Model for the Zircaloy-4 Cladding Considering the Water Chemistry and Metallurgical Effects

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A cladding of Zirconium alloy is the first barrier from the view point of safety and its performance is of consequence when increasing the maximum discharge burnup. The present corrosion models assess well the oxidation behaviors of Zircaloy-4 in a PWR. However, concerning the water chemistry, contradictory results have been reported as to whether or not there is a discernible oxidation enhancement by the presence of an elevated lithium concentration in the coolant. In addition, the trend of reducing Sn contents in the cladding and an effort for obtaining the optimized microstructure have not been considered in the present corrosion models. By keeping in mind these regards, a precise corrosion model is developed and implemented in the fuel performance code, COSMOS.

The developed corrosion model additionally takes into account the Sn effect, water chemistry, and heat treatment condition as well as the irradiation effect. The corrosion rate equation in the pre-transition regime is given by

$$\frac{d\delta^3}{dt} = F_{Sn}\cdot F_{MPS}\cdot F_{Li,pre}\cdot F_B\cdot F_\phi\cdot F_{pre}\cdot \exp\left(-\frac{Q_{pre}}{R\cdot T_i}\right)(\mathrm{mm^3/day})$$

while the oxidation rate in the post-transition regime is given by

$$\frac{d\delta}{dt} = F_{Sn}\cdot F_{MPS}\cdot F_{Li,post}\cdot F_B\cdot F_\phi\cdot F_{post}\cdot \exp\left(-\frac{Q_{post}}{R\cdot T_i}\right)(\mathrm{mm/day})$$

where F_{Sn} = the Sn content enhancement factor, F_{Li} and F_B = the lithium enhancement and boron retardation factor, respectively and F_{MPS} = the second phase particle (SPP) enhancement factor.

The Sn effect was determined by analyzing the measured oxide data for the high burnup fuel rods of various claddings with different Sn contents. The SPP enhancement factor was formulated by the relevant in-laboratory and in-pile measurements of the corrosion rate of the Zr-4 cladding with various average diameters of the SPP. The average diameter of the SPP could be reasonably well correlated with the annealing parameter. In particular, it is assumed that the subcooled void present in the coolant is a prerequisite for the detrimental water chemistry effect to accelerate the corrosion in the cladding.

The validity of the developed corrosion model was first checked to see whether or not the corrosion model is adequate for predicting the corrosion behavior for 40 different fuel rods. The prediction by the corrosion model indicates that the model is suitable for a corrosion thickness estimation in the various irradiation environments as shown in Fig. 1.

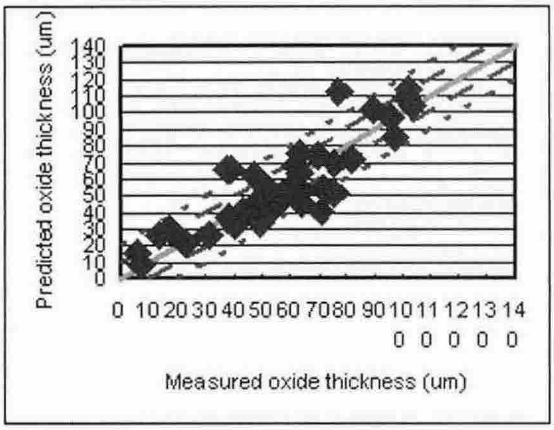

Fig. 1 Comparison between the measured and predicted oxide thickness

In addition, the model was verified by using the database obtained from the UO_2 fuel rods irradiated in Grohnde and Ringhals, and several MOX fuel rods. Fig. 2 demonstrates a good agreement between the measured and predicted oxide thickness profile of a MOX fuel rod.

Verification with the measured oxidation database shows the validity of the developed corrosion model and the applicability of the COSMOS code with a new corrosion model to analyze the cladding oxidation in UO_2 as well as MOX fuel with various claddings in different irradiation environments.

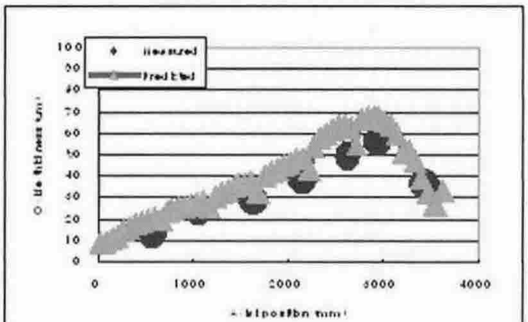

Fig. 2. The measured and predicted oxide profile of a MOX fuel rod.