Progress in Nuclear Energy 91 (2016) 153–158

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Effect of oxide layer growth on fuel temperature of mini fuel plates

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ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form
22 March 2016
Accepted 22 April 2016

Keywords:
Oxide layer
Preparation of irradiation test
Mini fuel plate
Fuel temperature

ABSTRACT

The effect of the oxide layer formed on the mini fuel plates is studied to evaluate fuel centerline temperature. For a part of U-Mo fuel qualification program, mini fuel plates, double-stacked as upper and lower plates, will be irradiated in the HANARO reactor for four cycles. In the present study, fuel performance and thermal hydraulic behavior during irradiation are numerically investigated using the MCNP and TMAP codes. The power released from the mini fuel plates is estimated using the MCNP code. From the neutronic analysis results, it is observed that the lower plate at the BOC during the 1st cycle releases the highest power, and the power gradually decreases during the irradiation test. The growth of the oxide layer thickness during the irradiation test is predicted using many correlations with various pH values ranging from 5.0 to 7.0. The pH value in the HANARO reactor is controlled between 5.7 and 6.2, and the oxide layer thickness is predicted by the Boehmite model for these two pH values. The oxide layer thickness predicted using the other correlations are bounded by these two predicted values. The maximum oxide layer thickness at the end of irradiation is approx. 9 and 68 μm with pH of 5.7 and 6.2, respectively. The Pawel model with a rate factor of 16 predicts the maximum oxide layer as 25 μm. Using the predictions of the oxide layer thickness, the centerline fuel temperatures are evaluated using the TMAP code. The maximum fuel temperature is not observed when the power released from the fuel is the highest. Because the temperature rise through the oxide layer is significant, the oxide layer thickness must be considered in the fuel temperature evaluation. The oxide formation saturates with time, and the fuel reaches the maximum temperature at the end of the saturation. After the maximum fuel temperature is reached, it starts decreasing, because the power decreases.

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1. Introduction

The oxides formed on the cladding surfaces need to be properly evaluated for the accurate prediction of fuel temperature. The growth of oxides on the cladding surfaces depends on the heat flux, wall temperature, flow rate, pH, and other factors (Griess et al., 1961; Lee and Sohn, 1994; Nabhan et al., 2015; Tahk et al., 2010). If the heat flux released from the nuclear fuel is high, and pH in the coolant system is poorly controlled, the fuel temperature rise through the oxide layer cannot be ignored. At a heat flux of 2.25 MW/m^2, an oxide layer of 1 μm may increase the fuel temperature by approx. 1 °C (Kim et al., 2008). With an oxide layer of 100 μm, the temperature rise would be approx. 100 °C. If there is an excessive thickness of oxides, it may cause safety and performance issues. While the reactor fuels loaded on the core are continuously burned, the power produced from the fuel gradually decreases, and the oxides keep forming on the cladding surfaces. Most of the research reactors that utilize plate type fuel use aluminum alloy for cladding. There have been many studies on the oxide growth on aluminum alloy, but their applicable ranges were limited to certain conditions with respect to the coolant pH, flow rate, and fuel life (Kim et al., 2008; Leenaers et al., 2008; Shaber and Hofman, 2005). Empirical correlations to predict the oxide layer thickness on aluminum alloy were developed by Pawel et al. (1995), and given as a function of the irradiation time. The rate of oxide growth on aluminum alloy can be expressed by the power law such as

$$\frac{dx}{dt} = kx^{-p} \tag{1}$$

By integrating Eq (1), the general form of the kinetic equation for the oxide layer thickness on aluminum alloy is expressed as

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http://dx.doi.org/10.1016/j.pnucene.2016.04.013
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$$x(t) = \left\{[x(t-\Delta t)]^{p+1} + (p+1)k\Delta t\right\}^{\frac{1}{p+1}} \quad (2)$$

where x, Δt, k, and p are the oxide layer thickness in μm, time increment in day, reaction constant, and power law factor, respectively.

The oxides formed on the aluminum alloy consist of various oxide-hydrates, and they generally exist as boehmite and bayerite. Since these oxide-hydrates are soluble in water, the solubility of oxides can be expressed as a function of wall temperature and pH (Dickinson and Lobsinger, 1963; Nabhan et al., 2015).

$$C_s = exp\left[-\left(-13.79 - \frac{1211.16}{T_w}\right)\left(0.041(pH)^2 - 0.41(pH) - 0.07\right)\right] \quad (3)$$

where T_w is the wall temperature in kelvin, and C_s is the solubility of oxides in g/g H_2O.

The dimensionless power law factor correlation p resulting from data fitting is given by

$$p = 0.12 + 9.22exp\left(-\frac{C_s}{6.82\times10^{-9}}\right) \quad (4)$$

The dimensionless reaction constant is expressed as

$$k = 3.9\times10^5 exp\left(\frac{-6071}{T_w + 0.37A\frac{q''x}{k_T}}\right) \quad (5)$$

where q'' is the heat flux in MW/m^2, x is the oxide layer thickness in μm, k_T is the oxide layer thermal conductivity in kW/(m^2 K), and A is the dimensionless augmentation factor given by

$$A = 0.43 + \frac{3.21}{1 + exp\left(-\frac{V_c - 13.39}{3.60}\right)} \quad (6)$$

where V_c is the average channel coolant velocity in m/s, and the applicable range of the coolant velocity is between 3 and 28 m/s.

The Boehmite model is used to evaluate the oxide layer thickness, considering the solubility of the oxide-hydrates (Dickinson, 1964; Dickinson and Lobsinger, 1963). In Griess et al., 1961 developed an empirical correlation, applicable to a pH of 5, and flow velocity up to 12 m/s. This correlation is applicable to the pH range between 5.7 and 7.0 with a pre-exponential factor of 3.3853×10^5, and a rate factor of 2.7 multiplied to k. The dimensionless reaction constant is expressed as

$$k = 3.3853\times10^5 exp\left(\frac{-5913}{T_w}\right) \quad (7)$$

The kinetic equation for the oxide layer thickness is expressed as

$$x(t) = \left\{[x(t-\Delta t)]^{1.28535} + 3.4703k\Delta t\right\}^{0.77803} \quad (8)$$

In 1983, another empirical correlation, also known as the Kritz model, similar to the Griess model, was developed by a team from the Savannah River Laboratory. The only difference between the Kritz model and the Griess model is that, in the former, the dimensionless reaction constant is expressed as

$$k = 8.68\times q''^{1.28535} exp\left(\frac{-2416.5}{T_w}\right) \quad (9)$$

In Pawel et al., 1995 updated the power law factor p and the reaction constant k. Using the updated power law factor and reaction constant, the kinetic equation can be expressed as

$$x(t) = \left\{[x(t-\Delta t)]^{1.351} + 1.351k\Delta t\right\}^{0.74} \quad (10)$$

The dimensionless reaction constant is given by

$$k = 6.388\times10^7 exp\left(\frac{-9154}{T_w + 1.056q''}\right) \quad (11)$$

Except for pH = 5.0, the predictions made by the Kritz model without any correction were not comparable with measurement data. The Griess model with a rate factor of 2.7 predicts the oxide layer to be thicker than the measured post-irradiation data of RERTR (Reduced Enrichment for Research and Test Reactor)-6 and 7. For the pH range between 5.8 and 6.5, the Pawel model with a rate factor of 16 generally over-predicted the oxide layer thickness as compared to the data of RERTR-6 and 7, but these predictions are the most accurate ones among the existing models. If the power released from the fuel is constant, the maximum fuel temperature may exist at the end of the irradiation. However, the power gradually decreases as the fuel burns in the core, and hence, the maximum fuel temperature may be found somewhere in the middle of the irradiation period. In order to be conservative, the maximum power in the beginning of the irradiation, and the maximum oxide layer thickness at the end of the irradiation are chosen to evaluate the thermal margins, i.e., cladding and fuel temperatures (Jo and Kim, 2015; Tahk et al., 2013). In some research reactors that can control pH in the coolant system close to 5.0, the formation of oxides is ignored. Although the pH was well controlled, it has been observed that an oxide layer of approx. 5 μm was formed on the cladding surfaces of the mini fuel plates irradiated in ORR (Oak Ridge Research Reactor).

In the present study, the effect of the oxides formed on the mini fuel plates irradiated in the HANARO reactor is numerically investigated using the MCNP and TMAP code. The power released from the mini fuel plates during the entire irradiation test are estimated using the MCNP code (X-5, 2003). The oxide layer thickness from the beginning till the end of irradiation is predicted using many empirical correlations with pH ranging from 5 to 7. Using the TMAP code, the maximum fuel temperatures are calculated based on the history of the oxide layer formed on the cladding, and the power released from the fuel (Jo et al., 2014).

2. Fuel performance during irradiation in HANARO

The mini fuel plates, designed for investigating the performance of U-Mo fuel, will be irradiated in the HANARO reactor as a part of a new fuel qualification program. The detailed configurations of the mini fuel plates and the irradiation sites in the HANARO reactor are well described in a previous study done by Jo and Kim 2015. Two different uranium densities are loaded to the mini fuel plates: (1) 6.5 gU/cc and (2) 8.0 gU/cc. The mini fuel plates are double stacked as upper and lower plates, and each plate is divided into 7 segments along the axial direction, and 4 segments along the transverse direction, as shown in Fig. 1, for performing neutronic analyses. The mini fuel plates are irradiated in the HANARO reactor for 4 cycles (= 111 days). Each cycle, consisting of BOC (Beginning Of Cycle), EqXe (Equilibrium of Xenon), MOC (Middle Of Cycle), and EOC (End Of Cycle) takes approx. 28 days. Fig. 2 shows the heat flux distributions on the lower and upper plates, which have the highest power

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