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Effect of thermal conductivity degradation on the behavior of high burnup UO_2 fuel

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Abstract

The temperature distribution in the pellet was obtained from beginning the general heat conduction equation. The thermal conductivity of pellet used the SIMFUEL data that made clear the effect of burnup on the thermal conductivity degradation. Since the pellet rim acts as the thermal barrier to heat flow, the pellet was subdivided into several rings in which the outer ring was adjusted to play almost the same role as the rim. The local burup in each ring except the outer ring was calculated from the power depression factor based on FASER results, whereas the rim burnup at the outer ring was achieved by the pellet averaged burnup based on the empirical relation. The rim changed to the equivalent Xe film so the predicted temperature showed the thermal jump across the rim. The observed temperature profiles depended on linear heat generation rate, fuel burnup, and power depression factor. The thermal conductivity degradation modelling can be applied to the fuel performance code to high burnup fuel.

1. Introduction

The temperature distribution controls not only most of the physical process occurring during irradiation, but also the amount of stored energy in the fuel which is important under accident conditions. So, a proper understanding and accurate prediction of fuel thermal response are of prime importance for the evaluation of fuel rod performance under normal and transient conditions.

In general, to analyze the in-core fuel performance, the heat conduction equation in a solid fuel rod is assumed with a constant volumetric heat - generation rate Q and thermal conductivity k [1] such as

$$\int_{T_s}^{T_0} k\,dT = \frac{1}{4} QR^2 = \frac{P}{4\pi} \quad (1)$$

where P is linear heat generation rate, T_S temperature on the pellet surface, and T_0 temperature at the fuel centerline.

However, the assumptions are not fulfilled at high burnup when a strong buildup of Pu in the vicinity of pellet surface causes a marked variation in the power density. The vicinity of pellet edge, i.e., rim region is characterized by loss of optically definable grain structure, an increase in small intragranular porosity, a depletion of matrix xenon as measured by EPMA so rim region plays a significant role in heat flow as thermal barrier [2].

The primary objective as a preliminary study was to provide a method to predict an accurate temperature distribution considering the thermal conductivity degradation with burnup and the rim effect of thermal barrier.

2. Methodology

In the case of a volumetric heat generation rate dependent on the radial power depression in a pellet, the steady-state temperature distribution is governed by the general heat conduction equation:

$$\frac{1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right) + Q(r) = 0 \quad (2)$$

The pellet can be grouped into two regions, which are the interior normal burned fuel and rim region of pellet edge to obtain the accurate temperature distribution. The pellet is subdivided into M rings which have equal volume and in which the volumetric heat generation rate is uniform in the each ring. On the other hand, the pellet-edge burnup is linearly proportional to the pellet averaged burnup as shown Fig. 1. Then the rim burnup can be calculated from the following curve-fitted equation.

$$BU_{Rim} = 5.0553 + 1.30709 \times BU_{avg} \quad [MWd/kgU] \quad (3)$$

where BU_{Rim} and BU_{avg} are pellet-edge and pellet averaged burnup in MWd/kgU, respectively. Accordingly, the outer ring width is adjusted to be almost the same to the rim width. The rim width was experimentally defined by the fuel radius at which the relative xenon (matrix xenon retention) and the neodymium (xenon production) concentrations diverge. Therefore, the rim width, w_{rim}, is given by [2]

$$w_{rim}^2 = -21014 + 391.4 \times BU_{Rim} \quad [\mu m] \tag{4}$$

After calculation of rim burnup and width, the outer ring width changed to equivalent Xe film [3].

The thermal conductivity in the fuel region is assumed as follows

$$k = \frac{1}{(A + \beta \cdot Bu + C \cdot T)} + D\ \mathrm{Exp}(-E \cdot T) \tag{5}$$

The exponential term herein caused by electronic heat transfer can be negligible in nuclear fuel temperature region. From the integration from pellet surface into the pellet centerline step by step, then eqn. (2) can be described in a jth ring of pellet

$$\int_{T_i}^{T_{i-1}} k_j\ (T_j, Bu_j)\ dT = -\int_{r_i}^{r_{i-1}} \left(\frac{Q}{2} r\right) dr \tag{6}$$

Assuming that Q with a power depression factor is constant in the jth ring, the Q is given by

$$Q = Q_{avg} \cdot PF_j \tag{7}$$

where Q_{avg} is average volumetric heat generation rate and PF_j is the power depression factor in the jth ring which is given by

$$PF_j = a(Bu_j, U) + b(Bu_j, U)\left(\frac{r_{i+1} + r_i}{2}\right) + \frac{c(Bu_j, U)}{r_{i+1}^2 - r_i^2} \ln \frac{d(Bu_j, U) - r_i^2}{d(Bu_j, U) - r_{i+1}^2} \tag{8}$$

where Bu_j is local burnup in the jth ring [MWd/kgU], U is an initial U^{235} enrichment, and r_{i+1} and r_i are outer and inner radius of ring, respectively. In the other hand, the constants of a, b, c, and d are fitted from the FASER calculation. Then eqn. (6) with eqns. (5) and (7) is described as

$$\frac{1}{C} \ln \frac{(A + \beta \cdot Bu_j + C \cdot T_{i+1})}{(A + \beta \cdot Bu_j + C \cdot T_i)} = \frac{Q_{avg}\ PF_j\ (r_{i+1}^2 - r_i^2)}{4} \tag{9}$$

The inner temperature T_i in the jth ring can be obtained by outer temperature T_{i+1} as following equation

$$T_i = \frac{1}{C}\left[\mathrm{Exp}\left(C \cdot \frac{Q_{avg}\ PF_j\ (r_{i+1}^2 - r_i^2)}{4}\right) * (A + \beta \cdot Bu_j + C \cdot T_{i+1}) - (A + \beta \cdot Bu_j)\right] \tag{10}$$

Next, the thermal conductivity in the rim region is very low so that the rim is as a thermal barrier, which consists of loss of optically definable grain structure, an increase in small intragranular porosity, and a depletion of matrix xenon as measured by EPMA [3]. This assumption is reasonable because it is expected that the porosity present in the rim would be interconnected due to the large amount of porosity [4]. Kampf and Karsten [5] described the thermal conductivity of rare gases by

$$k_B = 0.72 \times 10^{-4} \cdot T^{0.79} \tag{11}$$

After insertion of thermal conductivity eqn. (9) and by using the assumption that the thermal barrier consists of only Xe gas, so the following integration is obtained.

$$\int_{T_{surf}}^{T_M} k_{rim,Xe}\, dT = -\int_{r_{surf}}^{r_{Xe}} \left(\frac{Q}{2} r\right) dr \tag{12}$$

where r_{Xe} is the radius given by the Xe equivalent film width.
After insertion of thermal conductivity and constant local power in the jth ring, the temperature across the rim can described

$$T_M = [\, T_{surf}^{1.79} - 1.6574 \times 10^4 \cdot Q_{avg} \cdot PF_j \; (r_{Xe}^2 - r_{surf}^2)]^{0.558659} \tag{13}$$

3. Results and Discussion

The main constants for temperature profile are in the thermal conductivity relation, which are obtained from SIMFUEL results [6]. And the calculated results are compared with RISO data which were made under transient conditions.

Fig. 2 shows the variation of centerline and surface temperatures of pellet with burnup. The calculated centerline temperature increases with burnup, while the surface temperature decreases with burnup. Whereas the centerline temperature increases linearly to about 40MWd/kgU, the centerline temperature increases rapidly after 40MWd/kgU. This is ascribed to the formation of rim region which consists of high porosity and grain boundary retained Xe. However, the results of KWU's fuel performance code decrease with burnup caused by the decrease of available fissile contents. The calculated results overpredicts the temperature after threshold burnup due to the simply assumption of equivalent Xe thickness and the disregard of exponential term in the thermal conductivity relationship. This will be developed by advanced rim region model.

Fig. 3 shows an example of the radial temperature distribution in the fuel pellet of linear heat generation rating 40kW/m. The fuel temperature increases with the liner heat generation rate. The temperature jump occurs at the pellet surface when the pellet averaged burnup goes beyond the threshold burnup [2]. Comparison with RISO data [3] indicates that the calculated radial profile is much higher than that by RISO results. This is because the RISO data was given by transient test which increased the fuel centerline temperature by 300℃ [7] and the inaccurate pellet surface temperature assumption.

Fig. 4 shows the radial temperature profile at a linear heat rate of 30, 35 and 40 kW/m at the pellet averaged burnup of 43.5MWd/kgU. In this case such as in Fig. 3, the calculated results are also higher than RISO results due to transient condition. The temperature jump in the pellet surface should be noticed. This is caused by rim effect at the high burnup, above 40 MWd/kgU of pellet averaged burnup.

4. Conclusion

The temperature distribution with rim effect was investigated from the general heat conduction equation because in the low temperature region at the pellet edge, local burnup is enhanced by local plutonium production and fissioning. The rim effect caused to the thermal jump across the pellet surface. The calculated thermal conductivity depended on linear heat generation rate, local burnup, and power depression factor. The thermal conductivity degradation modelling can be applied to the fuel performance code to high burnup fuel.

References

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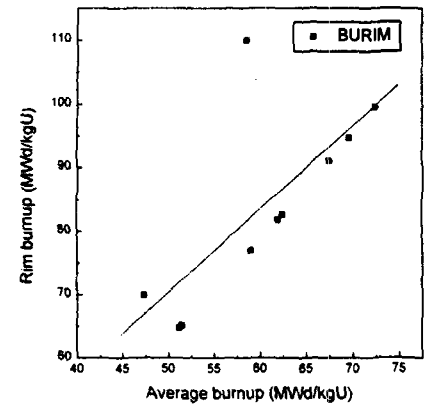

Fig. 1 Variation of rim bump as a function of pellet averege burnup

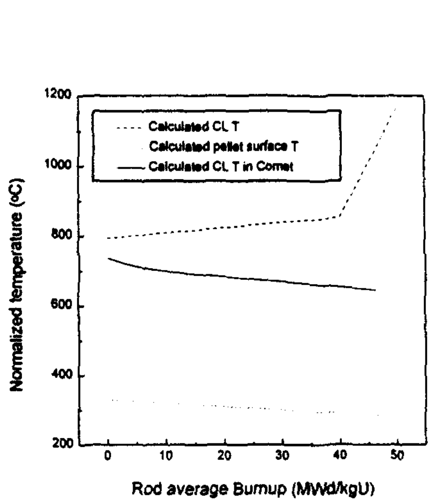

Fig. 2. Change of centerline and surface temperature of pelle showing the temperature jump across pellet surface.

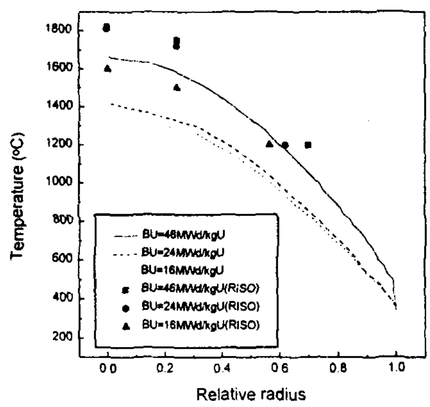

Fig. 3 Radial temperature profile at a burnup of 16, 24, and 46MWd/kgU.

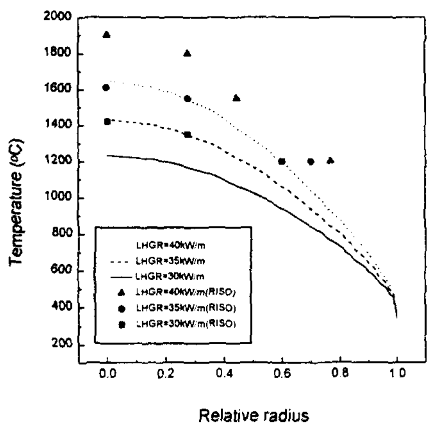

Fig. 4. Radial temperature profile at a linear heat rating *of 30, 35, and 40 kW/m. Burnup 43.5MWd/kgU*