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Pore pressure and swelling in the rim region of LWR high burnup UO_2 fuel

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Abstract

Based on measured rim characteristics of LWR high burnup UO_2 fuel, the pressure of rim pores and the additional pellet swelling due to rim formation have been modeled. Using the assumption that the number of Xe atoms retained in the rim pores is the same as that which is depleted from the rim matrix, excessive pore pressure is derived as a function of temperature, pellet average burnup and pore radius. The rim pores with small radii are calculated to be highly overpressurized at high burnup. Comparison with experimental data shows that, while the pellet swelling obtained with best-estimate rim width is underpredicted, the one calculated with conservative rim width agrees well with the measured data for rim burnups between 50 and 65 GWd/tU. On the other hand, the measured swelling at 85 GWd/tU is about in-between the two calculations. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

To improve the economics of nuclear fuel and to reduce spent fuel per unit energy production, the fuel assembly average discharge burnup of LWR fuel has increased in recent years from around 40 to 50–60 GWd/tU. This trend will continue if the cladding integrity is maintained and the fuel economics is improved. In this case, the maximum discharge burnup of fuel may reach up to 80 GWd/tU or even higher. Therefore, the extension of fuel burnup requires that the thermal and mechanical behavior of LWR high burnup UO_2 fuel be analyzed properly from the viewpoint of overall in-reactor performance and safety.

It has been observed that the characteristics of rim structure [1–6] formed in the periphery of high burnup UO_2 fuel are: (1) development of a subgrain microstructure with a typical grain size of 0.2–0.3 μm, (2) development of pores with a typical diameter of 1–2 μm, and (3) Xe depletion in the matrix. Analysis and operating experience so far show that, even though the rim structure develops and hence pores and bubbles are newly created in the outer part of fuel pellet resulting in high porosity, the performance of high burnup fuel seems to be acceptable during normal operation. However, if Xe atoms depleted in the matrix are retained in the newly created rim pores, the pores would have a propensity for high local swelling at increased temperature that could lead to strong pellet cladding mechanical interaction (PCMI). Consequently, gaseous swelling produced by the rim pores and the subsequent dimensional change of the fuel pellet should be assessed to consider its effect on PCMI and gas release [7] in high burnup fuel under both steady-state and transient operating conditions.

The fuel behavior under RIA conditions depends on high burnup phenomena such as the formation of rim structure, migration and distribution of gas atoms, cladding corrosion and hydriding, and power pulse shape and amplitude. The fuel temperature in the rim region increases rapidly from coolant temperature to far above 600°C in a typical RIA that might occur in hot standby conditions of LWR [8]. If the size of rim pores changes or if their pressures increase rapidly due to increased fuel temperature during RIA, this might

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produce pore pressures high enough to cause crack propagation along subgrain boundaries and hence lead to the ventilation of gas atoms retained in the pores. This could ultimately increase rod internal pressure and cause fuel failure in the cladding area where mechanical properties are degraded.

In this paper, based on measured rim characteristics such as rim width, porosity, pore density, and pore size distribution, the pressure of pores existing in the rim region of high burnup UO_2 fuel pellet will be derived as a function of temperature, pellet average burnup, and pore radius. In addition, gaseous swelling of a fuel pellet caused by the rim pores will be calculated.

2. Thickness of the rim

Data on the thickness of the rim region, which is usually defined by the radius where the relative amount of Nd representing Xe production and the measured Xe concentration begin to diverge, have been measured by many investigators by both EPMA and optical microscopy [2,9–18]. At present, several correlations are available that express the rim width [1,19–21]. Using all relevant information, a new linear correlation that describes the rim width in terms of rim average burnup has been developed by using the linear least square method:

$$r_{\mathrm{rim}} = 3.55 bu_{\mathrm{rim}} - 185, \tag{1}$$

where r_{rim} is the rim width in μm and bu_{rim} is the rim average burnup in GWd/tU, which will be called rim burnup hereinafter. Since the burnup in the narrow rim region sharply increases toward the surface of fuel pellet that has high burnup, bu_{rim} is defined as a burnup averaged over the measured rim width. A more conservative linear formula that covers almost all the data shown in Fig. 1 is

$$r_{\mathrm{rim}} = 5.28 bu_{\mathrm{rim}} - 178. \tag{2}$$

The measured rim width is displayed as a function of rim burnup in Fig. 1. In the case where the rim burnup is not given explicitly, it is taken to be the average of the two burnups; the one at the position where the rim structure starts and the other at the pellet edge. The filled symbols in Fig. 1 represent data measured by EPMA and the open ones by optical microscopy. Fig. 1 shows that a linear formula of Eq. (1) represents a best-estimate relationship between the rim width and rim burnup up to 120 GWd/tU, indicating that the threshold local burnup required for rim formation is about 52 GWd/tU. This value is similar to the threshold burnup of 56 GWd/tU derived by Lee et al. [19]. There exists still some controversy over whether rim width increases linearly or exponentially with fuel burnup. While some data show the tendency of exponential growth of the rim width up to a pellet average burnup of 75 GWd/tU [1], others support the linear increase with burnup [2,21].

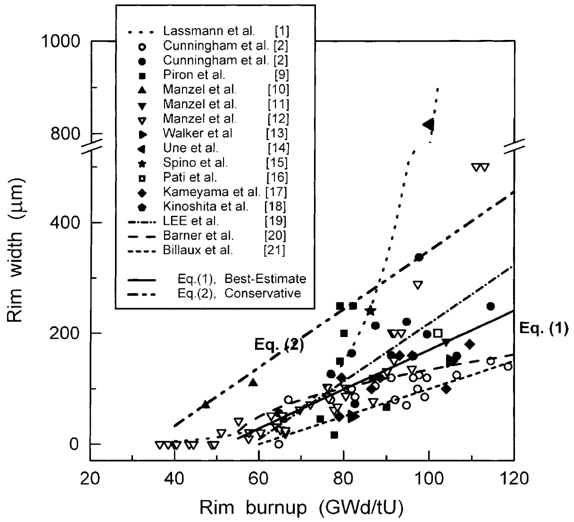

Fig. 1. Measured rim width both by EPMA and optical microscopy (Kinoshita et al. [18]: 7.9% FIMA (99.6) GWd/tU, 1650 μm).

Recent data [22] obtained under typical PWR conditions indicate that, while the rim structure increases linearly up to a pellet average burnup of 70 GWd/tU, it expands exponentially thereafter. Therefore, this suggests that the rim width increases linearly with burnup at least up to 70 GWd/tU. According to Eq. (5) given below that defines the ratio of rim to pellet average burnup, the latter corresponds to a rim burnup of about 93 GWd/tU. Similarly, Fig. 1 indicates that exponential fitting of the rim width shows the tendency to overpredict the width for rim burnups above around 90 GWd/tU. Consequently, the data accumulated so far appear to show that the rim width increases linearly with rim burnup at least up to 90 GWd/tU.

3. Fraction of fission gas in the rim

Lassmann et al. [1] examined a lot of data for Xe concentration, Xe_m (wt%), in the matrix of the rim region measured by EPMA and expressed it as follows:

$$\mathrm{Xe_m} = c\left[\frac{1}{a} + \left(bu^0_{\mathrm{rim}} - \frac{1}{a}\right)\mathrm{e}^{-a(bu_{\mathrm{rim}} - bu^0_{\mathrm{rim}})}\right], \tag{3}$$

where c is the Xe production rate in wt% per unit burnup (1.46×10^{-2} wt% per GWd/tU), a is a fitting constant of 0.0584, bu_{rim} is the rim burnup, and bu^0_{rim} is the threshold burnup for rim formation. Since almost no Xe gas is released from the rim to the fuel exterior due to low operating temperature up to as high as 100 GWd/tU

[2,4,10,17,20,22–24], it is assumed that all the depleted Xe atoms from the rim matrix are retained in the rim pores. Then the Xe concentration in the rim pores, Xe_g (wt%), is calculated to be

$$Xe_g = c\,bu_{rim} - c\left[\frac{1}{a} + \left(bu^0_{rim} - \frac{1}{a}\right)e^{-a(bu_{rim}-bu^0_{rim})}\right]. \qquad (4)$$

Eqs. (3) and (4) give the Xe concentration retained in both the matrix and the rim pores, respectively, for different threshold burnups for rim formation.

Fig. 2 shows the Xe concentration in the rim pores for four threshold burnups of 52, 60, 65 and 70 GWd/tU, where 52 GWd/tU has been derived from Eq. (1) and the other three burnups are chosen based on other works [1,2,13,18,23,25]. Furthermore, enrichment and grain size influence the process of rim structure formation. It has been found that with higher enrichment [15] and larger grain size [15,23,26,27], higher local burnup is required for the rim formation. Fig. 2 shows that the Xe concentrations in the rim pores converge to one value irrespective of the threshold burnup. This is because the amount of Xe retained in the matrix approaches the equilibrium value of 0.25 wt% [1] and thus the fraction of Xe present in the rim pores becomes dominant.

Since the burnup profile in the pellet edge depends on enrichment, pellet diameter, epithermal fluence and neutron spectrum, a relationship between rim burnup and pellet average burnup was statistically derived based on the measured data relevant to typical LWR operation [16,28,29]. A linear correlation that best fits the rim burnup as a function of pellet average burnup was obtained by the linear least square method as follows:

$$bu_{rim} = 1.33 bu_{avg}, \qquad (5)$$

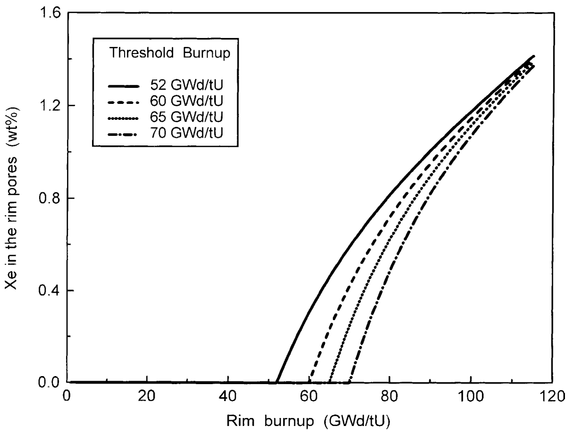

Fig. 2. Xe concentration in the rim pores for various threshold burnups for rim formation.

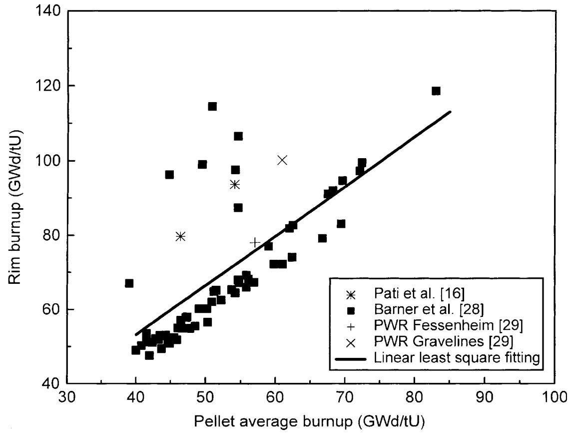

Fig. 3. Relationship between rim burnup and pellet average burnup in typical LWR fuel.

where bu_{avg} is the pellet average burnup. Fig. 3 suggests that correlating the pellet average burnup with rim burnup as a linear relation is reasonable because most data lie around the line. The main source of data scattering would come from different enrichment, epithermal fluence and neutron spectrum. Difficulty in measuring burnup variation across the narrow rim region would also contribute to the scattering.

If the same assumptions used in deriving Eq. (4) are applied, that is, if no gas is released in the rim and all the depleted Xe atoms are retained in the rim pores, the fraction of Xe atoms retained in the rim pores, f_{rim}, would be expressed as follows:

$$f_{rim} = \frac{Xe_g}{Xe_m + Xe_g}\,\frac{V_{rim}\rho_{TD}}{V_{pel}\rho_p}\left(1 - \frac{\overline{P}_{rim}}{100}\right)B_r, \qquad (6)$$

where V_{rim} is the rim volume in a pellet, V_{pel} is the pellet volume, ρ_{TD} is the theoretical density of pellet, ρ_p is the density of pellet, $\overline{P}_{rim}$ is the average porosity in the rim, and B_r is the ratio of rim burnup to pellet average burnup. For a threshold burnup of 52 GWd/tU and for the total Xe atoms produced in a pellet, Fig. 4 shows that the Xe fraction in the rim available for release is 10–20% in a pellet with average burnup of 80 GWd/tU. The depleted Xe fraction measured in the rim ranged from 10% to 35% [2,28] for a rim burnup of 60–100 GWd/tU, which would be equivalent to the pellet average burnup of around 45–75 GWd/tU. In addition, it was estimated from the Xe profiles of EPMA [14,30] that fission gas retention in the rim pores was 17–21% at the pellet average burnups of 70–80 GWd/tU. Therefore, it can be concluded that the present calculation, which yields the maximum depleted fraction of 20% for the pellet average burnup of 80 GWd/tU, is comparable to the measured values [2,14,28,30].

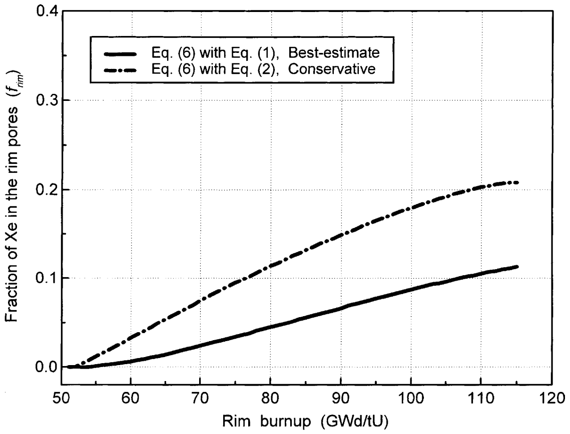

Fig. 4. Fraction of Xe atoms retained in the rim pores for total Xe atoms produced in a pellet.

4. Porosity and pore size distribution in the rim

Spino et al. [3] measured fuel porosity, pore density and pore size distributions at several radial positions of pellet specimens with cross-sectional average burnups between 40.3 and 67 GWd/tU. A formula of the type $b_1 + \exp[-b_2 + b_3(r/r_o)]$ was developed to represent the measured porosity in terms of pellet average burnup and relative pellet radius r/r_o. Then integrating the function and averaging its value over the rim thickness yields the average porosity in the rim $\overline{P}_{rim}$. As in the case of porosity, a fitting formula $d_1 \exp[-(\ln r_p - d_2)^2/2d_3]$, which describes the pore density in the rim as a function of the relative pellet position and pore radius r_p in μm, was derived based on measurement for pellet specimens with 40.3 GWd/tU. The measured data [3] indicate that pellet position affects the pore density more strongly than pellet average burnup. Therefore, although pore density increases with local burnup, it is assumed that the three constants d_1, d_2 and d_3 are not affected by the pellet average burnup at least for the burnup range between 40.3 and 67 GWd/tU. The pore density in the rim f (pores/mm^3) is then described as follows in terms of pore radius r_p and relative pellet position (via d_1, d_2 and d_3) for the pellet average burnup between 40.3 and 67 GWd/tU:

$$f = d_1 \times 10^7 \exp\left[-\frac{(\ln r_p - d_2)^2}{2d_3}\right]. \tag{7}$$

5. Pore pressure in the rim

The gas pressure within small bubbles in a nuclear fuel can be very large and deviations from the perfect gas law must be considered. The van der Waals equation of state, which is most commonly used to describe the thermodynamic state of fission Xe atoms in gas bubbles, can be written as [31]

$$p\left(\frac{1}{\rho_g} - B\right) = kT, \tag{8}$$

where p is the pressure of gas of molecular density ρ_g, B the volume occupied by the atoms proper (85 Å^3/atom), and k is the Boltzmann constant. It is assumed that Eq. (8) can be applied to the rim pores filled with Xe atoms depleted from the rim matrix. The pressure in a rim pore is then

$$p = \sigma + \frac{2\gamma}{r_p} + p_{ex}, \tag{9}$$

where σ is the uniform hydrostatic stress, γ the surface tension (1 N/m), r_p the pore radius, and p_{ex} is the excessive pressure above equilibrium one due to a large number of gas atoms retained in the rim pores. The excessive pressure is assumed to be much larger than the sum of σ and $2\gamma/r_p$, which is usually the case if the gas release is not high enough to cause the rod internal pressure to increase significantly and if there exists no strong PCMI. Our calculation shows that the assumption is valid for the ranges of burnup and pore radius investigated in this paper. The molecular density is then simplified as

$$\rho_g = \left(B + \frac{kT}{p_{ex}}\right)^{-1}. \tag{10}$$

Since the number of gas atoms m retained in a pore of radius r_p is given by

$$m = \left(4\pi r_p^3/3\right)\rho_g, \tag{11}$$

m is expressed as

$$m = \left(\frac{4\pi r_p^3}{3}\right)\left(B + \frac{kT}{p_{ex}}\right)^{-1} = \frac{4\pi r_p^3 p_{ex}}{3kT\alpha}, \tag{12}$$

where $\alpha = 1 + Bp_{ex}/kT$.

Greenwood et al. [32] showed through simple analysis that p_{ex} should be greater than $\mu b/r_p$ for dislocation creation to be energetically favorable. Here μ is the shear modulus and b is the Burgers vector (0.39 nm). It is to be noted that there are some arguments against using Greenwood's analysis for deducing bubble overpressurization for both very small and large bubbles. However, it could be argued that the formula $p_{ex} = \mu b/r_p$ can be used to derive excessive pressure in the bubbles with radii of intermediate range. Nogita and Une [33] observed the dislocation punching around the coarsened bubbles, which is the clear evidence of high pressure bubbles. This also implies that p_{ex} would have been equal to or larger than $\mu b/r_p$. The bubble excessive pressure p_{ex} of $\mu b/r_p$ is regarded as the controlling growth mechanism of gas bubbles with radii between 0.1 and 1 μm on the grain boundaries by plastic flow [34]. These two facts suggest that, when the bubbles relieve their overpressure by plastic deformation of the surrounding UO_2 matrix, the excessive bubble pressure is likely to be close to $\mu b/r_p$. In addition, the formula $p_{ex} = \mu b/r_p + p_{eq}$ was used to calculate the pressure of rim bubbles [30]. Therefore, it is assumed in this paper that, if $p - 2\gamma/r_p - \sigma$ is larger than $\mu b/r_p$, Eq. (13) can be used as an approximation to calculate the pressure of rim pores whose radii range mostly from 0.5 to 1.3 μm [3]:

$$p_{ex} = \frac{C}{r_p}, \tag{13}$$

where C is a constant to be determined as a function of fuel temperature and burnup. Here $p_{ex} = C/r_p$ is introduced instead of $p_{ex} = \mu b/r_p$ to consider the effect of temperature and burnup on pore pressure. Combination of Eq. (12) with (13) yields

$$m = \frac{4\pi r_p^2 C}{3kT\alpha}. \tag{14}$$

If M is defined as the number of Xe atoms retained in the rim pores with radius r_p per unit rim volume, M can be obtained by

$$M = mf, \tag{15}$$

where f is the number of pores with radius r_p per unit rim volume as described by Eq. (7). The total number of Xe atoms in the rim pores per unit rim volume, Xe_{vol}^{tot} (atoms/mm^3), is derived by integrating M over the pore radius

$$Xe_{vol}^{tot} = \int_{r_{min}}^{r_{max}} M \, dr_p. \tag{16}$$

In addition, Xe_{vol}^{tot} can also be calculated as follows:

$$Xe_{vol}^{tot} = Xe_g \frac{\rho_{TD}}{m_{Xe}} N_{av}, \tag{17}$$

where Xe_g is given by Eq. (4), ρ_{TD} is the theoretical density of UO_2 fuel, m_{Xe} is the mass of Xe per mole, and N_{av} is the Avogadro number (6.023×10^{23} atoms/mol). If Eqs. (15)–(17) are combined together, C is derived as

$$C = \frac{\phi}{1 - B\phi/r_p kT}, \tag{18}$$

where

$$\phi = \frac{10^5 3\sqrt{2} kT Xe_{vol}^{tot}}{4\pi^{1.5} e^{1.5(2d_2+3d_3)} d_1 \sqrt{d_3} Y}, \tag{19}$$

and the constant 10^5 appears from the unit conversion. Besides, Y is

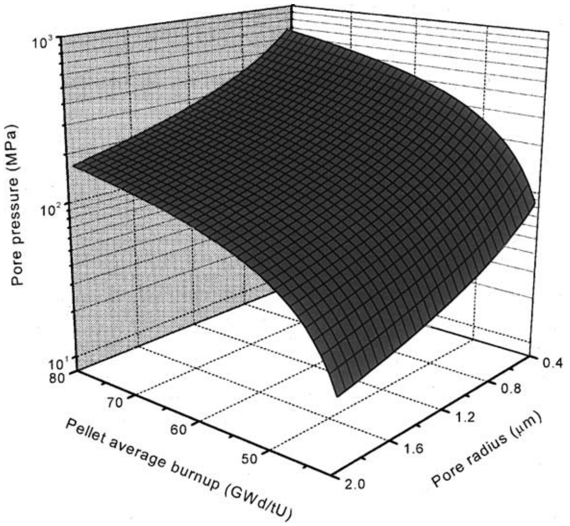

Fig. 5. Calculated pore pressure in the rim as a function of pellet average burnup and pore radius.

$$Y = \text{erf}\left(\frac{d_2 + 3d_3 - \ln r_{min}}{\sqrt{2d_3}}\right) - \text{erf}\left(\frac{d_2 + 3d_3 - \ln r_{max}}{\sqrt{2d_3}}\right), \tag{20}$$

where erf represents the error function, and r_{min} and r_{max} are 0.5 and 2.0 μm, respectively [3].

Fig. 5 shows the calculated pore pressure as a function of pellet average burnup and pore size for the following conditions; no hydrostatic pressure ($\sigma = 0$), a threshold burnup of 52 GWd/tU, a rim temperature of 800 K, and a relative radial pellet position of 0.996. Since the present model is based on the measured pore density and pore size distribution up to a specimen-average burnup of 67 GWd/tU [3], the calculated pore pressure beyond 67 GWd/tU should be considered as an extrapolated one. The calculated pore pressure at 67 GWd/tU is 477 MPa in a pore with radius 0.5 μm. In this case, the fraction of gas retained in the rim pores is 20% and the density of pores with a radius of 0.5 μm is about 2.3×10^7/mm^3. It was shown that the pore pressure at 800 K becomes 90–210 MPa [30] when an equation of state for rare gases [35] was used for the following conditions: pore radius of 0.5 μm, pore density of 6×10^7/mm^3, and fractional gas retention of 30–50% in the rim pores, and a pellet-average burnup of 80 GWd/tU. Therefore, there exists a difference of at least a factor of two between the two calculations. The present model yields an about 1.7 times higher pressure than 90–210 MPa when it is assumed that not only all pores are of the same size and follow the perfect gas law but also the burnup effect on pore pressure is negligible.

Recently, Rest et al. [36] have argued that it is difficult that the bubbles with a radius between 0.5 and 0.8 μm would be sufficiently overpressurized in an irradiation environment, because irradiation provides an overabundance of defects that work toward bubble equilibration in the temperature range associated with rim formation (<773 K). They have also stated that the estimates of overpressure for bubbles with a radius of 0.5–0.8 m are more than three times lower than the stress required for irradiation-induced creep of UO_2. Since the stress where irradiation-induced creep of UO_2 fuel would start at typical rim temperature is 100 MPa [37,38], this implies that the bubble pressure would be less than around 30 MPa. On the other hand, the present model predicts that the excessive pressure is always higher than 100 MPa in the pores with radius between 0.5 and 1.3 μm if the pellet burnup is larger than 50 GWd/tU. This suggests that the increased fracture toughness of the rim material in a high burnup UO_2 fuel [3] might have been caused by these high pressure pores as a result of relieving pore overpressure by plastic flow.

6. Swelling of a pellet caused by rim pores

The volume increase in the rim per unit rim volume, V_b, due to pores newly created in the rim can be derived as follows:

$$V_b = \int_{r_{min}}^{r_{max}} \frac{4\pi r_p^3}{3} f \, dr_p. \tag{21}$$

The total volume increase caused by the rim pores, V_b^{rim}, in a fuel pellet with height H_p can be obtained by integrating Eq. (21) over the rim volume of a pellet

$$V_b^{rim} = \int_{r_o - r_{rim}}^{r_o} V_b 2\pi r \, dr \int_0^{H_p} dH_p = 2\pi H_p \int_{r_o - r_{rim}}^{r_o} V_b r \, dr. \tag{22}$$

Since the volume of a pellet V_p is $\pi r_o^2 H_p$, the fractional swelling of a fuel pellet due to the rim pores is

$$\frac{V_b^{rim}}{V_p} = \frac{2\pi H_p \int_{r_o - r_{rim}}^{r_o} V_b r \, dr}{\pi r_o^2 H_p} = \frac{2 \int_{r_o - r_{rim}}^{r_o} V_b r \, dr}{r_o^2}. \tag{23}$$

Numerical integration of the numerator of Eq. (23) gives the fractional swelling of a pellet as a function of temperature and rim burnup.

The fractional swelling caused by rim pores in a fuel pellet with a diameter of 8 mm was calculated as a function of rim burnup (Fig. 6) for a threshold burnup of 52 GWd/tU and a rim temperature of 800 K. The calculated pellet swelling increases linearly with burnup, which has been also observed in MTR–U_3Si_2 dispersion fuel [39]. Pore swelling rates are predicted to be around 2.2–3.5% per 10 GWd/tU, respectively, for the best-estimate (Eq. (1)) and for the conservative (Eq. (2)) rim thickness. It was observed [30] that, if the measured matrix swelling rate of 0.5% per 10 GWd/tU is eliminated from the total pellet swelling, the swelling rate caused by the rim pores was about 1.5% per 10 GWd/tU. Pore swelling was measured in the rim in terms of the microstructural change fraction (MCF) [26]. MCF, which was defined by the ratio of the total Xe atoms retained in the pores of the region where microstructural change occurred to the total Xe atoms generated in the same region, would be similar to $1 - f_{rim}$ (see Eq. (6)). The pellet swelling was also derived from the measured cladding plastic deformation as a function of MCF. Both data sets are plotted in Fig. 6 against local burnup, where the MCF was converted into rim burnup using the measured relationship between MCF and local burnup [26]. While the pellet swelling obtained with the best-estimate rim width is underpredicted, the one obtained from the conservative rim width agrees well with the measured data for rim burnups between 50 and 65 GWd/tU. The measured swelling at 85 GWd/tU is about in-between the two calculations.

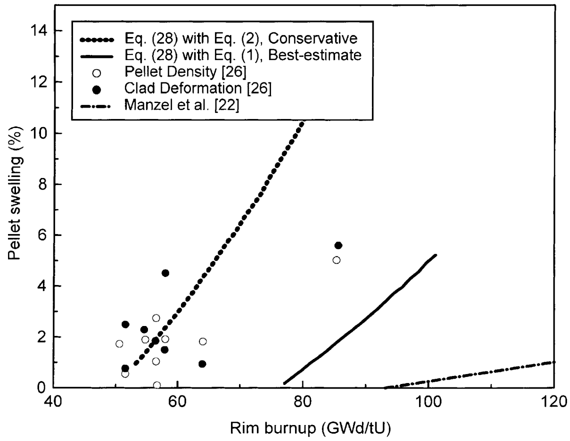

Fig. 6. Comparison of calculated and measured pellet swelling caused by the rim pores.

The matrix swelling rate is 1% per 10 GWd/tU up to a pellet average burnup of about 70 GWd/tU [22], which is equal to a theoretical one due to the accumulation of solid fission products [40]. Above 70 GWd/tU, the swelling rate increased to 1.5% up to 102 GWd/tU. This suggests that the pores created in the rim caused the additional swelling rate of 0.5% between 70 and 102 GWd/tU. If this were the case, the swelling in the pellet with average burnup 102 GWd/tU (rim burnup; 135 GWd/tU) would be 1.6%. Fig. 6 shows linear interpolation yields the rim pore swelling of 1% at 90 GWd/tU (rim burnup; 120 GWd/tU). This lower rim pore swelling is expected because the rim structure began to develop at the rim burnup of 93 GWd/tU in the fuel [22].

7. Uncertainty

The parameters used in the present model such as rim width, rim burnup, pore density, and pore size distribution, have uncertainties depending on manufacturing features and irradiation conditions. For example, the mean pore size in the rim changes with burnup [22]; the mean pore diameter of 1.5–2 μm at a pellet-average burnup of 67 GWd/tU increases to a mean value of 4 μm at 102 GWd/tU. In addition, a mean pore diameter was found to be 1.5 μm [33] in a BWR fuel that was irradiated with a maximum power of about 280 W/cm up to 49 GWd/tU.

The relationship between rim burnup and pellet average burnup is another source of uncertainty. The threshold burnup for rim formation ranges from 60 to 75 GWd/tU; the lower value can be attributed to the beginning of transition from normal UO_2 structure towards rim structure and the higher value is the threshold for the fully developed rim structure [1,2,13,18,23,25]. Based on EPMA measurement, other workers reported differently that the rim was formed beyond a threshold local burnup of 70–80 GWd/tU [16]. On the other hand, optical microscopic examination of fuel pellets revealed that a porous rim structure was formed at the periphery of UO_2 pellet with average burnup greater than 40 GWd/tU [15], which roughly corresponds to a rim burnup of 53 GWd/tU.

Some controversy exists over the reliability of Xe data supplied by EPMA. It has been reported that Xe depletion in the fuel matrix occurs before recrystallization [15], which clearly indicates that EPMA provides incorrect values for both rim width and local threshold burnup. However, Walker [41] argues that EPMA provides a true indication of the zone width of recrystallization because it detects the islands of recrystallized fuel that were not considered in the optical microscopy results so far reported.

A certain fraction of gas atoms depleted in the rim matrix is also retained in nm-range gas bubbles [33]. Unfortunately, the amount of gas present in the rim bubbles is not given quantitatively at the moment. Therefore, the present model assumes that all the depleted gas atoms reside in the rim pores and thus this would lead to the overestimated pore pressure.

8. Conclusion

The pore pressure in the rim was derived as a function of temperature, pellet average burnup and pore radius. For a rim pore with a radius of 0.5 μm retained in a pellet with average burnup 67 GWd/tU, the pressure is calculated to be 477 MPa for a threshold burnup of 52 GWd/tU and a rim temperature of 800 K. This suggests that an increased fracture toughness of the rim region in a high burnup UO_2 fuel [3] might have been caused by these high pressure pores as a result of relieving pore overpressure by plastic flow.

The calculated fractional pellet swelling caused by rim pores increases linearly with burnup. The pellet swelling rate is calculated to be 2.2% and 3.5% per 10 GWd/tU. Comparison with experimental data shows that, while the pellet swelling obtained with the best-estimate rim width is underpredicted, swelling derived by the conservative rim width agrees well with the measured data for rim burnups between 50 and 65 GWd/tU. The measured swelling at 85 GWd/tU is in-between the two calculations.

The present model can be linked with a fuel performance code such as COSMOS [42] to treat the effect of pore swelling on PCMI in high burnup UO_2 fuel and to generate the pore pressure that would be an important initial condition for the analysis of the rim behavior during RIA.

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