Bubble Pressure in the Rim Structure of High Burnup UO$_2$ Pellet without PCMI

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1. Introduction

The porous structure is observed in the periphery of high burnup UO$_2$ pellet, which is called rim structure. Because the bubbles in the rim structure have a large amount of fission gas accumulated, they could affect the integrity of fuel rods. Hence the formation, distribution and behavior of bubbles are carefully observed [1]. However, the bubble pressure, which is one of main parameters to predict bubble behavior, was calculated only by the assumption of dislocation punch model. Hence, to obtain more accurate bubble pressure, it was calculated by experimental results and reasonable assumptions based on the no PCMI restraint condition in this paper.

2. Methods and Results

2.1 Observation of rim bubbles

The bubble distribution in rim structure depends on the various factors such as temperature, burnup, as-fabricated microstructure, PCMI restraint, and so on. Especially, the PCMI restraint force makes it difficult to obtain the accurate parameters required in rim bubble model because the PCMI restraint force is generally applied to high burnup fuel pellet and decreases the size of rim bubbles. To exclude the effect of PCMI restraint force, the observation results of UO$_2$ fuel disk, which had been irradiated at an isothermal condition to 90 GWd/t and showed no PCMI [2,3], were used in the analysis. The 2 dimensional bubble size distribution was converted into the 3 dimensional bubble size distribution, and the calculated fuel swelling based on the conversion was compared with the measured one. This comparison showed the good agreement between calculation and measurement.

2.2 Xenon gas in rim bubble

Although the fission gases in rim bubbles consist mainly of xenon and krypton, xenon gas was assumed as only fission gases in rim bubbes because the only xenon data was available in the reference [2,3] and the amount of krypton was much smaller than that of xenon.

The total number of Xe atoms in the rim bubbles per unit rim volume, Xe_{bubble}^{total} , could be derived by summation of the number of Xe atoms of each rim bubble in a unit rim volume as following [4]:

$$Xe_{bubble}^{total} = \sum V(r) \cdot N_V(r) \cdot \rho_g(r), \quad (1)$$

where $V(r)$ is the volume of one bubble with radius, r, $N_v(r)$ is the number of bubbles in 3 dimensional distribution, and $\rho_g(r)$ is molecular density of gas in bubbles. 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 [5]

$$p\left(\frac{1}{\rho_g} - B\right) = kT , \quad (2)$$

where p is the pressure in a rim bubble with molecular density, B is the volume occupied by Xe gas atoms, k is the Boltzmann constant, and T is the absolute temperature. The pressure, p, is described as [4]

$$p = \sigma + \frac{2\gamma}{r} + P_{ex} , \quad (3)$$

where σ is the uniform hydrostatic stress, γ is the surface tension, r is the bubble radius, and P_{ex} is the excessive pressure. If the dislocation tangles surrounding the Xe bubbles by loop punching, limiting excessive pressure is Gb/r [6], where G is the shear modulus and b is the Burgers vector. It could be argued that the Gb/r can be used to derived excessive pressure in the rim bubbles, but the form of equation, *constant/r*, is assumed in our analysis and applied to equation (3). Then the bubble pressure is

$$p = \sigma + \frac{C}{r} \quad (4)$$

where C is a constant as a function of temperature and burnup.

On the other hand, Xe_{bubble}^{total} can also be calculated as follows:

$$Xe_{bubble}^{total} = Xe_g \frac{\rho_{TD}}{m_{Xe}} N_{av} , \quad (5)$$

where Xe_g is Xe weight concentration in the rim bubbles, 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.

2.3 Bubble pressure

If fuel pellet is not restrained, uniform hydrostatic stress, σ in equation (4) is 0 (zero). Hence if equations (1), (2), (4), and (5) are combined together and the bubble distribution and Xe depression of the fuel disk

without PCMI restraint [2,3] is used, a constant C, can be obtained at given burnup and temperature; C is 54 N/m at 823K and local burnup 90 GWd/t. This value is higher than 21 N/m calculated by $2\gamma + Gb$ at 823K.

And the pressure of the bubble with typical 1 diameter is calculated to be 108 MPa without no PCMI restraint condition. The irradiation-induced creep of UO_2 would start at stresses above 100 MPa in the temperature range of rim structure [1]. The relationship between bubble pressure and irradiation-induced creep is investigated in the further study.

3. Conclusion

Based on the rim bubble distribution and Xe depression in the UO_2 fuel disk, the parameter required for the bubble pressure in the rim structure of high burnup UO_2 pellet was calculated at 823K and local burnup 90 GWd/t. The obtained parameter is greater than that of loop punching model, and the pressure in the bubble with typical size is similar to the stress at which irradiation-induced creep starts.

Acknowledgments

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