Migration of Fission Products in a Fuel Element of a Pebble Bed Modular Reactor

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1. Introduction

A pebble bed modular reactor (PBMR) contains lots of fuel elements called pebble which is equivalent to a fuel assembly in a pressurized water reactor. Solid and gaseous fission products are produced in the fueled region of a pebble and released into a coolant. It is very important in a safety analysis of a PBMR to quantitatively evaluate a fission product release in the PBMR. The computer models treating a fission product release should predict a fission product release from a coated fuel particle, and a migration through a graphite fuel element into a coolant. This study set up a numerical model to estimate the migration of the fission products in a pebble of a PBMR.

2. Modeling for Fission Product Transport

The pebble consists of fuel and graphite regions like Fig. 1. The fuel region is a graphite sphere containing many coated fuel particles. Fission products are generated in the coated fuel particles in a pebble. They transport through the fuel region and the graphite, and finally release into the surrounding He coolant.

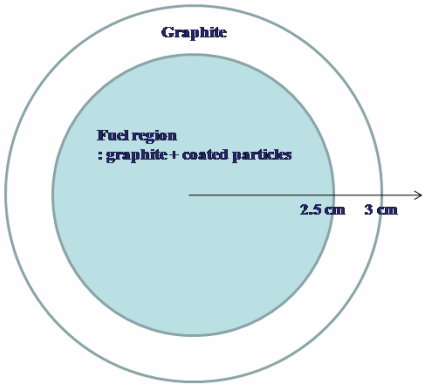

Fig. 1 A typical pebble of a PBMR

The major transport mechanism of the fission products within the pebble is a diffusion. The diffusion process can be described by the following Fickian diffusion equation [1].

$$\frac{\partial C(r,t)}{\partial t} = S(r,t) - \lambda C(r,t) + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D(r,t)\frac{\partial C(r,t)}{\partial r}\right], \quad (1)$$

where C = concentration (μmol/cm^3), S = source term (μmol·s^{-1}·cm^{-3}), D = diffusion coefficient (cm^2/s) = D_0 exp(-E/(RT)), D_0 = pre-exponent factor of a diffusion coefficient (cm^2/s), E = activation energy (J/mol), R = gas constant (8.314 J/(mol·K)), T = temperature (K), λ = decay constant (s^{-1}), r = radial coordinate (cm), t = time (s). The initial concentration is zero over the entire region. The current at the center of the pebble is zero. The fission products evaporate on the outer surface of the pebble. The concentration on the outer surface of the pebble is in equilibrium with the vapor pressure on the graphite side of the boundary layer which forms between the graphite surface and the coolant. The mass transfer occurs from the boundary layer into the coolant as follows [1].

$$\left[-D\frac{\partial C}{\partial r}\right]_{r=r_P} = h\left(C_a - C_\infty\right), \quad (2)$$

where r_P = pebble radius (cm^2), h = mass transfer coefficient (cm/s), C_a = concentration on the graphite side of the boundary (μmol/cm^3 of coolant), C_∞ = mixed mean concentration in the coolant (μmole/cm^3 of coolant). The mixed mean concentration in the coolant is usually assumed to be zero. The concentration on the graphite side of the boundary, C_a, is given by

$$C_{a,i} = \frac{10^6 P_i}{RT}, \quad (3)$$

where i = isotope, R = gas constant (82.0567 cm^3·atm/(mol·K)), and P_i = vapor pressure of isotope i (atm). The vapor pressure of the isotope i can be obtained by the Freundlich sorption isotherm [2].

$$P_i = P_{mi}\frac{C_i}{C_{mi}}\left(\sum_j \frac{C_j}{C_{mj}}\right)^{u_i - 1}, \quad (4)$$

and

$$u_i = \gamma_i + \delta_i(10^3/T), \quad (5)$$

$$P_{mi} = \exp\left[A_{mi} + B_{mi}\left(10^3/T\right)\right], \quad (6)$$

$$A_{mi} = \alpha_i + \gamma_i \log\left(C_{mi}/4\right), \quad (7)$$

$$B_{mi} = \beta_i + \delta_i \log\left(C_{mi}/4\right), \quad (8)$$

where $C_{m,i}$ = monolayer concentration (μmol/cm^3), α_i, β_i, γ_i, δ_i = constants.

A finite difference method was used to solve Eqs. (1) to (8) [3]. The fuel and graphite regions of the pebble were divided into N_f and N_g intervals, respectively. It is assumed that the diffusion coefficient is dependent on the time only within each interval.

3. Estimation of a Fission Product through a Pebble

The release of Sr^{90} was calculated by using the above finite difference method. The data for calculating the Sr^{90} release is shown in Table 1 [2,4]. The source term was assumed to be constant throughout the fuel region and was zero in the graphite region of the pebble. A large number was chosen as the value of the diffusion coefficient in the fuel region in order to express a fast uniform distribution in the fuel region. Temperature was assumed to be constant throughout the pebble for a simple calculation.

Fig. 2 shows the concentration evolution of Sr^{90} in a pebble at 1000 °C. The concentration is flat in the fuel region and decreases rapidly in the graphite. The concentration increases with time. Fig. 3 displays the release of Sr^{90} from the pebble surface at 900, 1000, and 1250 °C. The release amount increases with the temperature.

Table I. Data for calculating Sr^{90} migration

Data	Values
S (μmol/(cm^3·s))	7.3×10^{-9}
D_0 in graphite (cm^2/s)	1.66×10^{2}
E (J/mol)	2.68×10^{5}
α_i	13.4
β_i	-38.1
γ_i	0.079
δ_i	4.10
C_m (μmol/cm^3)	20.8
h (cm/s)	3.92

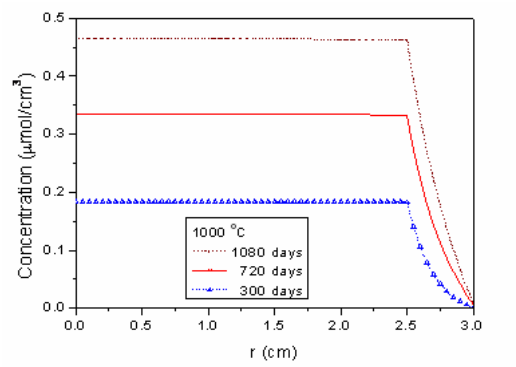

Fig. 2 Sr^{90} concentration evolution in a pebble at 1000 °C

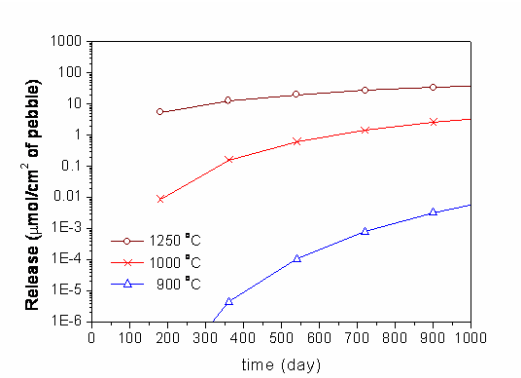

Fig. 3 Sr^{90} release from a pebble

4. Conclusion

A computer program using a finite difference method was developed to estimate the transport of fission products through a pebble of a PBMR. The program described the effects of the time and temperature on the release of Sr^{90} very well. It is necessary to verify the present results with experimental data. The developed numerical scheme can be applied to the estimation of a fission product release in a compact of a prismatic high temperature gas-cooled reactor.

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