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Leakage Fractions of Fission Products from a Fuel Rod to a Coolant in a Prismatic High Temperature Gas-cooled Reactor

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1. Introduction

Fission product release is very important in the source term calculation for a high temperature gas-cooled reactor (HTGR) under normal and accident conditions. The computer models treating the fission product release should predict the fission product release from the kernel, transport through failed coatings, deposition fraction within a fuel element, deposition fractions within graphite dust and metallic surfaces in a primary circuit, re-entrainment of the deposited fission products during an elevated temperature accident, or depressurization event, and transport of fission products on dust particles and subsequent release to the environment [1]. This study calculated the leakage fractions of the fission products from a fuel rod into a coolant in a prismatic fuel element of the HTGR.

2. Transport of Fission Products from a Fuel Rod into a Coolant

Fission products are created in the kernels of intact TRISO-coated fuel particles. They transport through a buffer, coating layers, a fuel compact or matrix graphite, and a fuel element into a coolant. The major transport mechanisms of the fission products within the fuel components are diffusion and trapping. The trapping has been frequently ignored because of scarce experimental data. Some TRISO particles can break during a manufacturing process and a reactor operation. The TRISO particles, fuel compacts, and fuel elements may be contaminated with the kernel material (it is called heavy metal contamination). The failure and heavy metal contamination increase the release of the fission products. The reactor operation condition also affects the release of the fission products. Gaseous and metallic fission products show different transport behaviors.

2.1 Gaseous Fission Products

It can be assumed that the sorption and trapping of the gaseous fission products (Xe and Kr) are not significantly occurred in the fuel element (graphite sleeve). The gaseous fission products release instantaneously into a coolant through the graphite pore regardless of the reactor conditions since the porosity of the graphite sleeve is about 50%.

2.2 Metallic Gaseous Fission Products

Fig. 1 shows the transport process of the metallic fission products (Cs, Ag, Rb, Sr, Ba, Ce, Eu, Sm) from a fuel rod into a coolant. The metallic fission products in the fuel rod release into a gap between the fuel rod and the graphite sleeve. The concentration of the fission product on the surface of the fuel rod is in equilibrium with the vapor pressure in the gap. The so-called sorption isotherm describes the concentration-vapor pressure equilibrium [2]. The vapor pressure in the gap is also in equilibrium with the concentration on the inner surface of the graphite sleeve.

$$P = e^{x}\left(C_m^{y} + C_{m,t}^{y-1}C_m\right), \quad (1)$$

where P = isotherm vapor pressure (Pa), C_m = concentration on the surface of the compact or graphite sleeve (mmol/kg of the compact or graphite sleeve), $C_{m,t}$ = transition concentration between Freundlich and Henrian isotherms (mmol/kg of the compact or graphite sleeve), $x = A+B/T$, $y = D+E/T$, T = temperature (K). A, B, C, and D are all constants determined experimentally for the fission products.

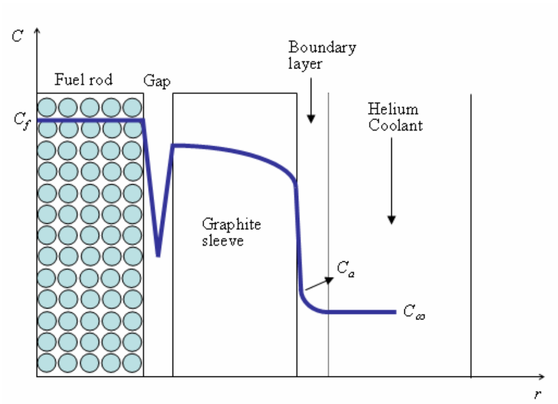

Fig. 1 Transport profile of fission products in a fuel element

The fission products transport within the graphite sleeve through diffusion process only if they are not significantly trapped by the graphite. The diffusion process can be described by the following Fickian diffusion equation [2].

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

where C = concentration (mmol/m^3 of a graphite sleeve), S = birth rate (mmol·s^{-1}·m^{-3} of a graphite sleeve), D = diffusion coefficient (m^2/s), λ = decay constant (s^{-1}), r = radial coordinate (m), t = time (s).

The fission products evaporate on the outer surface of the graphite sleeve. The concentration on the outer surface of the graphite sleeve is in equilibrium with the vapor pressure on the graphite side of the boundary layer which forms between the graphite sleeve and the coolant. The isotherm equilibrium is applied to this equilibrium. The mass transfer occurs from the boundary layer into the coolant as follows [2].

$$J_L = h(C_a - C_\infty) \,, \tag{3}$$

where J_L = mass flux (mmol·s^{-1}·m^{-2}), h = mass transfer coefficient (m/s), C_a = concentration on the graphite side of the boundary (mmol/m^3 of coolant), C_∞ = mixed mean concentration in the coolant (mmol/m^3 of coolant).

The leakage fraction in a concentration ratio is

$$C_a / C_f \,, \tag{4}$$

where C_f = concentration of a fuel rod (mmol/m^3 of a fuel rod). The leakage fraction is also expressed in a molar ratio.

$$\frac{C_a V_{coolant} / 12}{C_f V_f / 6} \,, \tag{5}$$

where V_f = volume of a fuel rod (m^3) and $V_{coolant}$ = volume of coolant (m^3).

3. Leakage Fractions of Fission Products from a Fuel Rod into a Coolant

The leakage fractions of the gaseous fission products are all one according to Section 2.1. In order to evaluate the leakage fractions of the metallic fission products, it is assumed that the graphite sleeve is not contaminated and the diffusion process approached equilibrium. The constants of equilibrium isotherm of the fission products for the fuel rod and the graphite sleeve and the diffusion coefficients of the fission products are given in the reference [3]. Table I shows the dimensions and physical properties for fuel compact and fuel element, an active core height, coolant pressure and flowrate [4]. Temperature in Table I was calculated by using a COPA-TEMBL [5]. The leakage fractions of the metallic fission products from a compact into a coolant are shown in Table II.

Table I. Data for calculating the leakage fractions

Structure	Material and dimensional data	Values
Fuel compact	Density (kg/m^3)	1000
	Diameter (m)	0.01245
	Surface temperature (K)	1253
Fuel element	Density (kg/m^3)	1012.4
	Coolant hole diameter (m)	0.01588
	Web thickness of equivalent slab (m)	0.00418
	Inner surface temperature (K)	1233
	Outer surface temperature (K)	1228
Core	Active core height (m)	7.93
	Coolant pressure (MPa)	7.042 ~ 7.1
	Coolant flowrate (kg/s)	320

Table II. Leakage fractions of the metallic fission products from a compact into a coolant

Element	Leakage fraction	
	Concentration ratio (C_a/C_f)	Molar ratio
Cs-137	0.1784×10^{-12}	0.1451×10^{-12}
Ag-110m	0.7495×10^{-12}	0.6097×10^{-12}
Rb-87	0.1100×10^{-11}	0.8950×10^{-12}
Sr-90	0.1023×10^{-15}	0.8319×10^{-16}
Ba-137	0.4574×10^{-15}	0.3721×10^{-15}
Ce-144	0.2819×10^{-16}	0.2293×10^{-16}
Eu-154	0.9239×10^{-16}	0.7516×10^{-16}
Sm-151	0.1076×10^{-15}	0.8751×10^{-16}

4. Conclusion

The leakage fractions of the gaseous and metallic fission products in the prismatic fuel element of a HTGR were evaluated. The gaseous fission products, Xe and Kr, are instantaneously released into a coolant through the pores in the graphite. The leakage fractions of the metallic fission products were 10^{-15} ~ 10^{-11}. Most of the metallic fission products were judged to be deposited within the graphite web. The leakage fractions can be utilized in evaluating the source terms during a reactor safety analysis.

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