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A Nuclide Transfer Model for Barriers of the Seabed Repository Using Response Function

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응답함수를 이용한 해저처분장의 방벽에 대한 핵종전달 모델

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Abstract

A nuclide transfer by utilizing mass transfer coefficient and barrier response function defined for each barrier is proposed, by which the final nuclide transfer rate into the sea water can be evaluated. When simple and immediate quantification of the nuclide release is necessary in the conservative aspect, using this kind of approach may be advantageous since each layered barrier can be treated separately from other media in series in the repository system, making it possible to apply separate solutions in succession to other various media. Although one disadvantage is that while flux continuity can be maintained at the interface by using the exit nuclide flux from the first medium as the source flux for the next one, there may be no guarantee for concentration continuity, this problem could be eliminated assuming that there is no boundary resistance to mass transfer across the interface. Mass transfer coefficient can be determined by the assumption that the nuclide concentration gradient at the interface between adjacent barriers remains constant and barrier response function is obtained from an analytical expression for nuclide flow rate out of each barrier in response to a unit impulse into the barrier multiplied by mass transfer coefficient. Total time-dependent nuclide transfer rate from the barrier can then be obtained by convoluting the response function for the barrier with a previously calculated set of time-varying input of nuclide flow rate for the previous barrier.

요 약

해저에 건설된 방사성폐기물 처분장 방벽에서 핵종전달을 평가할 수 있는 한 모델이 제시되었다. 방벽의 출구에서의 물질전달계수와 각 방벽에 대하여 정의된 방벽응답함수를 이용하여 이들 방벽으로 부터의 핵종의 전달률을 구할 수 있다. 이러한 접근은 단순하고 즉각적인 계산결과가 보수적인 측면에서 요구되어지는 경우 방벽들을 연속된 별개의 매질로 다루어 각각의 응답함수를 적용할 수 있기 때문에 유용하다. 단점으로는 인접한 두 방벽사이에서, 이전의 방벽으로 부터의 핵종의 유출율이 연속되는 방벽으로의 유입율로 되어 핵종속은 보존되는 반면 핵종의 농도는 반드시 보존되지는 않는다는 것으로, 이는 두

방벽매질의 경계에서 핵종전달저항이 없다고 가정할 수 있는 것으로 해결될 수 있다. 물질전달계수는 방벽의 출구쪽 경계에서의 핵종의 농도가 일정하다고 보아 구할 수 있고, 매질의 응답함수는 각 방벽에 대하여 핵종의 단위 펄스입력에 대해 경계에서의 농도에 대한 해를 구한 후 물질전달계수를 적용하여 얻을 수 있다. 이리하여 한 방벽매질에 대한 시간 종속적인 핵종의 총전달률은 응답함수에 이전의 방벽에 대해 계산된 핵종의 전달률을 컨볼루트하여 구할 수 있다.

1. Introduction

In this paper, as a final disposal option, the case in which radioactive wastes are disposed of in an excavated tunnel under the seabed around the island is dealt with. Very typically in such an island disposal, nuclide release scenario could be identified, i.e., the final destination of the nuclide is likely to be the sea water, not directly human residence in the island especially when the repository is assumed to be located as described in Fig. 1, in which a freshwater zone called Ghyben-Herzberg lens normally resting on saline water originated from sea water. In an island aquifer, recharge is predominantly due to vertical inflow, whereas in a coastal aquifer, it is due to lateral inflow.[1] In such environment wherever the repository is located under the seabed around the island, nuclide released from the repository can hardly move directly into the human environment on the island.

Usually the release rate of nuclide from the repository through the various barriers can be simply described by diffusion and/or advection-dispersion equations for the system by transforming the dependent variable from nuclide concentration into the rate of nuclide transport by applying the flux operator to the equations.[2]

An alternative approach could be proposed: For the barrier system where the initial nuclide concentration in the whole system is taken as none and the source boundary condition is determined considering the release type of the source term or exit boundary condition of the previous barrier assuming that the nuclide release is proportional to the concentration at each interface between two medium layers, nuclide transfer between barriers can be evaluated. In such case mass transfer coefficient corresponds to the proportionality factor for nuclide transfer through the interface, representing the resistance to nuclide transfer across the interface.

In this context a simple nuclide transfer model by utilizing mass transfer coefficient and barrier response function identified for each barrier can be described, by which the final nuclide relase rate into the sea wat er can be evaluated.[3-6]

Mass transfer coefficient is determined by assuming that the nuclide concentration gradient at the interface between adjacent barriers remains constant, which means the steady state condition. However, at shorter time immediately after the closure of the repository when mass transfer coefficient would be larger, this assumption would be violating.

If simple and immediate quantification of the nuclide release in the aspect of conservative assessment is needed, then using this kind of approach may be advantageous since each layered medium can be treated separately. In other words, this approach makes it possible to apply the solution in succession to each media of various types. One distinct disadvantage is that while flux continuity can be maintained at the interface by using the exit nuclide flux from the first medium as the source flux for the next one, concentration continuity cannot be maintained. However this problem is eliminated by assuming that there is no boundary resistance to mass transfer across the interface.

2. Repository Barrier System

In the present study, reference disposal tunnel shown in Figs. 1 and 2 is assumed to be located at a shallow depth of less than a few tens of meters under the sea level providing relatively short travel

distance of nuclide to the biosphere. The waste containers are surrounded by concrete wall and all other excavated space is then backfilled by compacted bentonite clay.

In such repository system there may be various barriers in series that will prevent or retard nuclide release. Before starting to release, first of all, a nuclide must come in contact with groundwater and dissolve after which it penetrates the barriers and eventually reaches the sea bottom.

Two more natural barriers are also considered: (hydraulic conductivity of the order of 10^{-13} m/s ; effective diffusivity of $\sim 3\times 10^{-11}$ m^2/s assumed) and bentonite clay layer (hydraulic conductivity of the order of $10^{-11}\sim 10^{-9}$ m/s ; effective diffusivity of $\sim 10^{-10} m^2/s$ assumed) backfilled between concrete wall and tunnel wall are identified in this study as principal diffusive media.

Two more natural barriers are also considered : host rock (hydraulic conductivity of 10^{-8}m/s assumed) and sediments, thickness of which is at least 5 m. [7]

In case the repository is located under the sea bed, the predominant flow direction of groundwater around the repository is considered to be upward perpendicular to the repository plane as mentioned. Therefore, considering idealized uniform flow of groundwater the effective geometric cross sectional area through which groundwater flow and nuclide transfer can take place is considered as the repository area.

Once a nuclide is released from radioactive waste, it continues to move through the barriers by diffusion, followed by successive transport through the fractured channel of the host rock surrounding the repository. In the rock medium, transport may take place both by advection and dispersion along the flow path as well as molecular diffusion into the rock matrix as considered in models by Neretnieks[8] or Tang et al. [9] In this study, in the sense of conservatism, we consider the special case that a considerably wide band of the imaginary fracture zone—where a bundle of fractures exist—exists intersecting the repository tunnel so that groundwater flow and nuclide transport can be exclusively taken place through it.

In the present study, various barriers are modeled as a series of finite multilayered system as illustrated schematically in Fig. 3. Thus, if the nuclide transfer through the barrier system is considered to be a linear process having each impulse response $h(t)$, then, using convolution integral, one can find that the re-

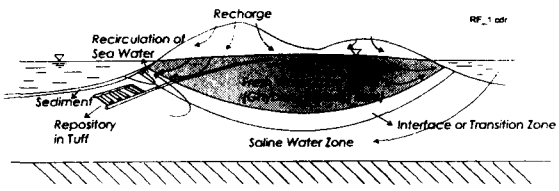

Fig. 1. Conceptual Repository System under the Seabed around an Island.

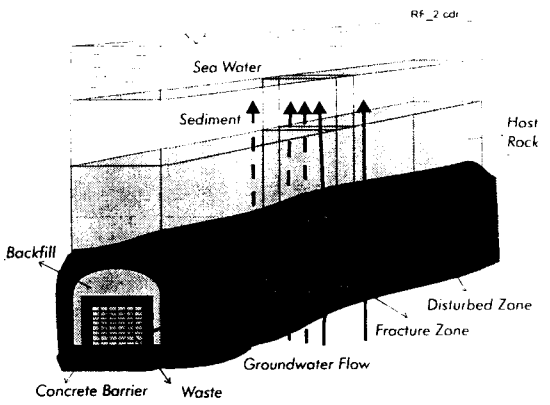

Fig. 2. Various Barriers and Groundwater Flow Perpendicular to the Repository Tunnel.

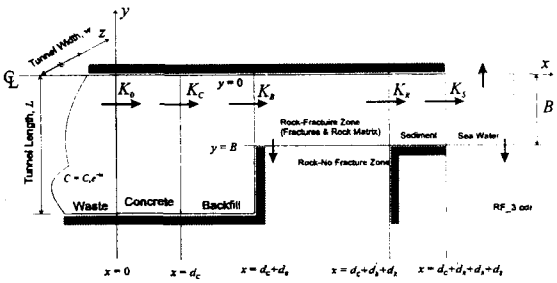

Fig. 3. A Series of Finite Barriers Schematically Described for Nuclide Transfer Modeling.

sponse of the system $m(t)$, i.e., outlet nuclide relase rate to the input flow rate $r(t)$ is as follows:

$$m(t)=\int_0^t r(\tau)h(t-\tau)d\tau \tag{1}$$

where $m(t)$, denotes nuclide flux or nuclide relase rate per unit area, expressed as $m(t)=\left(-D\frac{\partial}{\partial x}+v\right)C$.

3. Mass Transfer Coefficients and Barrier Response Function

As discussed in the introduction, the mass transfer coefficient is derived based upon the assumption that mass transfer across the interface of adjacent barriers is controlled by diffusion and/or by advection. The boundary condition assumed at the interface between barriers is that the nuclide flow out of the barrier is proportional to the concentration at the barrier boundary, which yields mass transfer rate as

$$A\left[-D\frac{\partial C}{\partial x}\bigg|_{x=d}+vC\right]=KCA \tag{2}$$

where

A=contacting area through which nuclide transfer takes place (m^2)

D=effective diffusion coefficient (m^3/year)

C=nuclide concentration (Ci/m^3)

d=thickness of barrier (m)

v=pore velocity (m/year)

K=barrier mass transfer coefficient (m/year).

The nuclide release rate $m(t)$ per unit area per unit impulse response of nuclide from a barrier is accordingly given by

$$m(t)=KC(d,t) \tag{3}$$

where C(d, t) denotes the concentration at the interface due to the unit impulse input into the system (Ci/m^3).

An analytical expression for nuclide release rate out of each barrier, in response to a unit impulse into the barrier is called a response function, which is again the nuclide mass transfer rate that corresponds to an impulse source nuclide at the barrier inlet. Then total time-dependent nuclide relase rate from the barrier can be obtained by convoluting the response function for the barrier with the previously calculated set of time-varying input of nuclide relase rate from the previous barrier.

To simplify the model, it is assumed that the groundwater flow carrying the nuclide takes place through the confined area of two media interface in the one-dimensional x direction.

The equation governing nuclide transport in the media such as concrete, backfill, and sediment is represented by the following Eq.(4) and the steady state solution in case $\lambda\rightarrow 0$, subject to the boundary conditions of Eq.(5) is represented by Eq.(6):

$$\frac{\partial C}{\partial t}=\frac{D}{R}\frac{\partial^2 C}{\partial x^2}-\lambda C \tag{4}$$

$$C(0)=C_0 \tag{5a}$$

$$C(x)=0 \quad x=d \tag{5b}$$

$$C(x)=C_0\left(1-\frac{x}{d}\right) \tag{6}$$

If the barrier of waste container is not considered, then from Eq.(2), the mass transfer coefficient K_0 between the waste and concrete barrier is obtained as Eq.(7)

$$K_0=\frac{D_C}{d_C R_C} \tag{7}$$

where

D_C=diffusion coefficient in the concrete (m^2/year)

d_C=thickness of the concrete barrier (m)

R_C=retardation coefficient of the concrete barrier.

Since the transport mechanism in the porous media such as concrete and sediment is considered to be mainly diffusion, the concentration at $x=d$ is determined by solving Eq.(4) with appropriate side conditions prescribed by following Eqs.(8) and (10). However, since we consider the solution for semi-infinite medium in the positive x direction, the solution is finally obtained by superposition after considering

the reflection of solution in the negative x direction. [10] Thus, by multiplying mass transfer coefficient, the response function for the impulse source can be obtained as Eq.(11). Response function is either in the form of nuclide concentration or in the form of nuclide flux as expressed in Eq.(11). The total amount of material associated with a delta-function in nuclide concentration is obtained by integrating over the spatial coordinate as expressed in Eq.(9); the total amount of material associated with a delta-function in nuclide flux is obtained by integrating over the time variable. In both cases, anyway, the delta-function represents an impulse of unit amount of nuclide.

$$C(x,0)=\delta(x) \tag{8}$$

which means

$$\int_{-\infty}^{\infty} C(x,t)dx=1 \tag{9}$$

$$C(x,t)=0 \quad |x|\to\infty \tag{10}$$

$$h(d,t)=\frac{K}{\sqrt{\pi\left(\frac{D}{R}\right)t}}\exp\left\{-\frac{Rd^2}{4Dt}-\lambda t\right\} \tag{11}$$

where $h(d, t)$ represents the barrier response function for different barriers (1/year).

In the meanwhile, in order to obtain steady state concentration for the backfill medium, facing rock mass, two dimensional approach is adopted with varying outlet boundary condition as done by, among others, Neretnieks. [11] (see Fig. 3.) The steady state governing equation as $\lambda\to 0$ and boundary conditions are expressed as Eqs. (12) and (13), respectively:

$$\frac{\partial C_B^2}{\partial x^2}+\frac{\partial C_B^2}{\partial y^2}=0 \tag{12}$$

$$C_B(0,y)=C_B^0 \tag{13a}$$

$$\left.\frac{\partial C_B}{\partial y}\right|_{y=0}=\left.\frac{\partial C_B}{\partial y}\right|_{y=L}=0 \tag{13b}$$

$$\left.\frac{\partial C_B}{\partial y}\right|_{x=d_C+d_B}=f(y)=\begin{cases}\dfrac{\dot{N}R_B}{A_R D_B}, & 0<y<B\\ 0, & B<y<L\end{cases} \tag{13c}$$

where

$C_B^0=C_C(d_C)$, considered to be nearly constant over the concrete interface

C_B = steady state nuclide concentration in the backfill barrier

N = nuclide relase rate from the backfill over the fractured zone (Ci/year).

The solution is found in the literature: [12]

$$\frac{C_B(x,y)}{C_B^0}=1-\frac{\dot{N}R_B}{A_R D_B C_B^0}\times$$

$$\times\left\{\frac{B}{L}x+\sum_{n=1}^{\infty}\frac{2L}{(n\pi)^2}\cos\left(\frac{n\pi}{L}y\right)\sin\left(\frac{n\pi}{L}B\right)\frac{\sinh\left(\frac{n\pi}{L}x\right)}{\cosh\left(\frac{n\pi}{L}d_B\right)}\right\}\equiv$$

$$\equiv 1-\frac{\dot{N}R_B}{A_R D_B C_B^0}F(x,y) \tag{14}$$

where the sum is denoted by $F(x, y)$.

Since at the backfill-fracture interface, by letting $d_C=0$ for simplicity, $C_B(x, y)=C_B(d_B, y)$, Eq.(14) is rewritten as

$$\frac{\dot{N}R_B}{A_R D_B\left\{C_B^0-C_B(d_B,y)\right\}}=\frac{1}{F(d_B,y)}, \quad 0<y<B \tag{15}$$

which shows how much of the diffusing nuclides is transferred through the fractured zone.

If the flow velocity in the fracture is known, $\dot{N}$ can be obtained by considering the diffusion in the groundwater passing through the backfill-groundwater interface. [11] Since $x\approx 0$ when $x\to\infty$, the result is expressed as

$$\dot{N}=A_R\left\{C_B(d_B,y)-C_B(x\to\infty,y)\right\}K_B$$

$$\cong A_R C_B(d_B,0<y<B)K_B \tag{16}$$

Accordingly, $C_B(d_B, y)$, can be eliminated with Eqs. (15) and (16). Then, Eq.(14) is explicitly expressed as follows:

$$\dot{N}=\frac{A_R C_B^0}{F(d_B,y)\frac{R_B}{D_B}+\frac{1}{K_B}} \tag{17}$$

In order to determine the only unknown variable K_B appeared in Eq.(17), the nuclide transfer through the backfill into the fractured rock medium is to be

considered. In the fractured medium in the very vicinity of the fracture interface, diffusion is dominant mechanism in x direction, whereas advection is large compared to diffusion in the z direction. When the concentration is kept constant at the backfill boundary, the following governing equation and boundary conditions are considered to be valid:

$$\frac{D_R}{R_R}\frac{\partial^2 C_R}{\partial x^2}=\frac{v_R^z}{R_R}\frac{\partial C_R}{\partial z} \tag{18}$$

$$C_R(x\to\infty)=0 \tag{19a}$$

$$C_R(@\text{inlet})=C_B(d_B,y) \tag{19b}$$

$$C_R(z=0)=0 \tag{19c}$$

where

D_R=dispersion coefficient in the fracture (m^2/year)

v^z_R=groundwater velocity in the z direction in the transfer zone of fracture (m/year).

Therefore, according to Fick's s law, the flow across the boundary can be evaluated by averaging the diffusive flux evaluated at the interface over the boundary of the transfer zone, and by multiplying the effective contacting area, as follows:

$$A_R\frac{1}{w}\int_0^w\left(-D_R\left.\frac{\partial C_R}{\partial x}\right|_{x=d_B}\right)dz=A_R C_B(d_B,y)\sqrt{\frac{4D_R v_R^z}{\pi w}} \tag{20}$$

With continuity of concentration and Eq.(2), the mass transfer coefficient for the rock medium is obtained:

$$K_B=\sqrt{\frac{4D_R v_R^z}{w\pi}} \tag{21}$$

In the meanwhile, $F(d_B, y)$ in Eq.(17) is expressed as

$$F(d_B,y)=\bar{F}(d_B,0<y<B)=\frac{1}{B}\int_0^B dyF(d_B,y)$$
$$=\frac{d_B}{L}B+\frac{1}{B}\sum_{n=1}^{\infty}\frac{2L^2}{(n\pi)^3}\sin^2\left(\frac{n\pi}{L}B\right)\tanh\left(\frac{n\pi}{L}d_B\right) \tag{22}$$

which is averaged for the width of fracture zone interfacing with backfill region.

Since mass transfer coefficient for the concrete barrier and the backfill boundary, K_C is finally expressed by

$$K_C=-\frac{D_B}{C_C(d_C)R_B}\left.\frac{\partial C_B}{\partial x}\right|_{\substack{x=d_C\\0<y<L}} \tag{23}$$

then, from Eq.(14), one can obtain the mass transfer coefficient for the concrete as

$$K_C=\frac{B}{L}\frac{1}{\bar{F}\frac{R_B}{D_B}+\frac{1}{K_B}} \tag{24}$$

where $\bar{F}=\frac{1}{B}\int_0^B F(d_C,y)dy$

The fractured rock medium is regarded as the bundle of fractures, each of which is modeled as representative or equivalent fracture existing in the rock matrix in the same way considered in the literature: [8-9, 13] i.e., the governing equations and the appropriate side conditions are

$$\frac{\partial C_R}{\partial t}=\frac{D_R}{R_R}\frac{\partial^2 C_R}{\partial x^2}-\frac{v_R}{R_R}\frac{\partial C_R}{\partial x}-\lambda C_R+\left.\frac{\phi_P D_P}{bR_R}\frac{\partial C_P}{\partial y}\right|_{y=b} \tag{25}$$

$$\frac{\partial C_P}{\partial t}=\frac{D_P}{R_P}\frac{\partial^2 C_P}{\partial y^2}-\lambda C_P \tag{26}$$

$$C_R(0,t)=\frac{1}{v_R}\delta(t)\quad\text{or}\quad C_R(x,0)=\delta(x) \tag{27a}$$

$$C_R(x,0)=0 \tag{27b}$$

$$\lim_{x\to\infty}C_R(x,t)=0 \tag{27c}$$

$$C_R(x,t)=C_P(x,b,t) \tag{27d}$$

$$C_P(x,\infty,t)=0 \tag{27e}$$

$$C_P(x,y,0)=0 \tag{27f}$$

where

C_R=nuclide concentration in the fracture (Ci/m^3)

C_P=nuclide concentration in the rock matrix (Ci/m^3)

D_P=pore diffusion coefficient in the rock matrix (m^2/year)

ϕ_P=porosity of the rock matrix

$2b$=representative fracture width (m)

v_R=groundwater velocity in the fracture (m/year)

R_R=retardation coefficient on the fracture surface

R_P=retardation coefficient in the rock matrix.

A solution subject to side conditions is found in the literature.[14-15] Therefore, for the rock medium, the response function is obtained from the following Eq.(28) at the outlet boundary of the rock medium by multiplying mass transfer coefficient.

$$C_R(x,t)=\frac{1}{\pi}\int_0^{\frac{D_B}{4R_B}}\frac{Gx}{8\sqrt{(t-4R_B\xi/D_B)^3\xi}}\times \times\exp\left\{-\frac{x^2}{16\xi}-\frac{v_R^2\xi}{D_R^2}-\frac{G\xi^2}{4(t-4R_B\xi/D_B)}+\frac{v_R x}{2D_R}\right\}d\xi \quad (28)$$

where

$$G=\frac{4\phi_p\sqrt{R_pD_p}}{(D_Rb)}$$

which represents the nuclide concentration due to the impulse nuclide input.

Meanwhile, there may be two processes associated with the nuclide transfer between the sediment and sea water: sedimentation from sea water down to the sediment and direct transfer from the sediment into the sea water. Therefore a balance equation between the two barriers can be set as [16]

$$\frac{dC_W(t)}{dt}=\lambda_1C_S(t)-\lambda_2C_W(t)+\frac{W(t)}{V} \quad (29)$$

$$\frac{dC_S(t)}{dt}=\lambda_3C_W(t)-\lambda_4C_S(t) \quad (30)$$

$$\lambda_1=\frac{K_S}{d_Sk_d} \quad (31a)$$

$$\lambda_2=\frac{q}{V}+\lambda+\frac{v_{sed}k_d}{d_S}+\frac{K_S}{d_S} \quad (31b)$$

$$\lambda_3=\frac{v_{sed}k_d}{d_W}+\frac{K_S}{d_W} \quad (31c)$$

$$\lambda_4=\lambda+\frac{v_{sed}}{d_W}+\frac{K_S}{d_Wk_d} \quad (31d)$$

where

C_W = nuclide concentration in the sea water (Ci/m^3)

C_S = nuclide concentration in the sediment layer (Ci/m^3)

V = volume of sea water block (m^3)

$W(t)$ = activity inflow rate into the sea water (Ci/year)

q = groundwater outflow rate into the sediment (m3/year)

K_S = mass transfer coefficient for the sediment (m/year)

d_S = thickness of the sediment (m)

k_d = sorption coefficient in the sediment (m^3/g)

v_{sed} = sedimentation velocity (m/year)

d_W = depth of the sea water (m).

To determine the mass transfer coefficient K_S for the sediment barrier, the similar disscusion as the case of K_B can be adopted: In the sea water diffusion in the x direction and advection in the y direction is assumed to be predominant mechanism for nuclide transport, respectively. Therefore, on the analogy of Eq.(21), K_S is expressed as Eq.(32) :

$$K_S=\sqrt{\frac{4D_Wv_W^y}{B\pi}} \quad (32)$$

where

D_W = diffusion coefficient in the sea water (m^2/year)

v_W^y = sea water velocity in y direction (m/year).

The solution for the case of instantaneous unit input into the sea water can be obtained as

$$C_W^{inst}(t)=\frac{1}{V(\omega_1-\omega_1)}\left\{(\lambda_4+\omega_1)e^{\omega_1t}-(\lambda_4+\omega_2)e^{\omega_2t}\right\} \quad (33)$$

where

$$\omega_{1,2}=\frac{1}{2}\left\{-(\lambda_2+\lambda_4)\pm\sqrt{(\lambda_2+\lambda_4)^2-4(\lambda_2\lambda_4-\lambda_1\lambda_3)}\right\}$$

Thus, for a continuous nuclide flow of $C_S(d_S, t)K_S$ from the sediment into the sea water, the nuclide concentration in the sea water at time t can be found by convolution of input flow rate with the impulse response expressed as Eq.(33), i.e.,

$$C_W(t)=\int_0^t C_W^{inst}(t-\tau)C_S(d_S,\tau)K_Sd\tau \quad (34)$$

4. Discrete Impulse Response Algorithm

To evaluate convolution integral such as Eqs.(1)

and (34) a numerical algorithm can be considered. Let s consider Eq.(1) as an illustration: For a linear system which has an impulse response $h(t)$, the response of the system $m(t)$ to the input $r(t)$ is rewritten equivalently as

$$m(t)=\int_0^t r(t-\tau)h(\tau)d\tau \tag{35}$$

Since the input $r(t)$ does not have the functional form it will be convenient to convert the above integral into a summation form. To this end the input flux $r(t)$ is approximated by a discrete but piecewise constant function as follows:

$$r(t)\approx\sum_{j=0}^{N} r_j\{u(t-jT)-u(t-jT-T)\} \tag{36}$$

where T is a discrete time interval T and $u(T)$ denotes the Heaviside step function.

By introducing Eq.(36) into Eq.(35) and evaluating at time kT we can get the output flux $m(kT)$ as follows:

$$m(kT)=\int_0^{kT} d\tau\, h(kT-\tau)\sum_{j=0}^{N} r_j\{u(\tau-jT)-u(\tau-jT-T)\}=$$

$$=\sum_{j=0}^{N} r_j\int_{jT}^{(j+1)T} h(kT-\tau)d\tau=\sum_{j=0}^{N} r_j\int_{(k-j-1)T}^{(k-j)T} h(\tau)d\tau\equiv m_k \tag{37}$$

In order to investigate the sensitivity to the size of the discrete time increment T, for several values of the T, the flux from concrete barrier at the backfill interface is calculated using above Eq.(37) by decreasing T. A calculated result from a numerical experiment is shown in Fig. 4, where the difference between the two results become larger as the discrete time gets larger as expected. Since when $T<0.1$, two results are almost coincide with each other, discrete time of 0.1 years is adopted for the whole calculations.

For the evaluation of numerical evaluation, DECADRE routine, which uses cautious adaptive Romberg extrapolation in IMSL numerical package is used. [17]

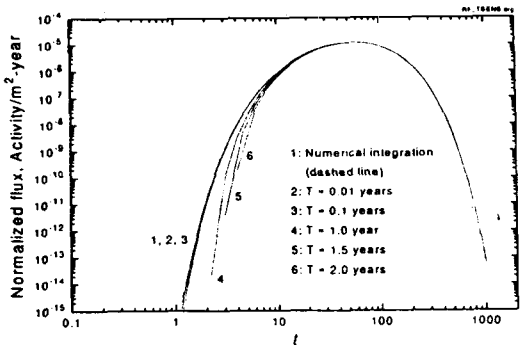

Fig. 4. Nuclide Relase Rates from the Concrete Barrier at the Backfill Boundary for Varying Discrete Time Step as a Function of Time.

5. Numerical Illustration

An illustrative result is shown in Fig. 5 as a function of time for an arbitrary nuclide.

Nuclide release rates per unit area from each barrier normalized to the concentration in the radioactive waste container are plotted. The assumed parameter values used in the calculation are chosen from literature and given as follows:

Pure diffusion coefficient in water, D^* (m^2/year) $=5\times10^{-3}$
Tunnel length, L (m) $=10.0$
Tunnel width, w (m) $=2.0$
Fracture zone width, B (m) $=1.0$
Fracture half width, b (m) $=0.001$
Concrete barrier thickness, d_C (m) $=0.6$
Backfill barrier thickness, d_B (m) $=0.9$
Rock medium thickness, d_R (m) $=60$
Sediment thickness, d_S (m) $=5.0$
Sea water depth overlying repository, d_W (m) $=50.0$
Retardation in concrete barrier, $R_C=1.0$
Retardation in backfill barrier, RB $=1.0$ (100.0)
Retardation in sediment, $R_S=1.0$ (10.0)
Retardation in fracture, $R_P=1.0$
Retardation in rock matrix, $R_P=1.0$ (10.0)

Diffusion coefficient in backfill barrier,
D_B (m^2/year) $=8\times10^{-3}$
Diffusion coefficient in porous rock matrix, D_P (m^2/year) $=5\times10^{-3}$
Diffusion coefficient in concrete barrier, D_C (m^2/year) $=4\times10^{-3}$
Diffusion coefficient in sediment,
D_S (m^2/year) $=8\times10^{-2}$
Diffusion coefficient in sea water,
D_W (m^2/year) $=5\times10^{-3}$
Groundwater velocity in fracture, v_R (m/year) $=5.0$
Groundwater velocity in y direction in fracture, v'_R (m/year) $=5.0$
Sea water velocity v'_W (m/year) $=1.0$
Sedimentation velocity, V_s (m/year) $=1.0$
Decay constant, λ ($year^{-1}$) $=0.023$
Porosity of rock matrix, $\phi_p=2\times10^{-3}$.

Since these values were selected from various literature as typical values, all numeric values were not examined seriously for their validity. In the figure two cases are plotted ; i.e., when no retardation is considered for all barriers (solid lines) and when assumed retardation coefficient (dashed lines) is applied for each barrier. For the cases where retardation is considered; the backfill barrier, the rock matrix, and the sediment layer, 100, 10, and 10 of retardation coefficients, were used, respectively. For the fracture and the concrete barrier, no retardation was assumed. The figure also shows that the nuclide transfer occurs very fast through the backfill barrier. This is probably due to comparatively higher mass transfer coefficient at the fracture boundary, where nuclide released from the backfill is swept away by passing water in the fracture.

The nuclide concentration in the block of sea water on the upper part of the repository is plotted together in normalized nuclide activity for illustrative purpose (curve 5 in the figure).

Meanwhile, for the evaluation of the summation in Eq.(14), which converges slowly for small fracture width 2b, summation over a finite value of N was

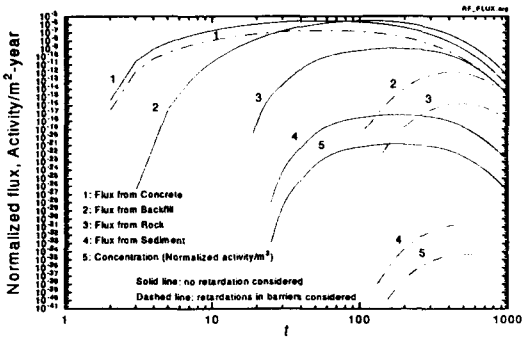

Fig. 5. Nuclide Relase Rates from Various Barriers in Series as a Function of Time. The Curve 5 Represents Nuclide Concentration in sea Water Due to Nuclide Flow from the Sediment Layer.

made until a desired error bound ($1/n^2<\varepsilon$) is attained, as the same way done by Lee et al.[12]

The numerical integral in Eq.(28) was evaluated by using QGAUS of *Numerical Recipe* routine.[18]

6. Summary

A simple nuclide transfer model by utilizing mass transfer coefficient and barrier response function defined for each barrier was proposed, by which the final nuclide relase rate into sea water can be evaluated.

Mass transfer coefficient was determined by making use of the assumption that the nuclide concentration gradient at the interface between adjacent barriers remains constant, which means the steady state condition anticipated long time after repository closure.

When simple and immediate quantification of the nuclide release is necessary in the conservative aspect, this kind of approach may be advantageous. This approach can treat each layered medium from other media in the repository system, making it possible to apply separate solutions in succession to other various media. Although one distinct disadvantage is that there may be no guarantee for concentration continuity while flux continuity can be maintained at the interface by using the exit nuclide flux from the

first medium as the source flux for the next one, this problem could be eliminated by assuming that there is no boundary resistance to mass transfer across the interface.

In order to obtain barrier response function, an analytical expression for nuclide relase rate out of each barrier, in response to a unit impulse into the barrier was multiplied by mass transfer coefficient.

Thus, total time-dependent nuclide release rate from a barrier was obtained by convoluting the response function for the barrier with a previously calculated set of time-varying input of nuclide release rate from the previous barrier.

To simplify the model, for all media except the fractured rock medium it is assumed that groundwater flow carrying a nuclide takes place through the confined area contacted by two media in the perpendicular x direction.

The present approach can be used for a preliminary performance assessment of a repository located in the seabed. The calculation results from the model can be utilized as an input to marine model such as MARINRAD.

References

1. Maidment, D.R., ed., *Handbook of Hydrology*, pp. 6. 31-6. 32, McGraw-Hill, New York (1993)
2. Hung, C.Y., "An Optimum Groundwater Transport Model for Application to the Assessment of Health Effects Due to Land Disposal of Radioactive Wastes," *Nucl. Chem. Waste Man.*, **6**, 41 (1986)
3. LeNeveu, D.M., *Vault Submodel for the Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal: Post-Closure Phase*, AECL-8383 (1986)
4. LeNeveu, D.M., "Response Function of the Convection-dispersion Equations Describing Radionuclide Migration in a Finite Medium," *Ann. Nucl. Energy*, **14**(2), 77 (1987)
5. Davison, C.C. et al., *The Disposal of Canada's Nuclear Fuel Waste: the Geosphere Model for Postclosure Assessment*, AECL-10719 (1994)
6. Johnson, L.H. et al., *The Disposal of Canada's Nuclear Fuel Waste: The Vault Model for Post-Closure Assessment*, AECL-10714 (1994)
7. Hahn, P.S. et al., *A Joint KAERI-SKB Study on the Planning for Radioactive Waste Repository*, Final Report (1990)
8. Neretnieks, I., "Diffusion in the Rock Matrix: An Important Factor in Radionuclide Retardation?," *J. Geophys. Res.*, **85**(B8), 4379 (1980)
9. Tang, D.H. *et al.*, "Contaminant Transport in Fractured Porous Media : Analytical Solution for a Single Fracture," *Water Resour. Res.*, **17**(3), 555 (1981)
10. Crank, J., *The Mathematics of Diffusion*, pp. 12-13, Clarendon (1975)
11. Neretnieks, I., "Stationary Transport of Dissolved Species in the Backfill Surrounding a Waste Canister in Fissured Rock : Some Simple Analytical Solutions," *Nucl. Tech.*, 72, 194 (1986)
12. Lee, H.S. et al., *An Estimation of Nuclide Release Rate near the Canister*, SKB TR 89-38 (1989)
13. Lee, Y.M. et al., "A Numerical Model for Nuclide Migration in the Far-field of the Repository", *J. Korean Nucl. Soc.*, **21**(4), 267 (1989)
14. Fujikawa, Y. and M. Fukui, "Adsorptive Solute Transport in Fractured Rock: Analytical Solutions for Delta-Type Source Condition," *J. Contam. Hydrol.*, **6**, 85 (1990)
15. Maloszewski, P. and A. Zuber, "Mathematical Modeling of Tracer Behavior in Short-Term Experiments in Fissured Rock," *Water Resour. Res.*, **26**(7), 1517 (1990)
16. Faw, R.E. and J.K. Shultis, *Radiological Assessment-Sources and Exposures*, pp. 499-502, Prentice-Hall, New Jersey (1993)
17. *IMSL Library-Problem Solving Software System for Mathematical and Statistical FORTRAN Programming* (1984)
18. Press, W.H. et al., *Numerical Recipes in FORTRAN*, Cambridge Univ (1986)