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Multiple-Silo Performance Assessment Model for the Wolsong LILW Disposal Facility in Korea – PHASE I: Model Development

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Abstract

An integrated model for groundwater flow and radionuclide transport analyses is being developed incorporating six underground silos, an excavated damaged zone (EDZ), and fractured host rock. The model considers each silo as an engineered barrier system (EBS) consisting of a waste zone comprising waste packages and disposal container, a buffer zone, and a concrete lining zone. The EDZ is the disturbed zone adjacent to silos and construction & operation tunnels. The heterogeneity of the fractured rock is represented by a heterogeneous flow field, evaluated from discrete fractures in the fractured host rock. Radionuclide migration through the EBS in silos and the fractured host rock is simulated on the established heterogeneous flow field. The current model enables the optimization of silo design and the quantification of the safety margin in terms of radionuclide release.

Key words : LILW radioactive waste disposal, Performance assessment, Multiple silos, EDZ, Flow and transport

요 약

중저준위 방사성폐기물 처분장의 안전성 평가를 위하여 지하 사일로와 그 주변의 굴착손상영역 (EDZ) 및 단열암반을 고려한 지하수유동해석과 핵종이동해석의 통합모델을 개발하였다. 사일로를 다중방벽개념으로 고려하여 사일로를 구성하는 3개의 특성지역 (waste, buffer, concrete)으로 구분하여 해석하였고, EDZ는 사일로 주변과 건설운영 터널 주변의 손상영역을 고려하였다. 단열암반의 불균일성은 분리단열 (discrete fractures)로 부터 해석된 불균일한 지하수 유속계로 도출하였고, 그 결과를 핵종의 이동경로를 모사하는데 사용하였다. 현 모델은 핵종누출에 따른 사일로 배치의 최적화와 안전성의 정량화를 도출하는데 사용가능하다.

중심단어 : 중저준위방사성폐기물처분, 안정성 평가, 다중사일로, 굴착손상대, 지하수 유동, 핵종이동

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Ⅰ. Introduction

According to the follow-up action program as a licensing condition of the Wolsong LILW (low and intermediate level radioactive waste) Disposal Center (WLDC) [1], a reassessment of the safety margin of a disposal facility is needed by incorporating tunnel excavation data, concrete silo design, and surrounding rock characteristics. With this in mind, a new 2-dimensional multiple-silo model, including a discrete fracture network (DFN), is being developed for the performance assessment of WLDC, focusing on the multiple-silo configuration[2, 3] and integrated analyses for the groundwater flow and the radionuclide transport in fractured rock media. This modeling concept is different from the approach used in the licensing stage insofar as the new model explicitly integrates groundwater flow and radionuclide migration analyses through engineered barrier systems in silos. These analyses also incorporated the heterogeneity of the fractured host rock. The numerical model is currently being developed, and thus this paper presents the conceptual model and theoretical background of the model, with some numerical demonstration.

II. Conceptual Model

The current model consists of sixunderground silos, an excavated damaged zone (EDZ), and fractured host rock in a two-dimensional model space. Figure 1 shows the schematic diagram of the model's concept. Each silo consists of waste, buffer, and concrete lining zones. The EDZ is the disturbed zone adjacent to silos and construction & operation tunnels.

Waste, buffer, and concrete zones comprise the homogeneous isotropic water-conducting medium with different hydraulic and material properties for each zone. Host rock is divided into two regions, a rock matrix region and a fractured region. The rock matrix region does not contain any water-conducting fractures, while the fractured region is considered to be an equivalent heterogeneous anisotropic medium characterized by water-conducting fractures and their hydraulic conductivity tensor [4]. The fractured host rock is represented by a DFN with the same parameters as the rock, i.e. intensity, orientation, size, aperture, and hydraulic conductivity.

1. Host Rock Heterogeneity in DFN

Fracture frequency (or intensity) is one of the fundamental measures representing the degree of fracturing in a rock mass [5]. The fracture frequency (λ [m^{-1}]), defined as the average number of fractures intersected by a unit length of sampling line, is the most commonly used measure of fracture intensity obtained from borehole data. The number of fractures in a finite domain can be determined from the linear frequency (λ), the orientation of the sampling scanline, the mean trace length (μ_l) of the fractures, and the orientation of fractures with respect to the scanline. A relationship between linear frequency, areal frequency (λ_a), and mean fracture size is given for two extreme cases [5, 6], i.e., perfectly parallel fractures ($\lambda=\mu_l\lambda_a$) and fractures of totally random orientation ($\lambda=2\lambda_a\mu_l/\pi$). Fractures showing some variability about a preferred orientation will have a fracture frequency between these two extremes [5]. For perfectly parallel fractures, the probability of fracture intersection is extremely small compared with that for the randomly orientated fractures. Thus, fractures with totally random orientation yield higher fracture connectivity, which can be considered the conservative case. In the current performance assessment model, λ is given as an input, and areal frequency of fractures (λ_a) is conservatively calculated [6] as:

$$\lambda_a = \frac{\pi\lambda}{2\mu_l} \qquad (1)$$

A Fisher distribution, which is the most commonly observed orientation (θ) distribution, is used to represent the probability density of fracture pole orientation [7]. The Fisher constant (κ) represents deviation of the variables. In the current model, up to four different orientation sets can be defined for DFN generation. The equation for a Fisher distribution is:

$$f(\theta)=\frac{\kappa\cdot\sin\theta}{(e^{\kappa}-e^{-\kappa})}e^{\kappa\cdot\cos\theta},0<\theta<\pi \qquad (2)$$

Studies in crystalline rocks have shown that a Power Law distribution often accurately represents fracture sizes [8, 9]. This is because the mechanical process of rock fracturing often results in a fractal or power law distribution [8, 9]. A power law distribution [7-10] is adopted in the current model to represent the distribution of fracture size (or length, l). This ensures a high frequency of large fractures, which are considered to be important in the nuclide transport analysis [7]. A probability density function of fracture length can be written by assuming that distribution of fracture radius is identical to that of fracture length [7], as:

$$f(l)=\frac{(d-1)}{l_{\min}}\left(\frac{l_{\min}}{l}\right)^{d},\ d>1,\ l>l_{\min} \qquad (3)$$

where d is constant and l_{min} is the minimum length of fractures.

In the current model, two types of EDZ are considered, i.e., EDZ surrounding silos (called EDZ-silos) and EDZ by tunnels (called EDZ-tunnels). EDZ-silos is treated as a highly permeable continuum as a conservative assumption. The secondary fractures are assumed to be generated only in EDZ by tunnel constructions.

2. Equivalent Heterogeneous Anisotropic Medium

The permeability (or hydraulic conductivity) of the fractured rock depends on the fracture intensity, connectivity, and hydraulic properties. Approaches for calculation of grid cell effective directional permeability include the tensor approach [4]. In Oda's method [4], the orientations of the fractures are considered as a unit normal vector **n**, and mass moment of inertia of fracture normals distributed over a unit sphere is written [4, 11] as:

$$N=\int_{\Omega}n_i n_j E(n)d\Omega \qquad (4)$$

where $E(\boldsymbol{n})$ is the probability density function that describes the number of fractures whose unit vectors **n** are oriented within a small solid angle $d\Omega$.

For a specific grid cell with known fracture area A_f, and hydraulic conductivities K_f, obtained from the DFN model, an empirical fracture tensor can be calculated by adding individual fractures weighted by their area and hydraulic conductivity [11]:

$$F_{ij}=\frac{1}{V_{cell}}\sum_{f=1}^{N}V_f K_f n_{i,f} n_{j,f} \qquad (5)$$

where V_{cell} and V_f are volume of cell and fractures, respectively. A cell volume contains N fractures, and $n_{i,f}$ and $n_{j,f}$ are the components of a unit normal to the fracture f.

Oda's permeability tensor (K_{ij}) is derived from F_{ij} by assuming that F_{ij} expresses fracture flow as a vector along the fracture's unit normal. Assuming that fractures are impermeable in a direction parallel to their unit normal, F_{ij} must be rotated into the planes of permeability [11] using the equation:

$$K_{ij}=(F_{kk}\delta_{ij}-F_{ij}) \qquad (6)$$

where $F_{kk} = F_{11} + F_{22} + F_{33}$ and δ_{ij} is Dirac delta function.

3. Groundwater Flow Analysis

The domain for groundwater flow is sub-divided into waste, buffer, concrete, EDZ-silos, and fractured zones. A homogeneous isotropic medium is assumed for waste, buffer, concrete, and EDZ-silos. A heterogeneous anisotropic medium is assumed for the fractured region based on primary and secondary fractures.

The governing equation for the steady-state space-dependent hydraulic head $h(x,y)$ is given in two-dimensional Cartesian coordinates for time-independent, incompressible Darcy flow with space-dependent anisotropic hydraulic conductivity $K_x(x,y)$ and $K_y(x,y)$ as:

$$\frac{\partial}{\partial x}\left[K_x(x,y)\frac{\partial h(x,y)}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y(x,y)\frac{\partial h(x,y)}{\partial y}\right]=0 \qquad (7)$$

$$h(x,y)=h_R(x,y)\ \text{on}\ C_1\ \text{boundary} \qquad (8)$$

For the homogeneous isotropic region, hydraulic conductivity is constant for each region, as $K_x(x,y)$ $=K_y(x,y)=K_w$, K_b, K_c, or $K_{EDZ\text{-}S}$ for waste, buffer, concrete, or

EDZ-silos, respectively. For the heterogeneous anisotropic region, $K_x(x,y)$ and $K_y(x,y)$ are obtained for each finite element, considering all primary and/or secondary fractures included in the element. A hydraulic head $h(x,y)$ is prescribed at the outer boundaries (i.e., C_l boundary) of the model space, based on the hydraulic head (h_R) obtained from the regional scale flow model.

The governing equation (7) is solved numerically, using the finite element method for the given boundary condition (8) [6]. Triangular finite-elements are used to discretize the domain. Hydraulic head at the internal nodes and Darcy velocity at the center of weight for each of the elements are obtained numerically. As a result, a heterogeneous flow field is established over the entire model, excluding the rock matrix region, that is, the unfractured zone in the host rock.

4. Radionuclide Transport Analysis

Radionuclide migration is simulated based on the established groundwater flow field. The transport equation for advection, molecular diffusion, sorption, and radioactive decay in a medium j (i.e., waste, buffer, concrete, EDZ, or host rock) for a single radionuclide is given as [12]:

$$R_j \frac{\partial C_j(\mathbf{X},t)}{\partial t} = D_{p,j} \nabla \cdot (\nabla C_j(\mathbf{X},t)) - \nabla \cdot (\mathbf{v}(\mathbf{X}) C_j(\mathbf{X},t)) - R_j \lambda C_j(\mathbf{X},t),\ t > 0, \quad \cdots\cdots\cdots (9)$$

where

$$R_j = 1 + \frac{(1-\varepsilon_j)\rho_{s,j}}{\varepsilon_j} K_{d,j} \quad \cdots\cdots\cdots (10)$$

X is the position vector of the radionuclide at time t. C [mol/m^3] is the concentration of the radionuclide in pore space. Subscript j represents the region which contains the radionuclide at position **X**. R [·] is the retardation factor for the radionuclide. The variable **v(X)** [m/yr] represents the pore velocity vector at position **X**, obtained from water flow analysis. The symbol ε [·] is the medium porosity, while ρ_s [kg/m^3] is the density of the solid materials. K_d [m^3/kg] is the distribution coefficient of the radionuclide. λ[1/yr] is a radioactive decay constant. D_p [m^2/yr] is the pore diffusion coefficient for the radionuclide and is assumed to be constant for each region.

The transport equation is simulated using the random-walk particle tracking method taking into account the local mass conservation (LMC) error [13, 14]. The random-walk method has been developed by using analogy between the *Ito-Fokker-Planck* equation and the transient advection-dispersion equation, such that the *Ito-Fokker-Planck* equation with the random-walk equation is equivalent to the transient transport equation [6]. The random-walk method was developed for the instantaneous input source condition (11) in the waste zone for each silo and absorbing boundary condition at C_l boundary (12). The equation is:

$$C(\mathrm{X}, t=0) = (M_0/\varepsilon_w)\delta(\mathrm{X}),\ \mathrm{X} \in \text{Waste zone}, \quad \cdots\cdots\cdots (11)$$

where M_0 is the total mass of nuclide contained in the waste (source) zone, ε_w is the porosity of the waste zone, δ is the Dirac delta function:

$$C(\mathrm{X}, t) = 0,\ t \ge 0, \text{ on } C_l \text{ boundary} \quad \cdots\cdots\cdots (12)$$

III. Numerical Modeling Demonstration

A numerical model, SIMSILO-2D (**S**imulation program **I**ntegrating local fracture flow with radionuclide transport for underground **M**ultiple-**SILO** in **2-D**imensional domain), is currently being developed. Thus, this section demonstrates modeling features for demonstration purposes, with hypothetical input data without justification

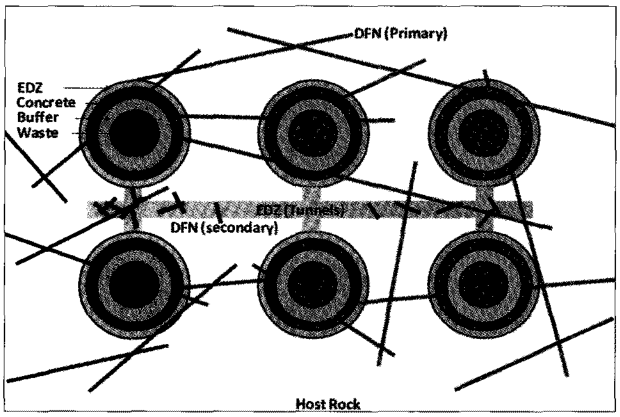

Fig. 1. Model Conceptualization of Multiple-Silo Model.

(see Figure 2). SIMSILO-2D is used for all numerical demonstration given in this paper.

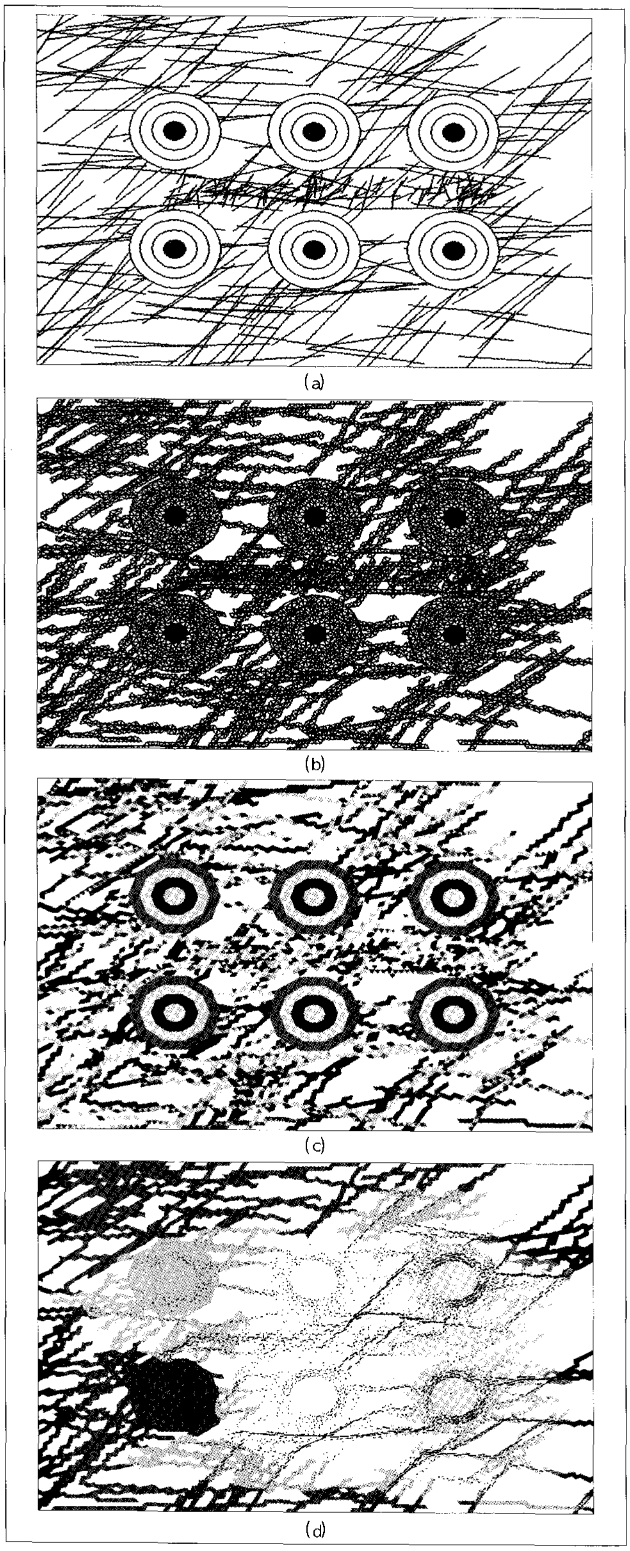

Fig. 2. Demonstration of Numerical Modeling (a) Primary & Secondary DFN, (b) Finite elements on conductive DFN, (c) $K_{xx}(x,y)$, (d) Hydraulic head contour with velocity vector (arrows).

Figure 2(a) shows a (primary & secondary) DFN generation with assumed EBS design thicknesses. Figure2(b) shows finite elements generated on a conductive DFN and connected Silos with conductive DFNs. Figure2(c) shows a hydraulic conductivity tensor (i.e., $K_{xx}(x,y)$) obtained from the DFN in Figure 2(a) for each element shown in Figure 2(b). Note that homogeneous isotropic hydraulic conductivities are prescribed for each zone (i.e., waste, buffer, concrete, EBS-silos). Figure 2(d) shows the resulting hydraulic head distribution (contour) and Darcy velocity vectors (arrows) from the flow analysis. As a boundary condition, a high constant head is prescribed at three outer boundaries (left, top, and bottom) and a low constant head is prescribed at the remaining outer boundary (right).

Figure 3 shows the tracks of radionuclide migration from the waste zone in each silo to the outer boundaries of the model space through buffer, concrete, EBS-silos, and host rock (fractured & rock matrix regions). As a result of radionuclide transport analysis, travel time and radionuclide mass release rate are also obtained from the model.

IV. Discussion and Limitations

In the current 2-D model, one should specify EDZ (tunnels) with the hydraulic and material properties from the most disturbed region (or worst case) in and around the tunnels, i.e., i) the backfill/buffer materials within the tunnels, and ii) disturbed rock properties surrounding the

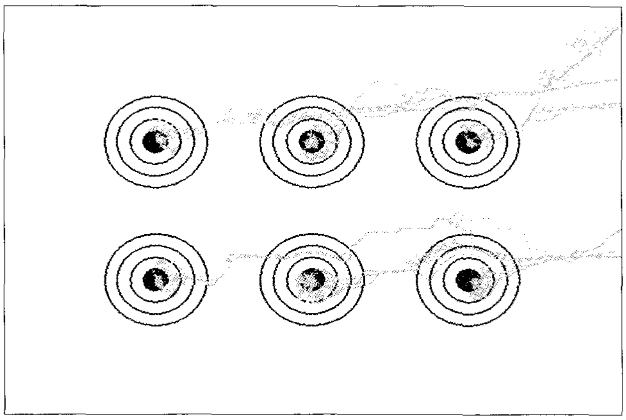

Fig. 3. Tracks of radionuclide migration.

tunnels. For the case where the tunnels are backfilled with very low permeability materials (i.e., bentonite) but the host rock surrounding the tunnels is highly disturbed due to the operation and emplacement, one can prescribe the disturbed rock properties (e.g., higher conductivity) surrounding the tunnel for EDZ (tunnels) for performance assessment modeling. For such a case, water can flow through the high permeable zone (i.e., EDZ) around the tunnels, but will not flow through the inside of the tunnels. Due to the intrinsic limitations of 2-D modelling, however, flow paths (vectors), especially inside of the EDZ (tunnels), should be interpreted appropriately with given conceptual model and input parameters.

In the current SIMSILO-2D model, time-independent incompressible Darcy flow for the heterogeneous anisotropic fractured medium is used for the flow analysis. For radionuclide transport, an instantaneous input source condition is adopted. A radioactive decay process is incorporated for single member decay without precursors of the decay chain.

Additional detailed transport processes for various nuclides, such as congruent release and solubility limit release, involved in nuclide release need to be incorporated in the future for the performance assessment of the LILW disposal facility. Source conditions (i.e., congruent release and solubility limit release) can be incorporated into the current model because the instantaneous input source condition is a basic source condition. Note that an analytical solution of the transport equation for the constant concentration source condition, which is closely related to solubility limit release, can be obtained by integrating the solution obtained for the instantaneous source condition [15].

V. Conclusions

An integrated model for groundwater flow and radionuclide transport analyses is being developed incorporating six underground silos, excavated damaged zone (EDZ) adjacent to silos and tunnels, and fractured host rock zone. In the current two-dimensional numerical model, primary and/or secondary DFNs can be simulated explicitly using site-characterized fracture parameters (i.e., intensity, orientation, size, aperture, and hydraulic conductivity) as input. Up to four fracture orientation sets can be simulated. For flow analysis, all EBS regions (waste, buffer, concrete, and EBS-silos) in the silos and connected DFN are taken into account, and thus Darcy velocity vectors are obtained for all water flowing regions. For radionuclide transport analysis, nuclides migrate based on established water velocity, medium porosity, and various transport properties (diffusivity, retardation by sorption) for a given nuclide in a specific transport medium. The dominant transport mechanism is determined from the hydraulic and transport properties for each region (waste, buffer, concrete, EBS-silos, fractured zone, or rock matrix). In the current model, the rock matrix region (or unfractured host rock) is treated as the waste-stagnant region, and thus molecular diffusion is the dominant transport mechanism.

The current integrated and robust numerical model enables, in terms of toxicity/hazard caused by radionuclide release, to i) optimize the design of silos (location, thickness of EBS, material properties of EBS) for a specific fractured rock site, and ii) quantify the safety margin of performance results obtained from simplified models (e.g., 1-D transport, single silo, homogeneous silo, host rock without DFN, no explicit rock matrix diffusion, etc).

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References

[1] J.-W, Park, J.-H. Yoon, and C.-L. Kim, "A Safety Assessment for the Wolsong LILW Disposal Center: As a part of safety case for the first stage disposal", J. Kor. Rad. Waste Soc. 6(4), pp.329-346 (2008).

[2] J.-W. Park, S.-W. Hong, and D.-H. Lim, "Conceptual Model for Local Two-Dimensional Radionuclide Transport with Discrete Fracture Network in Wolsong LILW Disposal Center", 한국방사성폐기물학회 춘계학술대회 논문요약집 8(1), pp.155-156 (2010).

[3] D.-H. Lim, M. Uchida, K. Hatanaka, and A. Sawada, "Modeling of Radionuclide Migration through Fractured Rock in a HLW repository with Multiple Canisters," Mat. Res. Soc. Symp. Proc. vol. 1107, pp.567-575 (2008).

[4] M. Oda, "Permeability Tensor for Discontinuous Rock Masses," Géotechnique, 35(4), pp. 483-495 (1985).

[5] S. D. Priest, Discontinuity Analysis for Rock Engineering, Chapman and Hall, London (1993)

[6] D.-H. Lim, Mass Transport Analysis in the Near Field of Geologic Repository, Ph.D. Thesis, University of California, Berkeley (2002).

[7] Japan Nuclear Cycle Development Institute (JNC), Second Progress Report on R&D for the Geologic Disposal of HLW in Japan, JNC TN 1410 2000, 001~005 (2000).

[8] A. Fox, P. R. La Pointe, J. Hermanson, and J. Öhman, Statistical geological discrete fracture network model: Forsmark modelling stage 2.2, Swedish Nuclear Fuel and Waste Management Co., SKB R-07-46 (2007).

[9] P. R. La Pointe, A. Fox, J. Hermanson, and J. Öhman, Geological discrete fracture network model for the Laxemar site: Site Descriptive Modelling SDM-Site Laxemar, Swedish Nuclear Fuel and Waste Management Co., SKB R-08-55 (2008).

[10] P. R. La Pointe, "Derivation of Parent Fracture Population Statistics from Trace Length Measurements for Fractal Fracture Populations," Int. J. Rock Mech. Min. Sci., 39, pp.381-388 (2002).

[11] W.S. Dershowitz, P. R. La Pointe, T. Eiben, and L. Wei, "Integration of Discrete Feature Network Methods With Conventional Simulator Approaches, "SPE Reservoir Eval. & Eng., 3(2) (2000).

[12] D.-H. Lim, "Modeling of Groundwater Flow and Radionuclide Transport in a High-Level Radioactive Waste Repository with Multiple Canisters," Mat. Res. Soc. Symp. Proc. vol. 932, pp. 243-250 (2006).

[13] D.-H. Lim, "Comment on Diffusion Processes in Composite Porous Media and Their Numerical Integration by Random Walks: Generalized Stochastic Differential Equations with Discontinuous Coefficients by E. M. LaBolle, J. Quastel, G. E. Fogg, and J. Gravner," Water Resources Research, 42, W02601, AGU (2006).

[14] D.-H. Lim, "Numerical Study of Nuclide Migration in a Heterogeneous Flow Field of a High-Level Radioactive Waste Repository with Multiple Canisters," Nuclear Technology, 156, pp 222-245 (2006).

[15] J. Crank, The Mathematics of Diffusion, Oxford University Press, New York (1975)