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Analytical modeling for colloid-facilitated transport of N-member radionuclides chains in the fractured rock

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Abstract A previous analytical model for N-member radionuclide decay chains has been extended to include the effect of radionuclide sorption with groundwater colloids. Published distribution coefficients were employed in the nuclide decay chain to illustrate the present model. The colloid concentration was assumed constant in time and space owing to equilibrium between colloid generation and sedimentation by chemical and/or physical perturbations. Furthermore, the diffusion of colloids into the rock matrix was ignored because the diameter of colloid is relatively large and colloids and fracture surfaces are like-charged. The results indicated that colloids could facilitate the transport of radionuclides and the large adsorbability of nuclides with colloids enlarged the effect of acceleration by colloids. The influence of colloids on the radionuclide transport was expected to be crucial to the actinides with large adsorbability; however, the present results revealed that the low-adsorbing nuclides whose parent nuclides have large capability of sorption could be also facilitated significantly by colloids indirectly. Therefore, the role of colloids played in the transport of the radionuclides decay chain should be assessed carefully in the radioactive waste disposal. The analytical method presented herein is helpful to verify/validate further complex far-field models.

Key words Analytical model, Decay chains, Colloids

CLC numbers X771, O648.1

1 Introduction

Colloids are tiny particles in the size range of 1 nm to 1 μm which can remain suspended in water. Groundwater often contains significant populations of natural colloids which can interact with pollutants and influence their transport. Natural colloids as well as waste- and repository-derived colloids in radioactive waste disposal may influence nuclide transportation significantly. Laboratory experiments [1] in terms of colloid-facilitated contaminant transport have confirmed that colloids can enhance the transport of cationic and anionic metals through fractured media. Moreover, the unexpectedly rapid transport of plutonium and americium at experimental sites may be also attributed to colloid-facilitated transport [2].

In many countries, the processes of colloid formation and colloid transport are included in the features, events, and processes (FEPs) list of their Performance Assessment (PA) programs for high-level waste/spent nuclear fuel disposal. Although some PAs have deferred the consideration of colloid-nuclide transport until detailed evaluations have been performed, other PAs, for instance, H-12 of Japan [3] and the Yucca Mountain Project of USA [4], have considered the effects of the presence of colloids. The experimental results [3] indicated that the engineered barrier designed to have the practical density bentonite more than 800 kg/m^3 had enough property to eliminate the colloid transport through the engineered barrier. However, failure of the engineered barriers and bentonite buffer to filter colloids should be considered as an alternative scenario [5], especially according to the colloid and radionuclide retardation experiments [6,7]

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recently carried out in situ at Grimsel test site.

In the past decades, the single radionuclide transport facilitated by colloids has attracted lots of researcher's attention [8-10]. When a radionuclide is adsorbed onto the colloidal surface, it cannot diffuse into the rock matrix and be adsorbed in the matrix rock, since the sizes of colloids are conservatively assumed to be larger than those of the rock matrix pores. Colloids may move along the groundwater, therefore, radionuclides attached to these colloidal surfaces will be transported further such that the concentration in the fracture will be higher than that in the absence of colloids. Those studies did not address the significance of the colloids in the chain decay, however, the in-growth and decay of actinides are crucial for assessing their transport ability owing to the long half-life times and radiotoxicity of actinides. Sun and Buscheck[11] reported an analytical model for N-member decay chains in a single fracture in the absence of colloids. We previously developed a semi-analytical model to access the co-transport of a two-member decay chain radionuclides and groundwater colloids [12]. Currently, the role of colloids in facilitating the transport of radionuclides is not fully understood to effectively model radionuclide transport. However, there is a growing body of evidence that suggested low-soluble and strong-absorbing radionuclides, such as actinides, could be accelerated by colloids [2,6].

This present study extends previous studies to investigate the effects of the presence of colloids on actinides decay chains transport. Parent and daughter radionuclides could perform completely different retardation properties which are explicitly represented within this study. Thus, the present model is useful to verify complex numerical models for multi-species transport with different retardation factors and to understand the significances of colloids on the retardation properties of radionuclide decay chains.

2 Conceptual model

The "far-field" (geosphere) is a physical region representing the natural barrier in the concept of geological disposal of nuclear waste. In the concept of deep geological disposal of nuclear waste, the natural barrier is the geological material hosting the repository. In determining the medium type of the far field, any potential pathways must be identified. Usually tight formations are considered ideal candidates for hosting repositories. Due to various reasons such as stresses, defects, and heterogeneities, geological materials are seldom perfect. The most common defects are fractures. Most rock formations considered in geological disposal of nuclear waste contain fractures. Because fractures have greater void spaces than rock matrix, they are considered, in PA modeling, as the fast pathway of the geological medium. Radionuclide transport in fractured rock is characterized by advection and diffusion/dispersion attenuated by sorption and matrix diffusion. Apparently, these transport process must be considered in the PA modeling.

Approaches to modeling flow and transport in fracture systems are not unique. However, it is known that knowledge of various processes taking place in a single fracture is fundamental to improve our understanding radionuclide transport in fractured subsurface formations[13]. Therefore, the case of a thin rigid fracture slab in a saturated porous rock is considered herein. Several assumptions are made regarding the properties of the groundwater colloids and the system[8-14]:

(1) The fracture is open and hence has unit porosity.

(2) In the fracture, groundwater flows in one direction. Radionuclides in the aqueous phase, both dissolved and sorbed on the mobile colloids, transport advectively and dispersed along the fracture.

(3) Transverse dispersion is efficient to ensure mixing of radionuclide concentrations across the fracture slab in the direction perpendicular to flow.

(4) In the matrix, groundwater is at rest and radionuclide diffusion only occurs in the direction perpendicular to the fracture.

(5) Considering radioactive in-growth and decay.

(6) Colloidal particulates are mobile in the fracture. However, they cannot diffuse into the rock matrix due to their large size.

(7) The colloidal concentration is constant and uniform along the fracture.

(8) Parameters (porosity, groundwater/colloid velocity, sorption coefficients, diffusion and dispersion coefficients, etc.) are assumed to be constant and uniform.

3 Mathematical model

A single fracture with a half width b situated in a saturated rock with a constant porosity is considered in the present study. Due to the very slow flow of hydraulic conductivity in a saturated rock matrix, water flow is postulated to occur only in the fracture. However, transport of the radionuclides to the interior of the rock occurs via molecular diffusion. Relating to the properties of the system, the following assumptions have been made:

(1) The aperture of the fracture is much smaller than its length.

(2) Complete mixing is ensured due to transverse diffusion and dispersion across the fracture, and concentration gradient does not occur across the width of the fracture.

(3) Water flow in the fracture is assumed to be laminar.

(4) Groundwater with constant velocity flows along the fracture.

(5) Transport along the fracture is much faster than what occurs in the porous matrix.

(6) Radionuclide transport within the porous matrix is primarily due to molecular diffusion and occurs perpendicularly to the fracture's axis which is z-direction.

Accordingly, the equation describing the i-th decay chain radionuclide transport with colloids in the fracture is[12,15,16]:

$$R^*_{\mathrm{f},i}\frac{\partial C_{\mathrm{f},i}}{\partial t}+v^*_{\mathrm{f}}\frac{\partial C_{\mathrm{f},i}}{\partial x}-D^*_{\mathrm{f}}\frac{\partial^2 C_{\mathrm{f},i}}{\partial x^2}-a_{\mathrm{f}}\theta_{\mathrm{m}}D_{\mathrm{m}}\frac{\partial C_{\mathrm{m},i}}{\partial z}\bigg|_{z=b}$$
$$=\lambda_{i-1}R^*_{\mathrm{f},i\text{-}1}C_{\mathrm{f},i-1}-\lambda_i R^*_{\mathrm{f},i}C_{\mathrm{f},i}$$
$$x\geqq 0,\ b\geqq z>0,\ t\geqq 0 \qquad (1)$$

where,

$$R^*_{\mathrm{f}}=1+Kd_{\mathrm{m}}\rho_{\mathrm{m}}La_{\mathrm{f}}+Kd_{\mathrm{c}}C_{\mathrm{C0}},$$

$$v^*_{\mathrm{f}}=v_{\mathrm{f}}+v_{\mathrm{c}}Kd_{\mathrm{c}}C_{\mathrm{C0}},$$

$$D^*_{\mathrm{f}}=D_{\mathrm{f}}+D_{\mathrm{c}}Kd_{\mathrm{c}}C_{\mathrm{C0}}.$$

Similarly, the transport equation for the i-th radionuclide in the matrix is:

$$R_{\mathrm{m},i}\frac{\partial C_{\mathrm{m},i}}{\partial t}-D_{\mathrm{m}}\frac{\partial^2 C_{\mathrm{m},i}}{\partial z^2}=\lambda_{i-1}R_{\mathrm{m},i-1}C_{\mathrm{m},i-1}-\lambda_i R_{\mathrm{m},i}C_{\mathrm{m},i}$$
$$x\geqq 0,\ z\geqq b,\ t\geqq 0 \qquad (2)$$

Symbols appearing in the above equations are defined as follows:

C is the aqueous concentration (kg/m^3),

$v_{\mathrm{f/c}}$ is the groundwater/colloid velocity in the fracture (m/a),

$D_{\mathrm{f/c}}$ is the longitudinal dispersion coefficient of radionuclide/colloid in the fracture (m^2/a),

θ_{m} is the rock matrix porosity,

D_{m} is the diffusion coefficient of radionuclide in the rock matrix pores (m^2/a),

λ is decay constant (1/a),

$Kd_{\mathrm{m/c}}$ is sorption (distribution) coefficient for radionuclide on rock/colloid (m^3/kg),

ρ_{m} is bulk density of the rock (kg/m^3),

R_{m} is the matrix retardation coefficient defined as:

$$R_{\mathrm{m}}=1+\frac{Kd_{\mathrm{m}}\rho_{\mathrm{m}}}{\theta_{\mathrm{m}}},$$

L is sorption length for radionuclide on the fracture surface (m),

b is the half of the fracture aperture (m),

a_{f} is specific flow-wetted area of fracture per unit flow volume (m^{-1}), for smooth fracture surface: $a_{\mathrm{f}}=1/b$,

C_{C0} is the colloidal concentration in the fracture (kg/m^3).

Subscripts "i" and "i-1" refer to the i-th and (i-1)-th radionuclides, respectively, and subscripts "f" and "m" refer to the fracture and rock matrix, respectively.

As for the case of the single radionuclide transport in the absence of colloids, Eq.(1) could be reduced to the form similar to that used in the literature[14] for modeling advective/dispersive radionuclide transport in a 1-D fracture. Initial and boundary conditions for the transport equations, Eq.(1) coupled with Eq.(2) are given as:

$$C_{\mathrm{f},i}\left(x=0,t\right)=C_{0,i}\delta\left(0\right) \qquad (3a)$$

$$C_{\mathrm{f},i}\left(x=\infty,t\right)=0 \qquad (3b)$$

$$C_{\mathrm{f},i}\left(x,t=0\right)=0 \qquad (3c)$$

$$C_{\mathrm{m},i}\left(x,z=b,t\right)=C_{\mathrm{f},i}\left(x,t\right) \tag{3d}$$

$$C_{\mathrm{m},i}\left(x,z=\infty,t\right)=0 \tag{3e}$$

$$C_{\mathrm{m},i}\left(x,z\geq b,t=0\right)=0 \tag{3f}$$

where C_0 is the initial concentration at the inlet of the fracture, $\delta(0)$ is the delta function, hence, it represents the pulse injection case at t=0. Any other injection model, e.g., time series outputs from near-field modeling, can be analyzed using the principle of superposition.

For the single-radionuclide modeling, the analytical solution of the transport equation, Eq.(1), subject to the conditions of Eqs.(3a-f) has been obtained and the total mobile concentration of radionuclide, C_{T}, in the fracture can be given as[14-16]:

$$C_{\mathrm{T}}=\frac{C_{\mathrm{T0}}}{\pi}\int_{\frac{\eta}{2\sqrt{t}}}^{\infty}\frac{Y}{T^{3/2}}\exp\left(\alpha x-\xi^2-\frac{\alpha^2x^2}{4\xi^2}-\lambda t-\frac{Y^2}{4T}\right)\mathrm{d}\xi \tag{4}$$

where $C_{\mathrm{T0}}=C_0\left(1+Kd_{\mathrm{c}}C_{\mathrm{C0}}\right)$, $Y=\dfrac{R_{\mathrm{f}}^{*}x^2}{4AD_{\mathrm{f}}^{*}\xi^2}$,

$A=\dfrac{bR_{\mathrm{f}}^{*}}{\theta\left(D_{\mathrm{m}}R_{\mathrm{m}}\right)^{1/2}}$, $T=t-YA$, $\alpha=\dfrac{v_{\mathrm{f}}^{*}}{2D_{\mathrm{f}}^{*}}$,

$\eta=\sqrt{\dfrac{R_{\mathrm{f}}^{*}}{D_{\mathrm{f}}^{*}}}x$, and ξ is the integration parameter.

Sun and Buscheck [11] employed a transformed function to decouple the "in-growth" and "decay" terms from Eqs.(1) and (2). The transport system of each radionuclide became independent with an identical mathematical format in the transformed domain. The transformed function is defined as:

$$C_{\mathrm{T},i}^{*}=C_{\mathrm{T},i}+\sum_{j=1}^{i-1}\left[\prod_{n=j}^{i-1}\frac{K_n\lambda_n}{\lambda_n-\lambda_i}\right]C_{\mathrm{T},j} \tag{5}$$

where $C_{\mathrm{T},i}^{*}$ is the analytical solution, with the form of Eq.(4), of the "i-th" radionuclide in the transformed domain and $K_n=\dfrac{R_{\mathrm{f},n-1}^{*}}{R_{\mathrm{f},n}^{*}}$. Therefore, the analytical solution of the "i-th" total mobile concentration of radionuclide in the presence of colloids could be expressed as:

$$C_{\mathrm{T},i}=C_{\mathrm{T},i}^{*}-\sum_{j=1}^{i-1}\left[\prod_{n=j}^{i-1}\frac{K_n\lambda_n}{\lambda_n-\lambda_i}\right]C_{\mathrm{T},j} \tag{6}$$

4 Numerical illustrations

The analytical solution of Eq.(4) can be integrated by Gauss-Legendre quadrature. Numerical demonstrations will be conducted by employing the parameters listed in Table 1. The colloid-facilitated transport of radionuclides within fractured rock media as well as the size effect of colloids (hydrodynamic chromatography) have been investigated in our previous work[10]. However, the main goal of this study is to focus the effects of colloids on actinides decay chains transport in the fractured media. Therefore, colloidal velocity is assumed equal to groundwater velocity and the value of colloidal dispersion coefficient is quoted from Grindrod et al.[17]. The colloidal concentration in groundwater could range from 10^{-4} (experimental data [18]) to 10^{-1} (assumed value [8]) kg/m^3. Our previous study[12] illustrated that the effect of the presence of colloids becomes significant when the colloidal concentration is greater than 10^{-4} kg/m^3. Thus, the colloidal concentration used in the present study is assumed as 10^{-1} kg/m^3, for a conservative point of view. However, the colloids are assumed as non-reactive and their composition is not included in our present modeling for simplification. Table 2 summarized the sorption coefficients of several elements used in different PA programs. The sorption coefficients of H-12, Kristallin-I and SITE-94 are basically the same order of magnitude; hence, the coefficients of H-12 are adopted for numerical illustrations herein. The sorption coefficients of H-12 and half-life of radionuclides are listed in Table 3.

First of all, the results obtained by our analytical model was compared with those solved by CRYSTAL, which is a numerical code for far-field radionuclide transport used in SKI's SITE-94 program[24]. CRYSTAL solves one-dimensional radionuclide transport through fractured media in the absence of colloids by implementing the numerical inversion of Laplace

Table 1 Transport parameters[8,10,12,17,18] used in the present work

Parameters	Value
Transport length /m	100
Sorption length, L /m	0.05
Fracture aperture, $2b$ /m	5×10^{-3}
Bulk density of the rock, ρ_m /kg•m^{-3}	2700
Rock matrix porosity, θ_m	0.02
Groundwater velocity in the fracture, v_f /m•a^{-1}	40
Longitudinal dispersion coefficient of nuclide, D_f /m^2•a^{-1}	50
Diffusion coefficient of nuclide in the rock matrix pores, D_m /m^2•a^{-1}	7.88×10^{-4}
Colloidal velocity in the fracture, v_c /m•a^{-1}	40
Longitudinal dispersion coefficient of colloid, D_c /m^2•a^{-1}	140
Colloidal concentration, C_{C0} /kg•m^{-3}	0.1
Initial concentration of the ith nuclide, $N_{0,i}$ /kg•m^{-3}	1

Table 2 Sorption coefficients Kd_m (m^3/kg) of several elements for different PA programs

PA program	U	Th	Am	Np	Ra
H-12[19]	1	1	5	1	0.5
Kristallin-I[20]	1	1	5	1	0.5
SITE-94[21]	5	1	5	1	0.5
TILA-99[22]	0.1	0.2	0.04	0.2	0.2
SR-97[23]	5	5	3	5	0.02

Table 3 Sorption coefficients and half-life of radionuclides (H-12)

Nuclide	Kd_m /m^3•kg^{-1}	Half-life /a
^{241}Am	5	4.33×10^2
^{237}Np	1	2.14×10^6
^{233}U	1	1.59×10^5
^{229}Th	1	7.34×10^3
^{238}U	1	4.47×10^9
^{234}U	1	2.45×10^5
^{230}Th	1	7.71×10^4
^{226}Ra	0.5	1.60×10^3

transform. Fig.1 shows the results obtained by the analytical solution and the numerical results by CRYSTAL for Neptunium decay chain: ^{241}Am-^{237}Np-^{233}U-^{229}Th. The retardation factors for sorption on fracture surface are all set to unity for all radionuclides in this case[25]. The analytical breakthrough curves at 100 m for the four radionuclides are almost identical with those obtained by CRYSTAL, as shown in Fig.1. The analytical solutions not only agree well with the numerical results, but also eliminate the phenomenon of oscillation, which is the inherent drawback while using numerical inversion of Laplace transform.

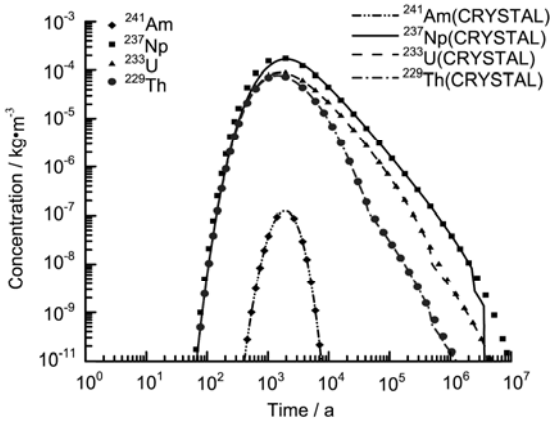

Fig.1 The breakthrough curves of four nuclides in the Neptunium decay chain at the distance of 100 m away from the radioactive source in the absence of colloids, obtained analytically by the present model and numerically by CRYSTAL codes.

Fig.2 depicts the breakthrough curves for the four nuclides in the Neptunium decay chain based on the published distribution coefficients for H-12[19], when the concentration of colloids is 0.1 kg/m^3. The distribution coefficients for nuclides with colloids are assumed as the same with those with the matrix rock in this case. The transport of radionuclides within the fracture is slightly enhanced by colloids. Furthermore, the concentration of the nuclide ^{241}Am has not been seen in this figure because of the relatively short half-life and its strong retardation effect of the rock, which delays the release of ^{241}Am greatly. However,

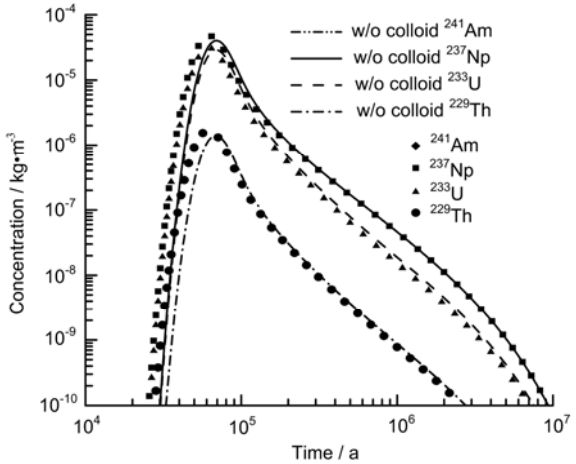

Fig.2 The breakthrough curves of four nuclides in the Neptunium decay chain at the distance of 100 m away from the radioactive source with/without colloids (the colloidal concentration is 0.1 kg/m^3; the distribution coefficient of nuclides with colloids (Kd_c) is assumed equal to that of matrix rock (Kd_m)).

the distribution coefficients for radionuclides with colloids (Kd_c) might be quite different than those with the matrix rock (Kd_m) due to the discrepancy in sorption surface area and/or composition. The nuclide-colloid sorption coefficients are then assumed to be an order of magnitude greater than the nuclide-rock sorption coefficients[1] to elucidate the effect of adsorbability of nuclides with colloids in Fig.3. As shown in Fig.3, it indicates that radionuclides transported in the fracture are greatly enhanced and accelerated by the presence of colloids. The peak concentrations of radionuclides when the colloids exist in the system are approximately one order of magnitude larger than those without colloids. The results herein show clearly that the transport of radionuclides in the fracture is facilitated by the large sorption of nuclides with colloids. The large adsorbability of nuclides with colloids, which provide an alternative mobile carrier for nuclides, implies the reinforcement of mobility of radionuclides. In other words, increasing the sorption coefficients of radionuclides with colloids will increase the capability of colloids to adsorb radionuclides and enhance the effects of acceleration by colloids. As illustrating in Table 2, the sorption coefficients of TILA-99[22] are extraordinarily smaller than other data. Fig.4 illustrates the breakthrough curves with and without colloids for the four nuclides in the Neptunium decay chain based on the published distribution coefficients for TILA-99 for both Kd_c=Kd_m and Kd_c=10×Kd_m. This figure indicates that the influence

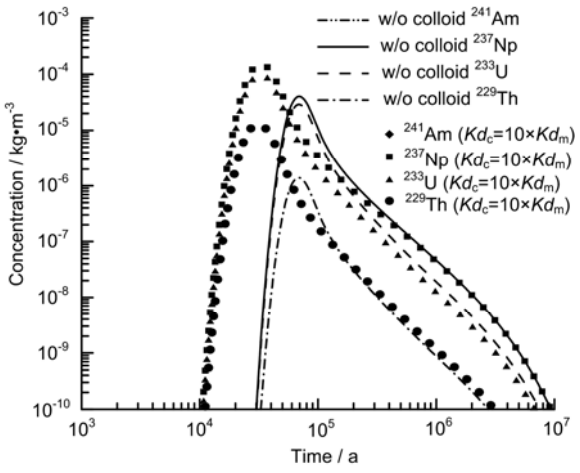

Fig.3 The breakthrough curves of four nuclides in the Neptunium decay chain at the distance of 100 m away from the radioactive source with/without colloids (the colloidal concentration is 0.1 kg/m^3 and Kd_c=10×Kd_m).

of colloids on the transport of radionuclides in the fractured media is insignificant because of their low adsorbability, even when the nuclide-colloid sorption coefficients are assumed to be an order of magnitude greater than the nuclide-rock sorption coefficients; there is only slightly enhancement on the transport of radionuclides.

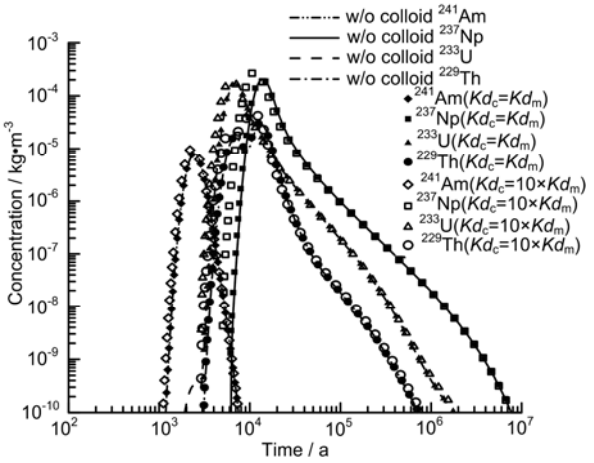

Fig.4 The breakthrough curves of four nuclides in the Neptunium decay chain at the distance of 100 m away from the radioactive source with/without colloids (the colloidal concentration is 0.1 kg/m^3) based on the parameters of TILA-99[22].

To further investigate the effect of colloids for the different decay chain, the breakthrough curves for the four nuclides in the Uranium decay chain based on the published distribution coefficients for H-12 [19] are plotted in Fig.5, for Kd_c is set to be equal to Kd_m and Kd_c is ten-fold of Kd_m. Similar to Fig.2, the transport of radionuclides in the Uranium decay chain is also slightly enhanced due to the existence of colloids when Kd_c is equal to Kd_m. The enhancement becomes significant while increasing the nuclide- colloid sorption. Moreover, Fig.6 shows the breakthrough curves for the four nuclides in the Uranium decay chain based on the published distribution coefficients for SR-97[23] to investigate the effect of colloids on the transport of radionuclides in the Uranium decay chain. The breakthrough curves of ^{238}U, ^{234}U and ^{230}Th in the right hand side of Fig.6 are enhanced and accelerated by mobile colloids because of the large sorption capability. There are two breakthrough curves of ^{226}Ra in the Uranium decay chain: one is contributed by ^{226}Ra itself; the other is imputed by the parent nuclide of ^{230}Th. The breakthrough curve of ^{226}Ra in the left of the figure, which is contributed by ^{226}Ra itself, shows that the

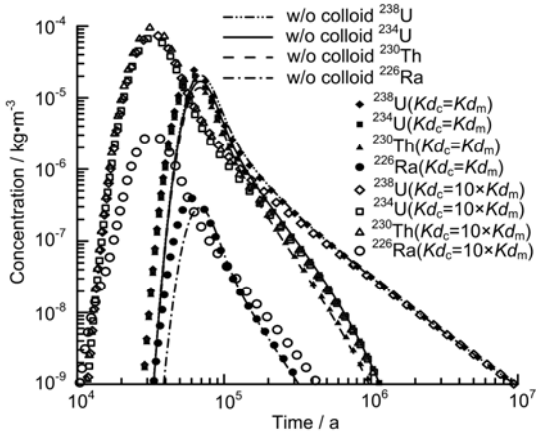

Fig.5 The breakthrough curves of four nuclides in the Uranium decay chain at the distance of 100 m away from the radioactive source with/without colloids (the colloidal concentration is 0.1 kg/m^3).

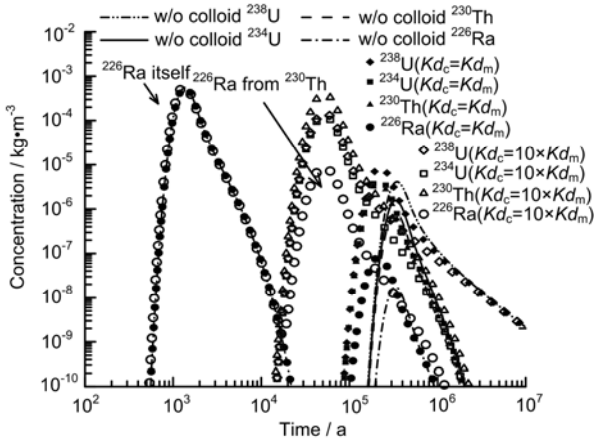

Fig.6 The breakthrough curves of four nuclides in the Uranium decay chain at the distance of 100 m away from the radioactive source with/without colloids (the colloidal concentration is 0.1 kg/m^3) based on the parameters of SR-97[23].

transport of ^{226}Ra is not facilitated by the colloids because of its low adsorbability (0.02 m^3/kg in Table 2); even Kd_c is ten times the value of Kd_m. However, another breakthrough curve of ^{226}Ra decayed from the parent nuclide of ^{230}Th in the right of the figure is significantly facilitated by colloids in the fractured media. The transport of ^{230}Th is enhanced by colloids; therefore, this enhancement facilitates the transport of ^{226}Ra indirectly. When Kd_c is ten times the value of Kd_m, the effect of colloids on the transport becomes stronger. The nuclide of ^{226}Ra with low adsorbability is accelerated unexpectedly because of the sorption of its parent nuclide of ^{230}Th on colloids. The ^{230}Th nuclide is kidnapped by the colloids in the aqueous phase to keep its mobility and decays into ^{226}Ra afterward, thus, the concentration of mobile ^{226}Ra in the fracture increases. The influence of colloids on the radionuclide transport was expected to be crucial to the actinides with large adsorbability[26]; however, the present results reveal that the low-adsorbing nuclides whose parent nuclides have large capability of sorption could be also facilitated significantly by colloids indirectly. This unexpected enhancement of the transport of such nuclides, for instance ^{226}Ra, indicates that the existence of colloids should be seriously treated in the transport of the radionuclide decay chain in the geologic system.

5 Conclusions

This present study has extended previous studies to consider the effects of colloids on actinides decay chains transport in the fractured media. The site-specific parameters were employed herein to demonstrate our model. The results indicated that colloids could enhance and facilitate the transport of radionuclides. The large adsorbability of nuclides with colloids would enlarge the effect of acceleration by colloids. An unexpected enhancement of the transport of the low-absorbing ^{226}Ra in the Uranium decay chain under the parameters of SR-97 occurred in the presence of colloids due to the large adsorbability of its parent nuclide of ^{230}Th. The mobility of ^{230}Th is maintained by adsorbing on colloids and decays into ^{226}Ra, therefore, the transport of ^{226}Ra contributed by the parent nuclide of ^{230}Th was enhanced indirectly. Consequently, the role of colloids played in the transport of the radionuclides decay chain should be assessed carefully in the radioactive waste disposal.

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