

A GoldSim-based screening and qualification framework for colloid-facilitated radionuclide transport in near-surface radioactive waste disposal

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Abstract

Colloids generated from waste materials, engineered barriers, and natural barriers can provide an additional mobile carrier phase for radionuclides in near-surface radioactive waste disposal facilities. This study develops a GoldSim-based screening and qualification framework for evaluating colloid-facilitated radionuclide transport in post-closure safety assessment. The model represents dissolved and colloid-associated radionuclides as separate transported species, allowing inventory partitioning, advective release, and mass-balance behavior to be evaluated along the pathway to the geosphere-biosphere interface. Nb-94, U-238, and Pu-239 were used to examine colloid-sensitive radionuclide transport, while I-129 was retained as a dissolved-transport reference. The model was checked using analytical partitioning relationships, mass-balance consistency, and comparison with reported experimental and modeling trends. Under base assessment conditions, colloids increased peak release concentrations by less than 0.1%, indicating limited influence in the reference case. Bounding sensitivity calculations showed that the strongest response occurred when dissolved and colloid-associated fractions became comparable. These results provide a practical screening basis for identifying cases that require more detailed mechanistic assessment of colloid transport, sorption, and retention processes.

1. Introduction

The long-term safety of a near-surface radioactive waste disposal facility should be demonstrated not only during operation but also during the post-closure period [1]. In post-closure safety assessment, radionuclide releases from waste packages, transport through engineered and natural barriers, and transfer to the biosphere are generally evaluated in an integrated assessment framework [1]. Studies on radionuclide transport in soil and groundwater also emphasize that the source term, hydrogeological framework, and transport model should be considered together when release behavior is evaluated in space and time [2]. Because repository performance is evaluated over long time scales, bounding and conservative assumptions are often used to address parameter uncertainty in quantitative performance assessment [3]. In a recent preliminary post-closure assessment for a planned near-surface facility, for example, the distribution coefficients of all radionuclides in the disposal zone and in the geosphere were assigned their minimum reported values, and 25 site- and scenario-related parameters were sampled over wide uniform ranges so that the calculated exposure would envelope the plausible radiological consequences at an early planning stage [4]. In such a framework, retardation by sorption and diffusion in waste forms, the concrete structure, soil, and rock has been regarded as one of the major safety functions controlling radionuclide migration [1,2]. However, it has long been recognized that transport behavior may be significantly modified when colloids are present and radionuclides are associated with them [5-8]. For this reason, colloid-facilitated transport has been considered an important issue in the safety assessment of radioactive waste repositories.

In a radioactive waste disposal system, colloids may originate not only from natural groundwater but also from waste materials, corrosion products, and the degradation of engineered barrier materials [7-

10]. In particular, cementitious materials have been reported to have some potential for colloid generation in repository environments [10], and long-term degradation and leaching of engineered barriers have been recognized as processes that may affect near-field evolution and transport behavior [11,12]. Calcium leaching is particularly relevant for concrete barriers because it can increase pore volume, reduce residual strength, and increase chloride diffusivity, thereby modifying the hydraulic and diffusive properties that control radionuclide transport through the engineered barrier. Therefore, in a near-surface disposal facility composed of waste materials, the engineered barrier, and surrounding soil and rock, several types of colloids may be generated and may participate in radionuclide transport.

In the safety assessment of nuclear waste repositories, sorption of radionuclides on colloid surfaces may significantly modify transport behavior where colloid concentration is sufficiently high [8]. In fractured geological media, this effect may become more pronounced because colloids may be excluded from matrix pores, and radionuclides bound to them are then not subject to the retarding effects of matrix diffusion and sorption onto matrix pore surfaces [8]. Colloids dispersed in groundwater provide an additional phase for radionuclides and may enhance radionuclide transport in fractured media when filtration, remobilization, and matrix diffusion are considered together [6].

Experimental observations indicate that colloids can play an important role in radionuclide migration. In transport experiments using bentonite colloids in a granite fracture, the breakthrough curves of europium and plutonium showed peaks at the same position as conservative tracers, indicating colloid-controlled migration [13]. Such results suggest that strongly sorbing radionuclides may migrate more rapidly than expected from conventional retardation assumptions when stable and mobile colloids are present. Although many previous studies have focused on deep geological environments, fractured crystalline rock, borehole disposal concepts, or bentonite-related colloid systems [6-8,13,14], the underlying implication is also relevant to disposal systems, where the engineered barrier and surrounding geologic media are relied upon to retard radionuclide transport.

Despite the considerable amount of previous work, relatively fewer studies have addressed colloid-facilitated radionuclide transport within an integrated post-closure safety assessment framework for a near-surface disposal facility in which waste materials, the engineered barrier, and the natural barrier are considered together. This point is important because colloids generated from these components may sorb radionuclides and alter both the timing and magnitude of release to the biosphere. In previous studies, a GoldSim-based program template was developed for the post-closure safety assessment of a near-surface disposal facility, and the facilitated transport of radionuclides by colloids and chelating agents was evaluated within a total system performance assessment framework [15,16]. These studies provided a useful basis for integrated assessment, but further development is still needed to explicitly evaluate the influence of key colloid-related parameters on radionuclide transport and release behavior in a disposal system representing waste materials, the engineered barrier, and the natural barrier.

Therefore, this study develops a GoldSim-based screening and qualification framework for analyzing colloid-facilitated radionuclide transport in a near-surface radioactive waste disposal facility. The model

is constructed around representative particulate waste materials expected from nuclear power plant operation and decommissioning, including glass fiber, scabbling concrete, and contaminated soil, and the target radionuclides are selected from the regulatory candidate list to represent both mobile dissolved species and radionuclides for which sorption and colloid association may be important. In contrast to a purely dissolved-species assessment, the proposed framework separates dissolved and colloid-associated radionuclide inventories and evaluates their release at the geosphere-biosphere interface within a mass-balance framework. The objectives of this study are: to implement dissolved and colloid-associated radionuclides as separate transported species in GoldSim, to qualify the model using analytical partitioning relationships, mass-balance checks, and comparison with relevant experimental and modeling studies, and to identify the colloid-related parameter regimes in which more detailed mechanistic assessment is required.

GoldSim is a dynamic simulation platform that represents a disposal system as a network of linked elements. In radionuclide transport calculations, inventories, transfer rates, decay, and transport pathways can be connected within a single probabilistic or deterministic framework. This structure is useful for post-closure safety assessment because near-field release, geosphere transport, and biosphere transfer can be evaluated consistently while preserving the logical connection among input parameters, pathway elements, and assessment endpoints. In the present study, GoldSim was used not to develop a new transport solver, but to implement a screening-level representation of dissolved and colloid-facilitated transport within the existing assessment framework.

2. Background and Modeling Scope

Previous studies have shown that colloid-facilitated transport should be considered when radionuclides are able to sorb onto mobile particles and when the resulting colloid-associated fraction is transported with groundwater [5–8]. In particular, colloids dispersed in groundwater provide an additional mobile phase for radionuclides and may enhance radionuclide migration by reducing the apparent retardation expected for dissolved species [5–6]. It has also been noted that the effect may become more pronounced in fractured geological media because radionuclides bound to colloids are not subject to the same extent of matrix diffusion and sorption onto matrix pore surfaces as dissolved radionuclides [8]. In addition, previous studies have shown that colloid-facilitated radionuclide transport is governed not by a single parameter but by a combination of colloid generation, colloid stability, radionuclide-colloid sorption/desorption, filtration, remobilization, and hydrochemical conditions [6,7,17]. These processes have been quantified separately in column experiments using bentonite colloids and altered granodiorite fracture fill material, which yielded colloid filtration rate constants of $0.01\text{--}0.02\text{ h}^{-1}$ while the associated americium was released from the colloids rapidly enough that colloid mobility alone did not guarantee enhanced radionuclide transport [17]. These observations indicate that a realistic model for repository assessment should not be limited to dissolved-species transport alone, but should also represent the additional transport pathway associated with colloids.

Experimental studies have also supported the importance of colloids in radionuclide migration. It has been reported that, in transport experiments using bentonite colloids in a granite fracture, the breakthrough curves of europium and plutonium exhibited a peak at the same position as conservative tracers, indicating largely colloid-driven migration [13]. Such observations suggest that strongly sorbing radionuclides may migrate more rapidly than would be expected from conventional retardation assumptions when stable and mobile colloids are present. Although many previous studies have focused on deep geological environments or fractured crystalline rock [6–8,13], the basic implication is also relevant to disposal systems. In such systems, the engineered barrier and surrounding soil and rock are relied upon as major retardation media, and any process that reduces retardation during transport should be carefully considered in post-closure safety assessment.

From the viewpoint of source characterization, previous studies further suggest that colloids in a disposal system may originate from more than one component. Colloids may be generated not only from natural groundwater systems but also from waste materials, corrosion products, and engineered barrier materials [7–10]. In particular, cementitious materials have been reported to have some potential for colloid generation in repository environments [10], and long-term degradation and leaching of engineered barriers have been recognized as processes that may affect near-field evolution and transport behavior [11,12]. Choi and Yang [11] experimentally showed that calcium leaching of concrete increases pore volume and chloride diffusivity while reducing residual strength, indicating that concrete degradation can alter both hydraulic transport properties and barrier performance. Clay minerals such as bentonite also provide important sorption sites for radionuclides because of their layered structure, high ion exchange capacity, and large specific surface area [9]. However, radionuclide adsorption by bentonite can vary with pH, ionic strength, competing ions, temperature, and other environmental conditions, indicating that colloid- and mineral-associated sorption should be treated as a condition-dependent process rather than as a fixed material property [9]. For Korean disposal-related materials, hydrothermal reaction of Gyeongju bentonite has been shown to alter swelling, hydrologic, and chemical behavior through smectite illitization, with forward modeling indicating a reduction in swelling pressure over long time scales [18]. Although bentonite is not the principal engineered barrier material in the present near-surface facility model, these findings support the general need to account for long-term material evolution when barrier-related sorption and transport parameters are interpreted. Therefore, for a near-surface disposal facility, it is necessary to consider at least three potential colloid source terms, namely, colloids originating from waste materials, colloids associated with the engineered barrier, and colloids generated from surrounding soil and rock. This point is important because the relative contribution of each colloid source may differ among the waste region, engineered barrier system, and natural barrier, thereby affecting the timing and magnitude of radionuclide release. In a different disposal context, numerical analysis of deep horizontal borehole disposal also showed that groundwater flow and the presence of low-permeability geological formations can strongly affect radionuclide migration [14]. This supports the general interpretation that geological barrier properties should be considered together with source-term and partitioning parameters when radionuclide release to the biosphere is assessed. The possible

source regions of colloids and the conceptual transport behavior considered in the present study are schematically represented in Fig. 1.

As shown in Fig. 1, colloids originating from waste materials, the engineered barrier, and the natural barrier may sorb radionuclides and contribute to their transport toward the biosphere. Previous GoldSim-based studies provide a useful basis for implementing these processes in an integrated post-closure assessment framework. A GoldSim program template has already been developed for the safety assessment of a near-surface disposal facility [15], and facilitated nuclide transport by colloids and chelating agents has also been modeled within a total system performance assessment framework [16]. In addition, S. Lee and Kim [19] performed a GoldSim-based post-closure safety assessment for Korean near-surface disposal of disused sealed radioactive sources, considering engineered-vault and rock-cavern disposal options and evaluating radionuclide transport through source-term, near-field, far-field, and biosphere components. Their study is relevant to the present work because it demonstrates the use of a system-level GoldSim framework for Korean low- and intermediate-level radioactive waste (LILW) disposal assessment and links radionuclide concentrations after the geosphere-biosphere interface to safety endpoints. A GoldSim-based biosphere model was also developed for the post-closure safety assessment of a LILW complex disposal facility, and the study showed that major assessment data can be organized in spreadsheet form and directly applied to the GoldSim-based assessment tool, while individual sub-models can be linked within an integrated assessment structure [20]. These previous studies indicate that GoldSim provides a practical platform for repository assessment because it can represent radionuclide release, transport through the near field and geosphere, and transfer to the biosphere within a single computational framework. At the same time, they imply that the adequacy of the assessment depends strongly on how colloid-related processes and parameters are represented in the model structure.

On the basis of the previous studies, several modeling considerations can be identified for representing colloid-facilitated radionuclide transport in GoldSim. First, the model should distinguish the major source regions of colloids in the disposal system and assign relevant parameters to each region. In the present study, these regions correspond to waste materials, the engineered barrier, and the natural barrier. Second, the model should explicitly represent the parameters governing radionuclide partitioning between dissolved and colloid-associated forms. Among these, colloid concentration and radionuclide-colloid distribution coefficient are considered to be the key parameters because they directly control the fraction of radionuclides associated with mobile colloids [6–8,16]. Third, because the assessment model includes repeated disposal units and multiple transport regions, the input structure should be organized so that parameter values can be modified consistently and efficiently. In practical GoldSim implementation, this means that input data should be managed through linked data elements and spreadsheet-based input structures rather than through repeated manual editing of individual model objects [20]. The modeling considerations derived from the previous studies and their implications for GoldSim implementation are summarized in Table 1.

Table 1

Summary of the key modeling considerations for representing colloid-facilitated radionuclide transport and their corresponding implementation approaches in the GoldSim-based assessment model.

Category	Modeling consideration	GoldSim implementation approach
Colloid source	• Waste materials • Engineered barrier • Natural barrier	• Region-specific input parameters
Key parameters	• Colloid concentration • Radionuclide-colloid distribution coefficient	• Main sensitivity parameters
Input management	• Repeated vaults • Multiple transport regions • Consistent parameter control	• Data elements • Spreadsheet linkage • Vector/Matrix structure
Suspended representation	• Mobile colloid carrier • Transport within pathway network	• Suspended element model
Concentration interpretation	• Effective concentration = dissolved + colloid-associated fraction	• Difference-based interpretation
Mass-balance	• Species mass tracked • Suspended solid mass not explicitly tracked	• Limitation of Suspended element model
Species representation	• Dissolved and colloid-associated radionuclides treated separately	• Species element model

Among these considerations, the representation of colloids within the GoldSim radionuclide transport (RT) module requires further discussion because it directly affects the treatment of radionuclide partitioning and mass balance. When colloids are represented as suspended solids, radionuclide mass associated with colloids can be transported through the pathway network together with dissolved radionuclide mass. Under such a representation, the effective radionuclide concentration in water includes both dissolved and colloid-associated fractions, and the colloid-associated radionuclide concentration can be inferred from the difference between the effective concentration and the dissolved concentration. This structure is useful because it provides a direct and practical way to express colloid-facilitated transport within the existing pathway framework. However, the same representation has an intrinsic limitation in that GoldSim tracks species mass but does not directly track the movement and mass balance of the suspended solid medium itself [21]. As a result, radionuclide mass balance can be evaluated, whereas the mass balance of the colloid medium itself cannot be explicitly confirmed in the same manner. This limitation becomes important when the purpose of the model is not only to evaluate

radionuclide release but also to explicitly distinguish dissolved radionuclides, colloid-associated radionuclides, and unreacted colloids in a physically consistent manner.

For this reason, an additional modeling approach was considered in which radionuclides sorbed onto colloids were represented as independent species rather than only through partitioning onto suspended solids. By defining dissolved radionuclides and colloid-associated radionuclides as separate species, the inventory assigned to each form can be calculated explicitly and transported independently through the model network. This approach makes it possible to evaluate the partitioning of radionuclide inventory between dissolved and colloid-associated forms more directly and to examine mass balance in a more transparent way over the entire transport pathway. It is also advantageous when the model needs to reflect region-specific colloid effects in waste materials, the engineered barrier, and the natural barrier by directly assigning inventory fractions or transfer relations to the colloid-associated species.

Based on the previous studies and the modeling considerations described above, it was considered appropriate to examine two GoldSim representations for colloid-facilitated radionuclide transport, namely, a model using the Suspended element to represent colloids as mobile particulate media and a model using the Species element to represent colloid-associated radionuclides as independent transported species. The former approach is useful for directly implementing colloid-facilitated transport within the existing RT module framework, whereas the latter approach is advantageous for explicit inventory partitioning and mass-balance evaluation. Both approaches were therefore considered in the present study for the development of a GoldSim-based post-closure safety assessment model for a near-surface disposal facility.

The present work does not explicitly model colloid generation, aggregation, filtration, attachment, remobilization, or unsaturated-zone retention. These processes are treated as unresolved mechanisms that may affect the effective mobility of colloid-associated radionuclides. Accordingly, the model should be interpreted as a screening-level partitioning and transport assessment rather than as a mechanistic colloid transport model.

3. Materials and Methods

This study extends the existing GoldSim-based post-closure safety assessment tool for the second-phase near-surface disposal facility developed by the Korea Radioactive Waste Agency (KORAD). The original tool was prepared for evaluating post-closure repository performance as part of the safety management framework for the facility [22]. On this basis, the present model was further developed by incorporating colloid-facilitated radionuclide transport to examine the potential acceleration of radionuclide migration after repository closure. Thus, the existing assessment framework was used as the base structure, while the influence of colloids originating from waste materials, the engineered barrier, and the natural barrier was additionally considered.

3.1. Reference Disposal Facility, Representative Waste Materials, and Source-Term Basis

Glass fiber, scabbling concrete, and soil were selected as representative particulate waste materials in this study. These materials were selected because they are relevant to particulate waste management in Korea, including glass fiber that has been stored for a long period as untreated waste and soil and scabbling concrete that are expected to be generated in large quantities during nuclear power plant decommissioning. In the existing GoldSim-based colloid model, colloids originating from concrete, soil, and glass fiber in the waste region were already considered as particulate sources, providing a practical basis for the present model development. To strengthen the connection between the model and actual nuclear-fuel-cycle waste streams, the representative waste materials were not treated as generic solids. Glass fiber was used to represent fibrous operational waste, scabbling concrete was used to represent concrete-derived decommissioning waste, and contaminated soil was used to represent particulate environmental or remediation waste. These waste types were selected because their physical form can provide particulate or colloidal source material and because their associated radionuclide inventories may include both mobile radionuclides and strongly sorbing activation or actinide radionuclides. The source-term definition therefore links the material origin of colloids to the radionuclide inventory used in the transport calculation. To make the source-term basis explicit, the representative waste materials, their relevance to nuclear power plant operation or decommissioning, the corresponding potential colloid sources, and the target radionuclides used in the screening calculation are summarized in Table 2. The table is not intended to represent a complete regulatory inventory for all radioactive waste streams. Instead, it defines the source-term linkage used in this study to connect representative particulate waste materials with the selected radionuclides and colloid-generation assumptions.

Table 2
Source-term basis for the representative waste materials and target radionuclides used in the screening assessment.

Representative waste material	Waste-stream relevance	Potential colloid source approach	Role of target radionuclides
Glass fiber	• Operational particulate waste	• Waste-derived fibrous colloids	• I-129: mobile reference; U-238/Pu-239: sorption-sensitive
Scabbling concrete	• Concrete decommissioning waste	• Cementitious/degraded concrete colloids	• Nb-94: activation product; U-238/Pu-239: colloid-sensitive
Contaminated soil	• Remediation/decommissioning particulate waste	• Soil- and mineral-derived colloids	• I-129: dissolved-dominated; U-238/Pu-239: sorption-controlled

The near-surface disposal facility developed by the KORAD was selected as the reference disposal system for model development [22]. This facility was selected as the primary environmental condition because most particulate waste is expected to be disposed of in the second-phase facility, although disposal in the first- or third-phase facilities may also be possible depending on the activity level. The existing post-closure safety assessment framework for the second-phase facility was adopted as the base model, and the colloid-facilitated transport process was incorporated into that framework. As a result, the model developed in this study reflects both the characteristics of representative particulate waste materials and the environmental conditions of the reference disposal facility. This pathway definition is consistent with the Korean near-surface disposal assessment reported by S. Lee and Kim [19], in which engineered-vault radionuclide transport was represented from the source term through the engineered barrier, unsaturated zone, and aquifer to sea or well endpoints, while the rock-cavern pathway was represented through the silo, concrete wall, and host rock before reaching the biosphere. In the present study, the same system-level pathway logic is retained, but the assessment endpoint is the peak release concentration at the geosphere-biosphere interface rather than public dose.

3.2. Selection of Target Radionuclides

Based on the Korean delivery regulation for low- and intermediate-level radioactive waste (LILW), an initial list of candidate radionuclides was established from the radionuclides subject to characterization and acceptance for disposal [23]. For this study, the candidate radionuclide set consisted of H-3, C-14, Ni-59, Nb-94, Tc-99, I-129, Ra-226, Ac-227, Th-228, Ra-228, Th-230, Pa-231, Th-232, U-234, U-235, U-238, and Pu-239. The target radionuclides were then selected to cover nuclides relevant to post-closure transport assessment and to compare radionuclides whose transport is mainly governed by dissolved-species migration with those that may be affected by colloid-facilitated transport.

The selection was made to include both mobile and strongly sorbing radionuclides. Highly mobile radionuclides are important in post-closure safety assessment because they can migrate mainly as dissolved species with limited retardation. Among them, I-129 was selected as a representative mobile radionuclide to provide a reference case for evaluating the relative influence of colloid-facilitated transport. In contrast, strongly sorbing radionuclides may show a greater sensitivity to colloids because radionuclides associated with mobile colloids can migrate with less retardation by fracture surfaces or matrix diffusion [6–8].

In previous studies, colloid-facilitated transport has been shown to be particularly relevant for radionuclides that have strong affinity for colloid surfaces or low mobility under conventional dissolved-species transport assumptions [6–8]. Experimental observations have also indicated that strongly sorbing radionuclides can exhibit colloid-controlled migration in the presence of bentonite colloids [13]. In addition, Wold [24] compiled sorption information for prioritized elements on montmorillonite colloids, including Pu, Pa, Ra, Tc, Cs, Nb, Ni, and U, and emphasized that sorption strength and sorption reversibility are key parameters for modeling colloid transport of radionuclides.

On this basis, Nb-94, I-129, U-238, and Pu-239 were selected as the target radionuclides in this study. Nb-94 was selected as a long-lived activation product included in the candidate list and as an element addressed in the prioritized element group for colloid sorption assessment [23,24]. I-129 was selected as a representative highly mobile radionuclide to compare the colloid response of dissolved-species-dominated transport with that of more strongly sorbing radionuclides [23]. U-238 was selected as a representative uranium isotope because uranium is included among the prioritized elements for montmorillonite colloid sorption and is relevant to long-term post-closure transport [24]. Pu-239 was selected as a representative strongly sorbing actinide because plutonium has been explicitly considered in previous colloid-facilitated transport studies and is also included among the prioritized elements for colloid sorption assessment [7,13,16,24]. Pu-239 has also been identified among the dose-relevant radionuclides in the post-closure assessment of a planned near-surface disposal facility, where its release behavior was controlled by a high distribution coefficient assigned to the degraded disposal zone together with a much lower value in the geosphere [4]; this contrast makes Pu-239 a suitable case for examining how association with mobile colloids modifies the retardation otherwise assumed for the dissolved phase. Accordingly, the target radionuclides considered in the present study were Nb-94, I-129, U-238, and Pu-239.

The selected radionuclides were not intended to represent a complete inventory set for regulatory safety assessment. Rather, they were used as a limited screening set to examine different transport responses in the proposed modeling framework. I-129 was retained as a highly mobile reference radionuclide, whereas Nb-94, U-238, and Pu-239 were selected to examine radionuclides for which sorption and colloid association may be more relevant. Long-lived transuranic radionuclides such as Np and Am should be included in an extended assessment because their sorption behavior and decay-chain contributions may differ from those of the radionuclides considered here.

3.3. GoldSim Model Structure

To represent colloid-facilitated radionuclide transport in the GoldSim-based assessment framework, two modeling approaches were examined, namely, a suspended solid-based representation and a Species-based representation. In the first approach, colloids were represented as suspended solid media within the RT module. For this representation, the colloid properties assigned to each region were linked to the Solid element through the input parameter module. The principal parameters required for each colloid medium were density, porosity, partition coefficient, and tortuosity. In the present model, density, porosity, and partition coefficient were linked to Data elements defined in advance in the input module in order to ensure consistency of the input structure and to reduce the possibility of manual input error. Although these values can be entered directly in the Solid element, the use of linked data elements was adopted in the present study as a more practical and consistent approach. If the partition coefficient is not separately defined, a default value of zero is applied. Tortuosity was assigned the default value of 1 unless otherwise required.

The colloid material defined in this manner was incorporated into the pathway elements of the RT module representing the waste region, engineered barrier, and natural barrier system. In particular, for

the Cell pathway elements representing the waste region and the concrete slab, colloids were added as an additional medium, and the quantity assigned to each vault was defined as the product of colloid concentration and the volume of pore water in the corresponding region. In this representation, the suspended option should be specified so that the colloid medium can move through the pathway network as a suspended particulate phase. If the colloid medium is not treated as suspended, the colloid-facilitated transport effect cannot be represented appropriately, because the colloid medium is not preserved as a mobile carrier during transport between adjacent cells.

However, the suspended solid-based representation has an inherent limitation in the GoldSim calculation structure. According to the GoldSim user's guide, GoldSim tracks species mass but does not explicitly keep track of the movement of suspended solid media through the pathway network [21]. Therefore, although radionuclide mass balance can be evaluated within the RT module, the mass balance of the colloid medium itself cannot be explicitly verified in the same manner. In addition, the behavior of colloid-associated radionuclides and unreacted colloids cannot be distinguished in a fully transparent way when colloids are represented only as suspended materials. As a result, the suspended solid-based approach is useful for directly expressing colloid-facilitated transport within the existing pathway framework, but it has a structural limitation for quantitative verification of colloid behavior and radionuclide-colloid interaction.

To address this limitation, a Species-based model was additionally developed in the present study. In this approach, radionuclides sorbed onto colloids were defined as independent Species elements rather than being represented only through partitioning onto suspended solids. The objective of this model was to explicitly calculate the distribution of radionuclide inventory in each region and thereby enable mass-balance verification over the entire transport pathway. This approach also overcomes the limitations of the previous material-based representation with respect to colloid movement across Pathway element boundaries and explicit tracking of colloid-associated radionuclides. The conceptual structure of the model developed in this study is illustrated in Fig. 2.

Radionuclide inventory in each region is treated as a time-dependent state variable governed by inflow from the upstream region, outflow to the downstream region, radioactive decay and ingrowth, and partitioning between the dissolved and colloid-associated species within the same region. Transport is solved sequentially along the pathway, so that processes occurring in a downstream region do not modify the inventory of an upstream region. This formulation preserves causality along the transport direction while maintaining a closed mass balance over the whole disposal system, and it allows the influence of colloids originating from the waste, the engineered barrier, and the natural barrier to be examined region by region. The model was implemented in GoldSim and applied consistently to the 20 disposal vaults considered in this study.

All results reported in Section 4 were obtained with the Species-based model; the suspended-solid representation is described only to document the rationale for that choice. The selected radionuclides were used as a source-term-linked screening set rather than as an exhaustive regulatory inventory. Nb-94

represents a long-lived activation product relevant to reactor-related metallic and concrete-associated waste streams. I-129 represents a highly mobile radionuclide for which dissolved-phase transport is expected to dominate. U-238 represents uranium-series long-lived radionuclides that may be present in contaminated particulate waste and whose mobility is strongly affected by sorption assumptions. Pu-239 represents a strongly sorbing actinide for which colloid association may substantially reduce the apparent retardation expected for dissolved transport. This selection allows the model to compare three transport classes: mobile dissolved transport, sorption-controlled transport, and colloid-influenced transport.

3.4. Mathematical Formulation

The partitioning between dissolved and colloid-associated forms was represented using a linear equilibrium approximation. The dimensionless colloid partitioning ratio was defined as

$$k = K_c \bullet C_c$$

1

and the corresponding mass fractions are

$$f_{col} = \frac{k}{1 + k}$$

2

$$f_{diss} = \frac{1}{1 + k}$$

3

where K_c is the radionuclide-colloid distribution coefficient and C_c is the mobile colloid mass concentration. Because K_c and C_c appear only as their product, the equilibrium partitioning is controlled by the single dimensionless group λ rather than by the two parameters independently. This linear equilibrium form presumes that exchange between the dissolved and colloid-associated phases is instantaneous and fully reversible. Column experiments have shown that this presumption is not always satisfied, because the desorption rate of a radionuclide from mobile colloids can itself limit the distance over which colloid-facilitated transport remains effective, and slow rates exert a greater influence on large-scale performance assessment than fast ones [17]; the equilibrium approximation is therefore retained here for screening purposes only.

The retardation of dissolved radionuclides by immobile solid media was represented using the conventional distribution-coefficient form

$$R_k = 1 + \left(\frac{\rho_b}{\theta} \right) K_{d,k}$$

4

where ρ_b is the dry bulk density of the medium, θ is the porosity, and $K_{d,k}$ is the dissolved-phase distribution coefficient of radionuclide k in the corresponding medium.

Under the equilibrium colloid-facilitated transport approximation, and assuming that colloids migrate at the pore-water velocity without filtration, the effective retardation factor becomes

$$R_{eff,k} = (1 + \frac{\rho_b}{\theta} K_{d,k} + k) / (1 + k)$$

5

This equation has the same form as the effective retention factor derived analytically for fractured media by Smith [8] and as the effective retardation factor given for equilibrium partitioning by Reimus et al. [7]. It shows that the colloid loading enters the transport calculation only through k , which provides the basis for the interpretation of the sensitivity results presented in Section 4.

The radionuclide mass balance for each region of the pathway network was expressed as

$$\frac{dM_{i,k}}{dt} = \sum_j (F_{ji,k} - F_{ij,k}) + \lambda_p M_{i,p} - \lambda_k M_{i,k}$$

6

where $M_{i,k}$ is the mass of radionuclide k in region i , $F_{ji,k}$ and $F_{ij,k}$ are the inflow and outflow mass fluxes between adjacent regions, λ_k is the decay constant of radionuclide k , and the subscript p denotes the parent radionuclide in the decay chain. Advective fluxes were represented separately for the two transported species as

$$M_i(t) = M_{i,diss}(t) + M_{i,col}(t)$$

7

The total inventory of radionuclide k in region i is the sum of the two species, $M_{i,k} = M_{i,diss,k} + M_{i,col,k}$, with the split equations. Because the dissolved and colloid-associated forms are defined as separate species, the phase into which a daughter radionuclide is generated must be specified; in the present model, radionuclides produced by decay of a parent are assigned to the equilibrium distribution of the region in which they are formed. The overall mass balance of the model was verified by comparing the initial inventory with

$$M_{tot}(t) = \sum_i \{M_{i,diss}(t) + M_{i,col}(t)\} + M_{rel}(t) + M_{dec}(t)$$

8

where M_{rel} is the cumulative mass released to the assessment boundary and M_{dec} is the cumulative mass removed by radioactive decay. The mass-balance expression was used as a numerical consistency check for the Species-based implementation. Facility-specific geometric and hydrogeological parameters were taken from the reference safety analysis model, whereas the sensitivity results are reported in terms of relative changes and the dimensionless colloid partitioning parameter.

4. Results and Discussion

The GoldSim-based model developed in this study was applied to the target radionuclides selected in Section 3.2. Nb-94, U-238, and Pu-239 were used to examine radionuclides for which colloid association may affect transport, whereas I-129 was retained as a reference case representing predominantly dissolved-phase transport. Model outputs were taken at the geosphere-biosphere interface (GBI), defined in this study as the release point where radionuclides transported through the saturated zone of the natural barrier enter the biosphere. The peak release concentration at this point was used as the main indicator for comparing the transport cases with and without colloids. The concentration profiles were also reviewed to determine whether the inclusion of colloids changed the apparent migration behavior of each radionuclide in the integrated assessment framework.

4.1. Colloid-Facilitated Radionuclide Transport Assessment

The assessment in this section was conducted using the model structure described in Section 3. The calculation was designed to examine how colloids affect radionuclide mobility in the second-phase near-surface disposal facility after repository closure. The reference case represented radionuclide transport without colloids. The comparative case used the same assessment conditions, but included colloids originating from waste materials, the engineered barrier, and the natural barrier. The assessment was performed along the transport pathway from the waste region to the engineered barrier system, natural barrier, and biosphere. The peak release concentration was evaluated at the GBI, which corresponds to the boundary where radionuclides released from the saturated zone of the natural barrier enter the biosphere. Therefore, the peak release concentration used in this study represents the maximum concentration released at the GBI rather than the concentration within an individual barrier region. For each target radionuclide, the influence of colloids was evaluated by comparing the peak release concentration at the GBI between the cases with and without colloids. A higher peak release concentration in the colloid case was interpreted as an increase in the apparent release to the biosphere caused by colloid-facilitated transport. The assessment results are summarized in Table 3, which were obtained using a colloid concentration of $1.00 \times 10^{-6} \text{ g/cm}^3$ and a radionuclide-colloid distribution coefficient of $1.00 \times 10^{-1} \text{ cm}^3/\text{g}$. For I-129, the peak release concentration was unchanged between the two cases, indicating that the effect of colloids was negligible for this highly mobile radionuclide. This result is consistent with the expectation that I-129 transport is mainly governed by dissolved-species migration rather than colloid-facilitated transport.

Table 3

Initial inventory and peak release concentration at the GBI for the four target radionuclides, comparing the cases without and with colloids under the base conditions.

Radioactive nuclide	Initial inventory [g]	Peak release concentration w/o colloids [g/cm ³]	Peak release concentration w/ colloids [g/cm ³]
Nb-94	2.217×10^0	4.181×10^{-21}	4.183×10^{-21}
I-129	1.737×10^1	1.990×10^{-11}	1.990×10^{-11}
U-238	3.385×10^3	3.592×10^{-11}	3.595×10^{-11}
Pu-239	3.892×10^1	6.861×10^{-17}	6.867×10^{-17}

Base conditions: $C_c = 1.00 \times 10^{-6}$ g/cm³, $K_c = 1.00 \times 10^{-1}$ cm³/g.

Although the increases for Nb-94, U-238, and Pu-239 were small, the results confirmed that colloids can increase the apparent release of radionuclides at the GBI by reducing the effective retardation of colloid-associated radionuclide fractions. The effect was more evident for U-238 and Pu-239 than for Nb-94 in terms of relative change, although the magnitude of the increase remained limited under the base assessment conditions. These results suggest that the colloid effect in the reference assessment case is not dominant, but may become more important when colloid concentration or radionuclide-colloid distribution coefficient increases. Therefore, additional sensitivity analysis was performed in Section 4.2 to examine the influence of key colloid-related parameters on radionuclide release behavior.

4.2. Sensitivity Analysis

Sensitivity analyses were performed to examine the influence of key colloid-related parameters on radionuclide release to the biosphere. Based on the modeling considerations discussed in Section 2, colloid concentration and radionuclide-colloid distribution coefficient were selected as the principal sensitivity parameters. The colloid concentration was varied from 1.00×10^{-12} to 1.00×10^0 g/cm³, and the radionuclide-colloid distribution coefficient was varied from 1.00×10^{-4} to 1.00×10^2 cm³/g. These ranges were applied as bounding ranges for sensitivity analysis rather than as site-specific deterministic values. This treatment is consistent with the use of bounding or conservative assumptions for uncertain parameters in long-term performance assessment [3], and with near-surface disposal assessments in which wide uniform parameter ranges and minimum distribution coefficients are deliberately adopted so that the calculated result envelopes the plausible consequences instead of reproducing a single realistic case [4].

Colloid concentrations may vary over several orders of magnitude depending on groundwater chemistry, ionic strength, colloid stability, colloid source, and particle characteristics [24]. In addition, the distribution coefficient is an empirical and system-dependent parameter that can vary depending on

colloid type, particle-size distribution, available sorption sites, groundwater chemistry, pH, ionic strength, competing ions, and sorption reversibility [9,24]. Therefore, wide logarithmic ranges were adopted to evaluate the model response under conservative assessment assumptions. The sensitivity ranges are summarized in Table 4. Figures S1 and S2 in the Supplementary Information present the complete sets of sensitivity plots for all fixed colloid concentrations and distribution coefficients, respectively. Broad uncertainty range derived from the sedimentary-rock distribution coefficient range and applied to represent system-dependent sorption behavior of colloid-associated radionuclides; higher values have been reported for actinide sorption on bentonite colloids [17].

Table 4

Ranges of the colloid-related parameters (colloid concentration and radionuclide-colloid distribution coefficient) used in the sensitivity analysis, together with the basis for each range.

Parameter	Range	Unit	Basis for range setting
Colloid concentration	1.00×10^{-12} $\sim 1.00\times10^0$	g/cm ³	Broad uncertainty range reflecting possible variation in colloid occurrence and hydrogeochemical conditions
Radionuclide-colloid distribution coefficient	1.00×10^{-4} $\sim 1.00\times10^2$	cm ³ /g	Broad uncertainty range derived from the sedimentary-rock distribution coefficient range and applied to represent system-dependent sorption behavior of colloid-associated radionuclides

Two sets of sensitivity calculations were performed. In the first set, colloid concentration was fixed and the radionuclide-colloid distribution coefficient was varied over the full range. This calculation examined the sensitivity of the peak release concentration at the GBI to radionuclide-colloid sorption strength. Representative results for fixed colloid concentrations of 1.00×10^{-12} , 1.00×10^{-6} , and 1.00×10^0 g/cm³ are shown in Fig. 3. For quantitative comparison, the no-colloid peak release concentrations listed in Table 3 were used as reference values, and the largest peak release concentration within each panel was used to calculate the relative increase.

At a colloid concentration of 1.00×10^{-12} g/cm³, no increase from the no-colloid case was obtained for any of the four radionuclides over the distribution coefficient range considered in Fig. 3(a). When the colloid concentration was increased to 1.00×10^{-6} g/cm³, the largest peak release concentrations occurred at a distribution coefficient of 1.00×10^2 cm³/g. Relative to the no-colloid values, the increases were $5.82\times10^1\%$, $3.97\times10^0\%$, $5.84\times10^1\%$, and $1.05\times10^2\%$ for Nb-94, I-129, U-238, and Pu-239, respectively, as shown in Fig. 3(b).

At the highest colloid concentration examined, 1.00×10^0 g/cm³, the largest peak release concentrations occurred at a distribution coefficient of 1.00×10^0 cm³/g. The corresponding increases from the no-colloid values were $1.08\times10^5\%$, $4.75\times10^4\%$, $1.09\times10^5\%$, and $1.71\times10^5\%$ for Nb-94, I-129, U-238, and Pu-239, respectively, as shown in Fig. 3©. Because the results in Fig. 3(a) were identical to the no-colloid values, the increases in Fig. 3(b) and (c) relative to Fig. 3(a) were numerically the same as those

calculated relative to the no-colloid case. In Fig. 3(c), the concentrations decreased above a distribution coefficient of $1.00 \times 10^0 \text{ cm}^3/\text{g}$, showing a non-monotonic response at the highest colloid concentration.

In the second set, the radionuclide-colloid distribution coefficient was fixed and colloid concentration was varied over the full range. This calculation examined the sensitivity of the peak release concentration at the GBI to the amount of mobile colloids available for radionuclide transport.

Representative results for distribution coefficients of 1.00×10^{-4} , 1.00×10^{-1} , and $1.00 \times 10^2 \text{ cm}^3/\text{g}$ are shown in Fig. 4.

At a distribution coefficient of $1.00 \times 10^{-4} \text{ cm}^3/\text{g}$, the largest peak release concentrations occurred at a colloid concentration of $1.00 \times 10^0 \text{ g/cm}^3$. Relative to the no-colloid values, the increases were $5.82 \times 10^1\%$, $3.97 \times 10^0\%$, $5.84 \times 10^1\%$, and $1.05 \times 10^2\%$ for Nb-94, I-129, U-238, and Pu-239, respectively, as shown in Fig. 4(a). At a distribution coefficient of $1.00 \times 10^{-1} \text{ cm}^3/\text{g}$, the largest values also occurred at a colloid concentration of $1.00 \times 10^0 \text{ g/cm}^3$. The increases from the no-colloid values were $4.58 \times 10^4\%$, $1.99 \times 10^4\%$, $4.61 \times 10^4\%$, and $8.60 \times 10^4\%$ for Nb-94, I-129, U-238, and Pu-239, respectively. Compared with Fig. 4(a), the corresponding panel maxima increased by $2.89 \times 10^4\%$, $1.92 \times 10^4\%$, $2.91 \times 10^4\%$, and $4.19 \times 10^4\%$, respectively, as shown in Fig. 4(b). At a distribution coefficient of $1.00 \times 10^2 \text{ cm}^3/\text{g}$, the largest peak release concentrations occurred at a colloid concentration of $1.00 \times 10^2 \text{ g/cm}^3$ rather than at the upper end of the concentration range. The increases from the no-colloid values were $1.08 \times 10^5\%$, $4.75 \times 10^4\%$, $1.09 \times 10^5\%$, and $1.71 \times 10^5\%$ for Nb-94, I-129, U-238, and Pu-239, respectively. Relative to Fig. 4(a), the corresponding increases were $6.81 \times 10^4\%$, $4.57 \times 10^4\%$, $6.90 \times 10^4\%$, and $8.35 \times 10^4\%$, respectively, as shown in Fig. 4(c). Beyond $1.00 \times 10^{-2} \text{ g/cm}^3$, the peak release concentrations decreased for all four radionuclides, resulting in the non-monotonic concentration response shown in Fig. 4(c). Because colloid filtration, aggregation, attachment, and straining were not represented as independent processes in the present model, the mechanism responsible for this decrease cannot be identified from the sensitivity results alone. Previous studies have shown that colloid-facilitated transport can be affected by rock interaction, mechanical retention, colloid attachment, aggregation, and physical straining, depending on the colloid type and hydrogeochemical conditions [14,17,25,26]. Dittrich et al. [17] further reported that bentonite colloids were recovered almost completely through successive columns of fracture fill material, whereas the colloid-associated americium fraction was progressively stripped by the immobile solid surfaces, indicating that the colloid-associated inventory can decline along the transport path even when the colloids themselves are not appreciably retained. Since neither filtration nor desorption kinetics is represented in the present equilibrium formulation, such a mechanism cannot be distinguished from the inventory-redistribution effect that produces the calculated decrease. Therefore, the present non-monotonic response should be interpreted as a screening-level indication of parameter-regime dependence rather than as direct evidence of a specific retention mechanism.

To integrate the two sensitivity analyses shown in Figs. 3 and 4, the peak release concentrations were normalized by the corresponding no-colloid peak release concentrations and reorganized as a function of the dimensionless colloid partitioning ratio, $k = K_c C_c$. This representation was used to examine

whether the calculated response was controlled by colloid concentration or radionuclide-colloid distribution coefficient separately, or by their combined partitioning effect. The resulting k -based response is shown in Fig. 5.

As shown in Fig. 5, the sensitivity response is governed primarily by k rather than by K_c or C_c alone. When k is much smaller than unity, the normalized peak release concentration remains close to the no-colloid reference value, indicating dissolved-dominated transport. As k approaches unity, the dissolved and colloid-associated fractions become comparable, and the normalized response increases sharply. This transitional regime is therefore the most important range for screening because small changes in colloid loading or radionuclide-colloid partitioning can substantially alter the calculated release concentration. At higher k values, the response should be interpreted within the assumptions of the equilibrium-partitioning and inventory-redistribution formulation, because filtration, attachment, aggregation, desorption kinetics, and colloid stability are not explicitly represented.

In the equilibrium-partitioning formulation used here, the sensitivity response is governed primarily by the dimensionless colloid partitioning ratio $k = K_c \cdot C_c$. Therefore, colloid concentration and radionuclide-colloid distribution coefficient should not be interpreted as independent physical controls unless additional process terms such as colloid filtration, attachment, aggregation, or stability are explicitly represented. The non-monotonic response at high k should be interpreted primarily as a feature of the present equilibrium-partitioning and inventory-redistribution formulation, rather than as direct evidence of a specific physical retention mechanism. Because Fig. 5 includes I-129 for comparison, the I-129 response should be interpreted only as a hypothetical bounding case in which the same radionuclide-colloid distribution coefficient range was applied to all radionuclides. It should not be interpreted as a physically realistic iodine-colloid sorption scenario. Instead, I-129 is retained as a dissolved-transport reference for comparing the k -dependent responses of more sorption-sensitive radionuclides.

Reported distribution coefficients for strongly sorbing actinides on bentonite colloids can be high enough to produce k values near unity when combined with the colloid concentrations examined in this study [17]. This supports the interpretation that the transitional regime, rather than the extreme upper bound of the parameter sweep, is the condition of practical interest for screening. Consistent with this interpretation, a recent review of laboratory- and field-scale colloid experiments for deep geological repositories concluded that whether colloids act as effective radionuclide carriers is governed by colloid stability and radionuclide-colloid interaction under the prevailing hydrogeochemical conditions, and identified the integration of these colloid processes into performance assessment models as a remaining challenge [27]. The purpose of the sensitivity analysis is therefore not to claim that the extreme upper-bound cases represent expected site behavior, but to identify the parameter regime in which a more detailed colloid transport model becomes necessary.

5. Conclusion

This study developed a GoldSim-based screening and qualification framework for evaluating colloid-facilitated radionuclide transport in a near-surface radioactive waste disposal facility. The model represents dissolved and colloid-associated radionuclides as separate transported species and evaluates release at the geosphere-biosphere interface within a mass-balance framework. The implementation was checked against analytical partitioning relationships, no-colloid reference behavior, and mass-balance consistency, providing a verified numerical basis for interpreting the sensitivity results.

Under the base assessment conditions, colloids increased the peak release concentrations of the selected radionuclides by less than 0.1%, indicating that colloid-facilitated transport is not a dominant release mechanism for the reference case. In contrast, the bounding sensitivity analysis showed that the model response can increase sharply near the transitional condition where dissolved and colloid-associated radionuclide fractions are comparable. The controlling parameter is the dimensionless colloid partitioning ratio, $k = K_c C_c$, rather than colloid concentration or radionuclide-colloid distribution coefficient alone. This result provides a practical screening criterion: cases with k much smaller than unity may be treated as dissolved-dominated, whereas cases approaching unity require more detailed evaluation of colloid mobility and radionuclide-colloid interaction.

The main implication of the framework is that colloid effects can be screened systematically before committing to more complex process-level modeling. However, direct site-specific prediction requires additional treatment of colloid generation, filtration, attachment, desorption kinetics, mechanical retention, unsaturated-zone retention, and time-dependent degradation of engineered barriers. Therefore, the proposed framework should be used as a qualified screening tool for prioritizing radionuclides, waste forms, and parameter regimes that warrant mechanistic or experimental follow-up, rather than as a substitute for full process-based colloid transport validation.

Abbreviations

Conventional units used in radionuclide transport are reported with SI-equivalent relationships where applicable; $1 \text{ cm}^3/\text{g} = 1.0 \times 10^{-3} \text{ m}^3/\text{kg}$ and $1 \text{ g}/\text{cm}^3 = 1.0 \times 10^3 \text{ kg}/\text{m}^3$.

Symbol	Definition	Unit
C_c	mobile colloid mass concentration	g/cm^3
$C_{\text{diss},k}$	dissolved concentration of radionuclide k	g/cm^3
$C_{\text{col},k}$	colloid-associated concentration of radionuclide k	g/cm^3
$F_{ij,k}$	mass flux of radionuclide k from region i to region j	g/yr
f_{col}	colloid-associated mass fraction	-
f_{diss}	dissolved mass fraction	-
K_c	radionuclide-colloid distribution coefficient	cm^3/g
$K_{d,k}$	dissolved-phase distribution coefficient on immobile solids	cm^3/g
$M_{i,k}$	mass of radionuclide k in region i	g
M_{dec}	cumulative mass removed by radioactive decay	g
M_{rel}	cumulative mass released across the assessment boundary	g
M_{tot}	total mass accounted for in the mass-balance check	g
Q	volumetric water flow rate	cm^3/yr
R_k	retardation factor of dissolved species	-
$R_{\text{eff},k}$	effective retardation factor in the presence of colloids	-
θ	porosity	-
k	dimensionless colloid partitioning ratio, $K_c C_c$	-
λ_k	decay constant of radionuclide k	$1/\text{yr}$
ρ_b	dry bulk density of the medium	g/cm^3

Declarations

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Figures

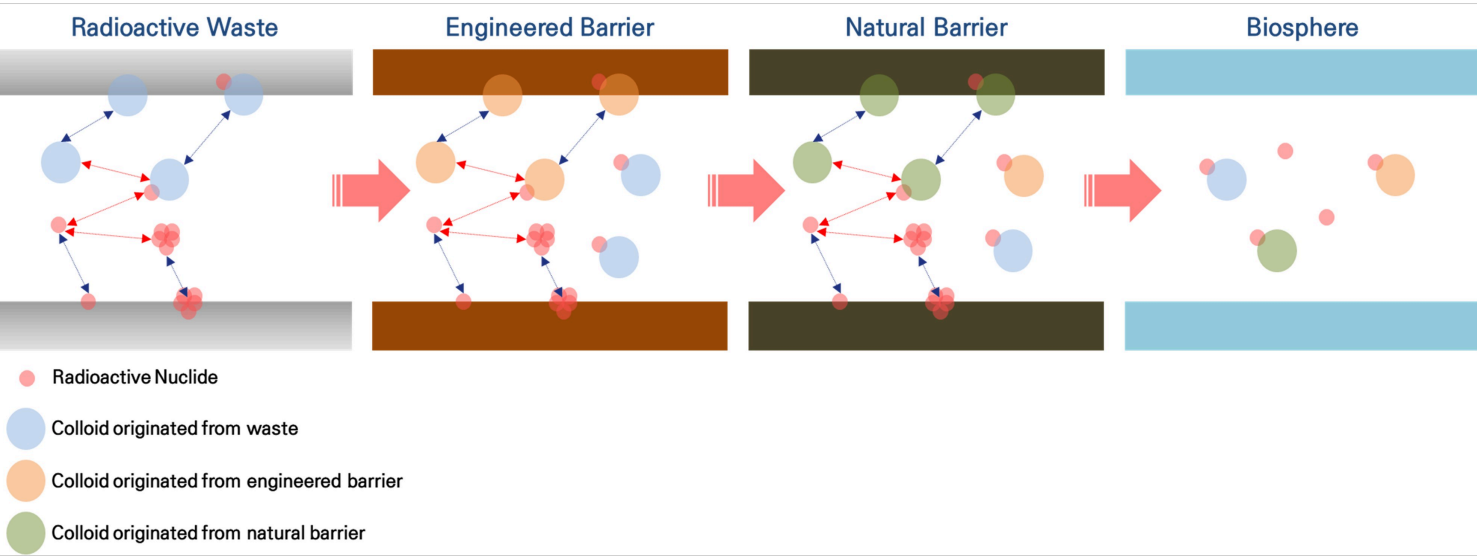


Figure 1

Conceptual model of colloid-facilitated radionuclide transport in a near-surface disposal facility, in which colloids generated from the waste, the engineered barrier, and the natural barrier sorb radionuclides and carry them through the successive barriers toward the biosphere.

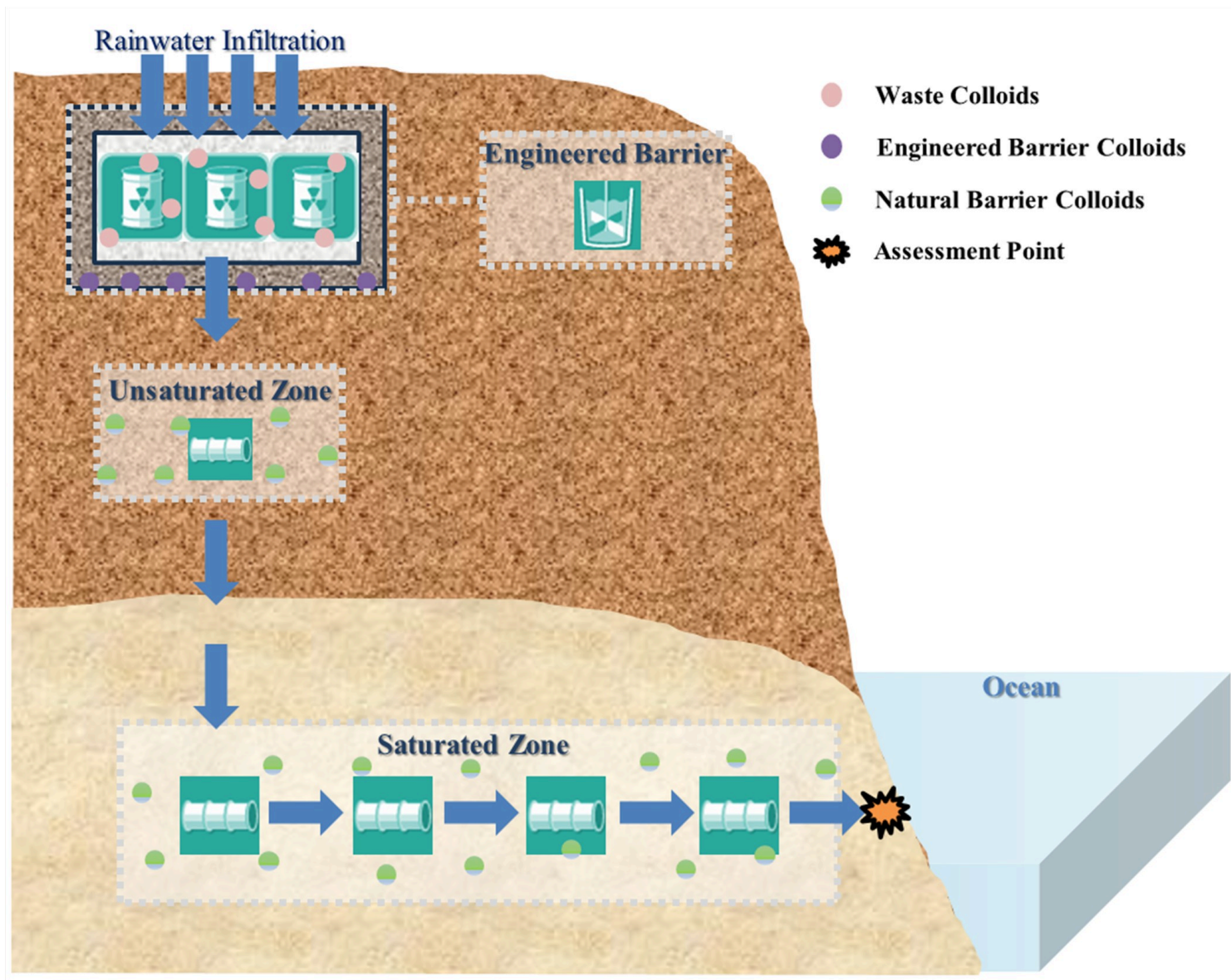


Figure 2

Structure of the GoldSim Species-based model, in which dissolved and colloid-associated radionuclides are treated as separate species and transported along the pathway from the waste vaults through the unsaturated and saturated zones to the geosphere-biosphere interface.

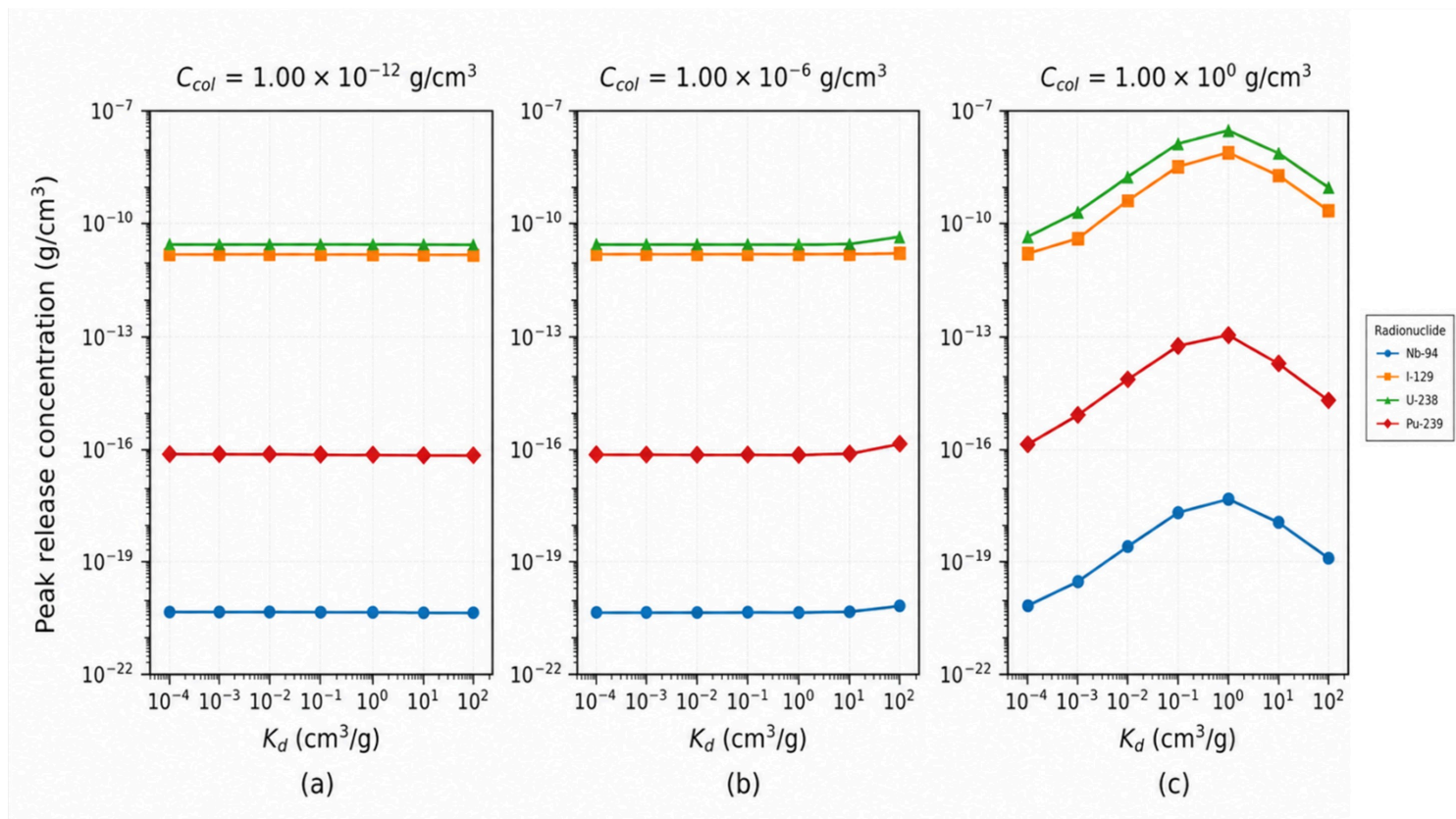


Figure 3

Sensitivity of the peak release concentration at the GBI to the radionuclide-colloid distribution coefficient for the four target radionuclides (Nb-94, I-129, U-238, and Pu-239), at fixed colloid concentrations of (a) 1.00×10^{-12} , (b) 1.00×10^{-6} , and (c) 1.00×10^0 g/cm³.

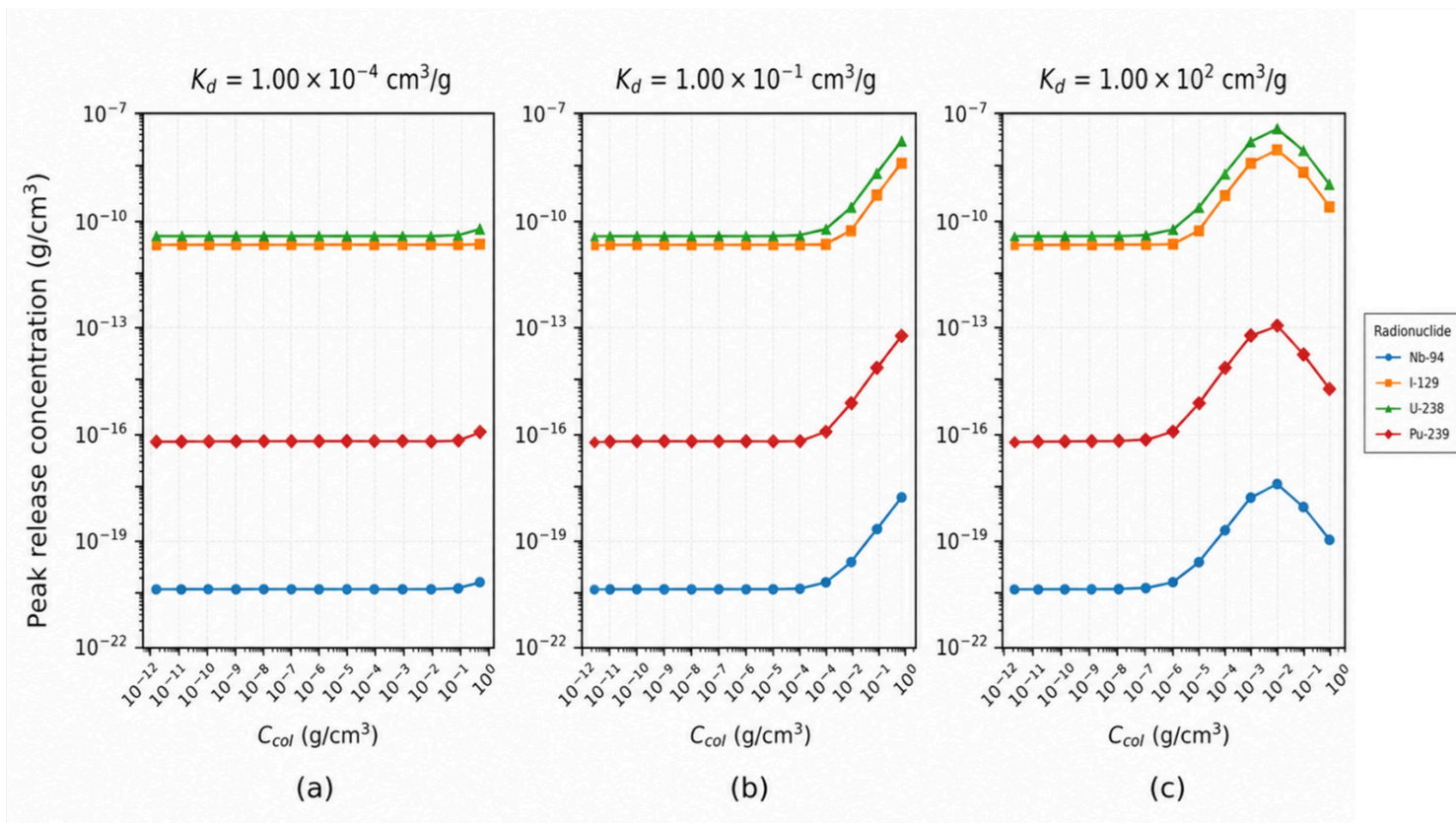


Figure 4

Sensitivity of the peak release concentration at the GBI to the colloid concentration for the four target radionuclides (Nb-94, I-129, U-238, and Pu-239), at fixed radionuclide-colloid distribution coefficients of (a) 1.00×10^{-4} , (b) 1.00×10^{-1} , and (c) $1.00 \times 10^2 \text{ cm}^3/\text{g}$.

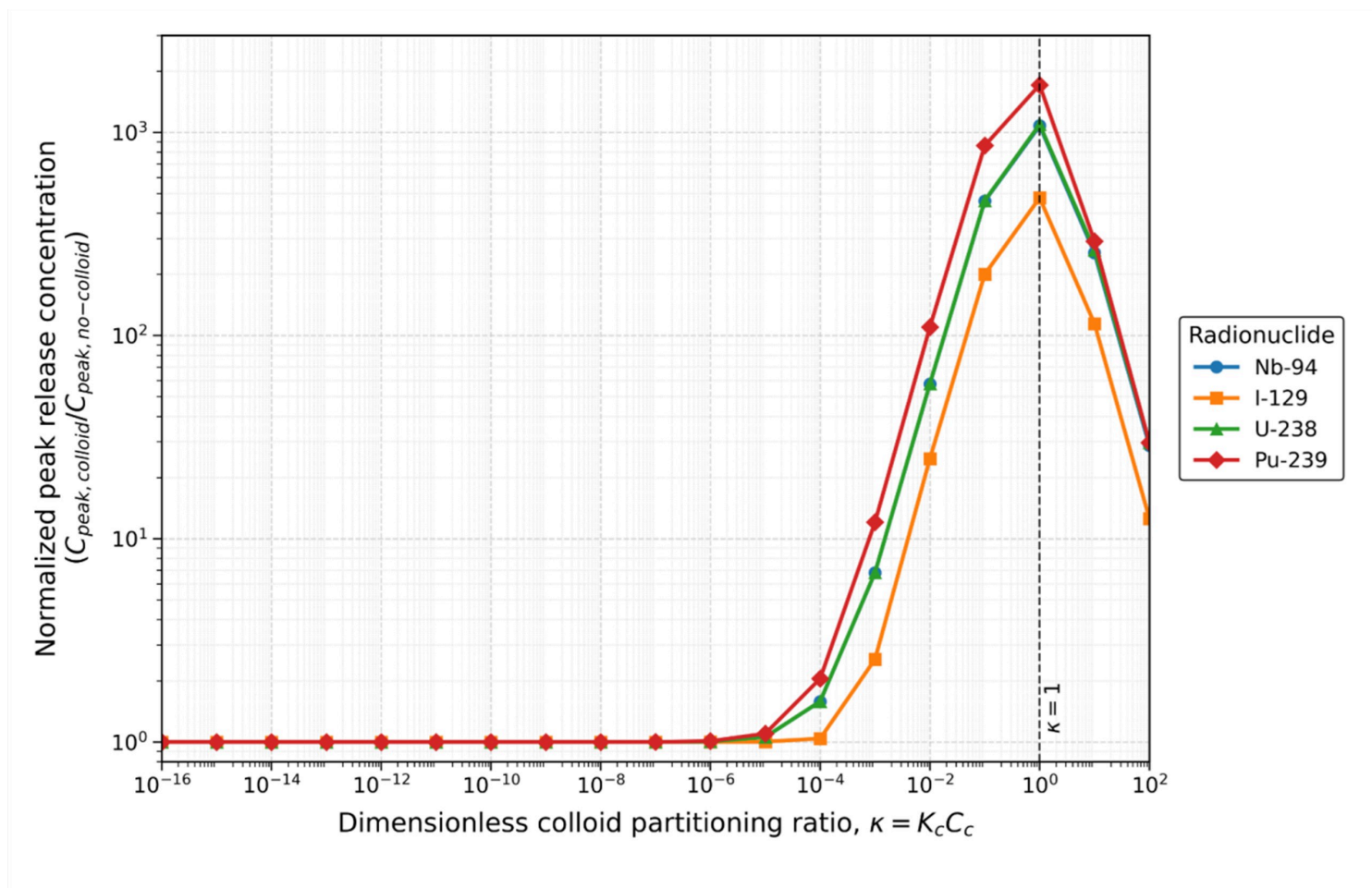


Figure 5

Collapse of the normalized peak release concentration as a function of the dimensionless colloid partitioning ratio, $k = K_c C_c$. The peak release concentration for each colloid case was normalized by the corresponding no-colloid peak release concentration. The vertical dashed line indicates $k = 1$, where dissolved and colloid-associated fractions become comparable.

Supplementary Files

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