Long-term Evolution of Radionuclide Migration in an Artificial Disposal System: Modeling using the APro Framework

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1. Introduction

The safe management of spent nuclear fuel (SNF) is essential for the long-term sustainability of nuclear energy. Deep geological disposal (DGD) is widely recognized as a viable approach due to its ability to ensure safety and minimize environmental impact. Long-term safety assessments of deep geological repositories (DGRs) must comply with regulatory standards, considering long-term evolution scenarios that encompass all relevant natural and low-probability events.

The Korea Atomic Energy Research Institute (KAERI) has been developing the Adaptive Process-based Total System Performance Assessment (APro) framework to simulate radionuclide migration in DGRs and evaluate associated radiation exposure. This paper presents a total system performance assessment (TSPA) procedure using the APro framework and its application to modeling radionuclide migration under long-term evolution scenarios. The results highlight the effectiveness of APro in assessing the long-term safety of deep geological disposal.

2. Methodology

2.1. TSPA procedure in the APro framework

The TSPA procedure for the long-term evolution scenarios using the APro framework has been established, as illustrated in Figure 1. The primary objective of this procedure is to evaluate radionuclide migration within a disposal system and the radiation exposure to representative individuals resulting from the release of radionuclides into the ecosystem, considering the defined characteristics of the disposal system and long-term evolution scenarios. To achieve this objective, the APro performance assessment framework is structured into three core stages: (1) performance assessment (PA), (2) radionuclide migration scenario definition, and (3) TSPA modeling and evaluation.

2.2. Artificial Disposal System

To demonstrate the applicability of the APro framework, radionuclide migration in a near- and a far-field of an artificial geological disposal system (ADioS) is simulated using the model built with the APro framework. The ADioS is a hypothetical DGR that is defined for modeling tests of the APro. Details on components, domain, properties, FEPs, and long-term evolution scenarios of the ADioS is explained elsewhere [1;2].

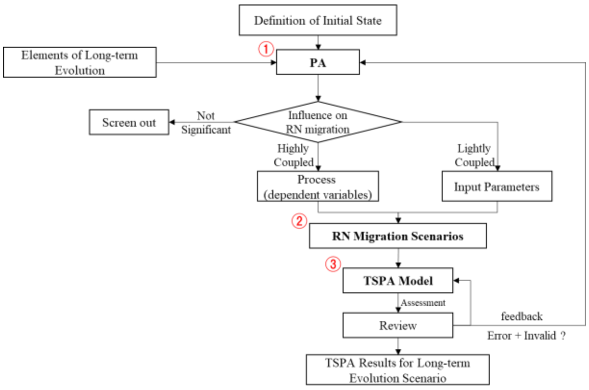

Figure 1. TSPA procedure in the APro framework

2.3. Assessment model flowchart

Given the TSPA procedure of the APro, assessment model flowchart for the reference scenarios of the ADioS is designed, as illustrated in Figure 2. Two PA cases are defined as: the hydraulic evolution of the disposal system by long-term climate changes; and determination of the location of canister with initial defect.

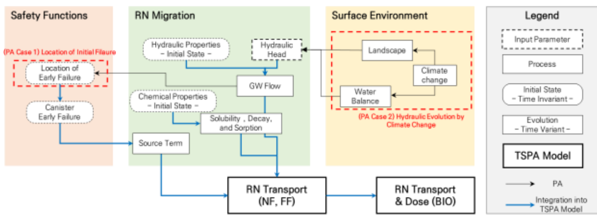

Figure 2. AMF for the Reference Scenario of the ADioS

3. Results and Discussion

3.1. Performance assessment cases

Changes in surface environment is defined in snapshot concept and the delineation of the changes over time for the reference scenario of the ADioS is illustrated in Figure 3 [3]. The change in hydraulic head over geosphere-biosphere interface (GBI) of each snapshot is evaluated using APro, as depicted in Figure 4. The results of this PA case are used as input parameters for the TSPA model.

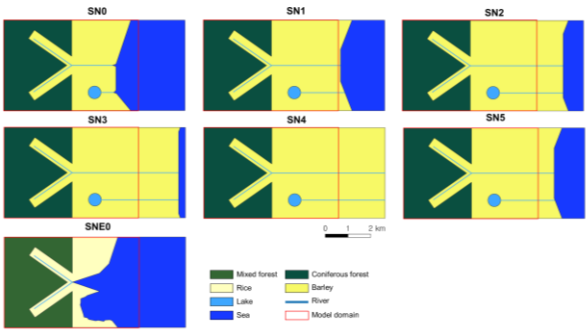

Figure 3. Illustration of surface environment evolution for the reference scenario of the ADioS [3]

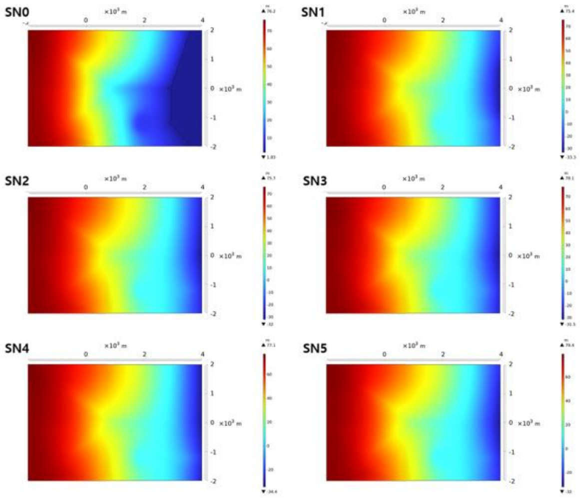

Figure 4. Changes in hydraulic head over geosphere-biosphere interface by climate change

The reference scenario of the ADioS specify that at least one disposal canister has initial defect [2]. In this study, we assumed that the single canister with initial defect is located in a deposition hole where the distance between a large fracture is minimum, as illustrated in Figure 5.

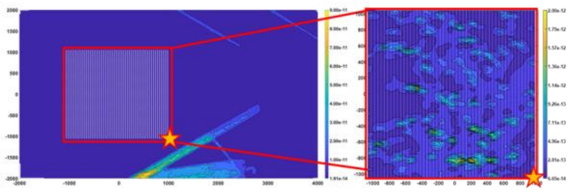

Figure 5. Flow velocity in the repository domain and the location of the canister with initial defect

3.2. Radionuclide migration in the ADioS

Groundwater flow in the near-field where the failed canister located is presented in Figure 6. The differences in groundwater flow across the snapshot models are negligible, indicating that the effects of climate change have minimal impact on the deep underground disposal facility.

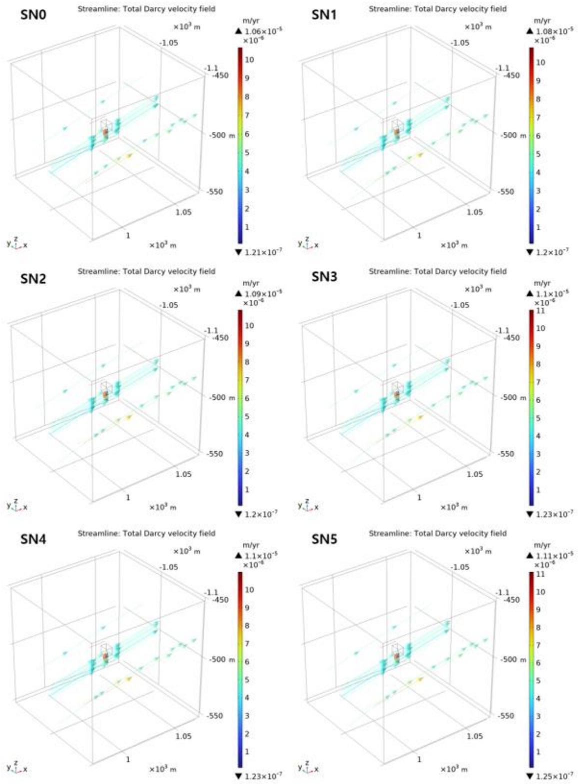

Figure 6. Groundwater flow in the near-field

The groundwater flow paths through the near-field for snapshots SN0 and SN1 are illustrated in Figure 7. As the coastline retreats due to climate change (see Figure 3), the end points of the path at the GBI also changes. The groundwater flow paths observed for SN2 and later snapshots closely resemble those of SN1. The bottom section of Figure 7 highlights a region within the host rock where the permeability exceeds 10^{-16} m², implicitly indicating the location of large fractures. This suggests that groundwater flow in the far-field region is predominantly governed by the fractured zone.

Figure 8 illustrates the temporal evolution of ^{129}I concentration contours in the near-field, revealing a transition from an initial spherical plume to an asymmetric shape influenced by groundwater flow. This shift indicates that radionuclide migration is diffusion-dominated in bentonite buffer materials but increasingly advection-driven in the host rock. The plume expands for approximately 10,000 years before gradually contracting, attributed to the rapid initial release from the Instant Release Fraction (IRF), followed by a sustained, lower-rate release from the spent nuclear fuel matrix.

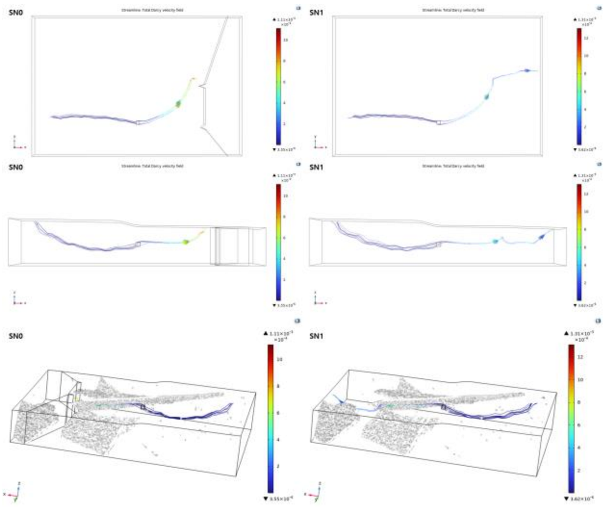

Figure 7. Groundwater flow in the far-field and the location of large fractures in the domain

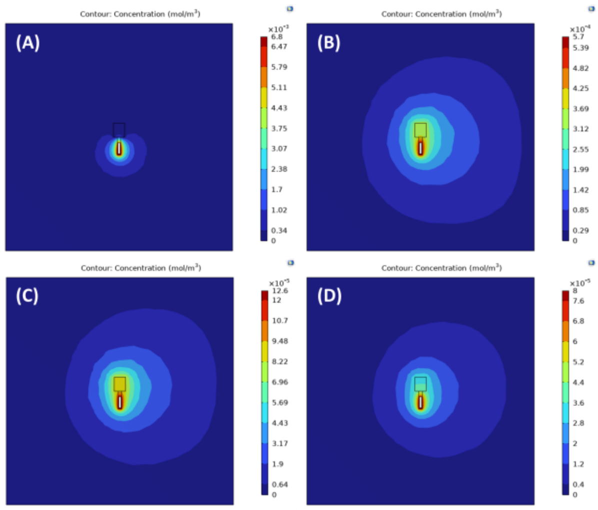

Figure 8. Changes in ^{129}I concentration in the near-field over time: (A) t = 10^3 years; (B) t = 10^4 years; (C) t = 10^5 years; (D) t = 10^6 years

The evolution of the ^{129}I plume in the far-field was evaluated, as shown in Figure 9. At 5,000 years, the plume remains nearly spherical. By 10,000 years, it reaches a major fracture zone near the repository, and by 30,000 years, it extends along the fracture toward the GBI. At 100,000 years, the plume size decreases compared to 30,000 years, indicating a decline in the initial high flux from the IRF, with long-term flux being predominantly governed by congruent release from the fuel matrix.

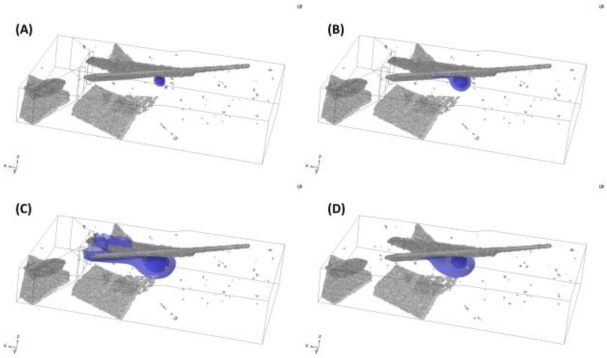

Figure 9. Changes in ^{129}I concentration in the far-field over time: (A) t = $5{\cdot}10^3$ years; (B) t = 10^4 years; (C) t = $5{\cdot}10^4$ years; (D) t = 10^5 years

The GBI flux of major fission products (^{36}Cl, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{129}I, ^{135}Cs, ^{147}Sm) is illustrated in Figure 10. The flux of ^{93}Zr, ^{107}Pd, ^{126}Sn, and ^{147}Sm was evaluated to be bellow 10^{-23} mol/s, making it undetectable in the graph.

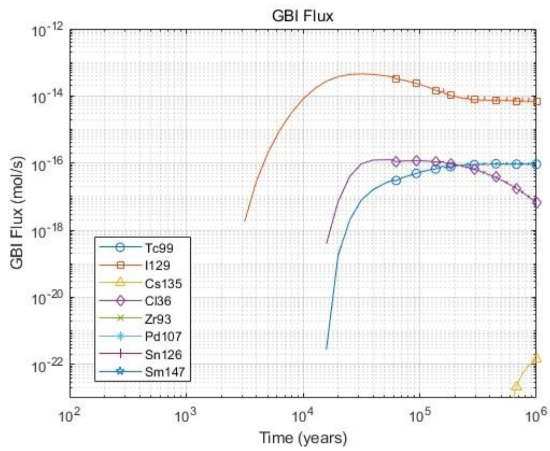

Figure 10. GBI flux of major fission products

4. Conclusions

This study aims to develop a methodology for the TSPA of the DGR systems considering long-term evolution scenarios using the APro framework developed by KAERI. The proposed TSPA procedure was applied to radionuclide migration evaluations in both the near- and far-field under the ADioS reference scenario, demonstrating the applicability of the APro. The findings confirm that APro can effectively assess primary and complementary safety indicators of the DGR.

Acknowledgements

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