Methodology for Generalized Risk Assessment of Multi Event Scenarios in Deep Geological Repositories

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ABSTRACT

The safety of deep geological repositories for long-term storage of spent nuclear fuel is internationally assessed using the concept of a safety case, with guidelines and regulatory requirements differing across countries. In South Korea, quantitative results of safety assessments must satisfy both dose exposure and risk criteria to meet regulatory requirements.

Unlike dose exposure, the risk of a disposal facility must be evaluated comprehensively across all scenarios. Authors' previous studies developed a customized PSA (Probabilistic Safety Assessment) framework for disposal facilities by selectively combining applicable features of methodologies used in commercial nuclear power plants, such as the judgmental method and fault tree/event tree analysis method. Furthermore, concept of deriving a risk profile was concretized into a time-dependent risk profile reflects the probability of events occurring within specific time intervals. A simulation quantification template on a spreadsheet program was developed for both normal scenarios and abnormal events. However, this template faced limitations requiring excessive computation when considering arbitrary abnormal events in terms of types, frequencies, and intensities.

To overcome these limitations, this study established a statistics-based algorithm applicable to such abnormal events. Additionally, an efficient quantification methodology was proposed to appropriately screen out intervals with expected low-risk values. The proposed methodology was verified by deriving risk profiles using the GoldSim code, used for radionuclide transport evaluations, and external spreadsheet programs.

This study enables more realistic and efficient risk assessment under general conditions encompassing arbitrary abnormal events. Future research will address the limitations and propose improved solutions.

Keywords: Risk assessment, Abnormal Events, Deep geological repository

I. Introduction

The safety of deep geological disposal facilities for spent nuclear fuel is internationally evaluated through a concept known as the "Safety Case." Guidelines and regulatory requirements related to this approach, however, differ from country to country. In South Korea, quantitative outcomes of safety assessments must satisfy established criteria for both radiation exposure and risk levels to meet safety objectives. To verify compliance with these criteria, an existing methodology—combining radiation dose evaluations with external events to derive and assess a risk profile—has been employed. This study aims to propose an enhanced risk assessment methodology considering arbitrary abnormal event scenarios.

During the operational period of deep geological disposal facilities, various abnormal events could impact facility integrity, potentially leading to radioactive leakage. Radioactive materials released from canisters within the facility migrate through engineered barriers (buffers), subsequently transferred through geological barriers into groundwater, soil, and further environmental pathways. Given that such leakage may directly affect ecosystems, risk assessments considering abnormal event scenarios are essential.

Unlike exposure dose assessments, facility risk assessments must integrate all potential scenarios comprehensively. Authors' previous studies developed a customized PSA (Probabilistic Safety Assessment) framework for disposal facilities by selectively combining applicable features of methodologies used in commercial nuclear power plants, such as the judgmental method and fault tree/event tree analysis method. Furthermore, the concept of deriving a risk profile was concretized into a time-dependent risk profile reflects the probability of events occurring within specific time intervals. A simulation quantification template was established considering normal scenarios and a single abnormal event scenario (such as one seismic event). If the peak values of the derived risk profile satisfy the established criteria, the evaluated scenarios confirm the facility's safety. However, this template faced limitations requiring excessive computation when considering arbitrary abnormal events in terms of types, frequencies, and intensities.

To overcome these limitations, this study presents an applicable to such abnormal events for deep geological disposal facilities. Additionally, an efficient quantification methodology was proposed to appropriately screen out intervals with expected low-risk values. The proposed methodology's validity is examined through a spreadsheet program and GoldSim, which is commonly used for radionuclide transport modeling and evaluation. In subsequent studies, software integration between a spread sheet (i.e. Microsoft Excel) and GoldSim will be developed, enabling the automatic transfer of input data regarding abnormal events and facility conditions from the spread sheet to GoldSim. This advancement is anticipated to overcome the limitations of previous methodologies and enable accurate and efficient risk assessments for generalized scenarios encompassing arbitrary abnormal events.

II.A. Statistics-based algorithm (methodology)

Deep geological repositories for high-level radioactive waste must be designed to ensure that radiation impacts after closure meet clearly defined safety objectives [1]. Specifically:

1. The annual total risk of radiation exposure to a representative individual, considering major scenarios including natural phenomena and human intrusion, must not exceed 10^{-6}.
2. For individual scenarios involving low-probability natural events or human intrusion, the expected annual radiation dose to a representative individual must not exceed $10\ mSv$.

These safety objectives are defined using the following equation:

$$Total\ Risk = r \sum_i P_i D_i \tag{1}$$

Where:
3. r is the risk coefficient ($0.05/Sv$)
4. i denotes each exposure scenario
5. P_i is the probability of occurrence for scenario i
6. D_i is the annual radiation dose to the representative individual for scenario i

It is important to note that Eq. (1) serves as a conceptual expression. Rather than expressing total risk as a single fixed value, the risk is expected to be represented in the form of a risk profile, where the risk values vary over different time periods.

This research proposes a novel approach to reduce excessive computations and keep reasonable conservatism, efficient risk assessment. The procedure steps are structured as follows:

1. Event count
   - The number of events N during the mission time T, given an annual occurrence rate r, is assumed to follow a Poisson distribution with a mean λ defined as:

$$\lambda = r \cdot T \tag{2}$$

   - The probability of exactly k events occurring is given by:

$$P(N = k) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{3}$$

   - To construct a realistic scenario space, a sufficiently conservative upper bound B is selected from the Poisson distribution based on a predefined confidence level. This defines the meaningful range of event counts $[A, B]$ to be considered in the analysis. Within this range, a specific value B is selected as the representative number of events to be used for scenario evaluation.

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2. Identification of the focus period using normal scenario simulation
   - The focus period is defined as the time interval $[t_i, t_f]$ showing the highest consequence in a baseline GoldSim simulation with no abnormal events. This ensures consistent and objective identification of the most critical period before risk scenario analysis.

3. Determining the number of events during the focus period using gamma CDF

$$F(t_i, t_f; \alpha, \beta) = \int_{t_i}^{t_f} \frac{1}{\Gamma(\alpha)\beta^{\alpha}} t^{\alpha-1} \mathrm{e}^{-t/\beta}\, \mathrm{d}t \tag{4}$$

   - Selected number of events G satisfying the probability threshold L are included in the analysis.

$$F(G; \alpha, \beta) \geq \mathrm{L} \tag{5}$$

4. Temporal allocation of events during and outside of the focus period.
   - Among the total number of events B selected from the Poisson distribution, the G events satisfying the probability threshold L are assumed to occur randomly within the focus period.
   - The remaining number of events $(B - G)$ are assumed to occur at evenly spaced intervals during the non-focus period.

5. Risk evaluation and aggregation
   - Since the objective is to evaluate the most conservative scenario for a given event frequency, the probability of the scenario is assumed to be 1 for assessment purposes.
   - A simulation is conducted using GoldSim to generate the dose-rate profile corresponding to this specific scenario.
   - The final risk profile is then obtained by multiplying the dose-rate profile with the scenario probability.
   - This completes the risk assessment for the event scenario with the specified frequency.
   - In a similar context, risk evaluations are performed for other event scenarios with different frequencies or different event types using the same methodology. The resulting risk profiles from all these scenarios are then aggregated to produce the final risk assessment for the set of abnormal events.

II.B. Deriving input parameters for GoldSim using spreadsheet program

To enable implementation of the risk assessment methodology in GoldSim, key simulation input parameters were derived using a structured spreadsheet approach. This process references the probabilistic framework introduced earlier, incorporating relevant equations and logical steps to represent event frequency and temporal distribution.

First, the Poisson probability density function (PDF) was used to determine the range $[A, B]$, which captures the statistically meaningful number of events during the Mission Time ($T = 10^7 years$) given an annual occurrence rate of $r = 10^{-5} event/year$. The resulting range, illustrated Fig. 1, was determined with reference to a sufficiently conservative confidence level, allowing the upper bound $B = 119$ to be selected for further analysis. As shown in Fig. 1, the range was chosen to meet a 95% probability, ensuring that the selected upper bound satisfies a conservative assumption for subsequent evaluations.

Determination of [A,B]		mission time	10000000
		r	0.00001
	Poisson distribution(CDF)		
count	probability	count	probability
80	2.265E-02	100	5.266E-01
81	2.907E-02	101	5.660E-01
82	3.689E-02	102	6.047E-01
83	4.632E-02	103	6.423E-01
84	5.755E-02	104	6.784E-01
85	7.075E-02	105	7.128E-01
86	8.611E-02	106	7.453E-01
87	1.038E-01	107	7.756E-01
88	1.238E-01	108	8.037E-01
89	1.463E-01	109	8.294E-01
90	1.714E-01	110	8.529E-01
91	1.989E-01	111	8.740E-01
92	2.288E-01	112	8.928E-01
93	2.610E-01	113	9.095E-01
94	2.952E-01	114	9.241E-01
95	3.312E-01	115	9.368E-01
96	3.687E-01	116	9.478E-01
97	4.074E-01	117	9.572E-01
98	4.468E-01	118	9.651E-01
99	4.867E-01	119	9.718E-01

FIGURE 1. Determination of $[A, B]$

Next, to account for the variability in the number of events during the designated focus period, the cumulative distribution function (CDF) of the gamma distribution, as introduced in Eq. (4), was applied. Probabilities of one, two, and three earthquakes occurring within the focus period $(10^5 years)$ were calculated, and the results are presented in Fig. 2. Based on the criterion (Eq. (5)), where $L = 0.05$ represents the minimum acceptable probability, the number of events satisfying this threshold was identified. Under the most conservative assumption, the value of $G = 3$ was selected

Determination of G			
	Focus Period	0~100000 year	
Time(year)	1 Event	2 Events	3 Events
0	0.E+00	0.E+00	0.E+00
1000	1.E-02	5.E-05	2.E-07
2000	2.E-02	2.E-04	1.E-06
3000	3.E-02	4.E-04	4.E-06
4000	4.E-02	8.E-04	1.E-05
5000	5.E-02	1.E-03	2.E-05
6000	6.E-02	2.E-03	3.E-05
7000	7.E-02	2.E-03	5.E-05
8000	8.E-02	3.E-03	8.E-05
9000	9.E-02	4.E-03	1.E-04
10000	1.E-01	5.E-03	2.E-04
11000	1.E-01	6.E-03	2.E-04
12000	1.E-01	7.E-03	3.E-04
13000	1.E-01	8.E-03	3.E-04
14000	1.E-01	9.E-03	4.E-04
15000	1.E-01	1.E-02	5.E-04
16000	1.E-01	1.E-02	6.E-04
17000	2.E-01	1.E-02	7.E-04
18000	2.E-01	1.E-02	8.E-04
19000	2.E-01	2.E-02	1.E-03
20000	2.E-01	2.E-02	1.E-03
21000	2.E-01	2.E-02	1.E-03
22000	2.E-01	2.E-02	2.E-03
23000	2.E-01	2.E-02	2.E-03
24000	2.E-01	2.E-02	2.E-03
25000	2.E-01	3.E-02	2.E-03
26000	2.E-01	3.E-02	2.E-03
27000	2.E-01	3.E-02	3.E-03
28000	2.E-01	3.E-02	3.E-03
29000	3.E-01	3.E-02	3.E-03
30000	3.E-01	4.E-02	4.E-03

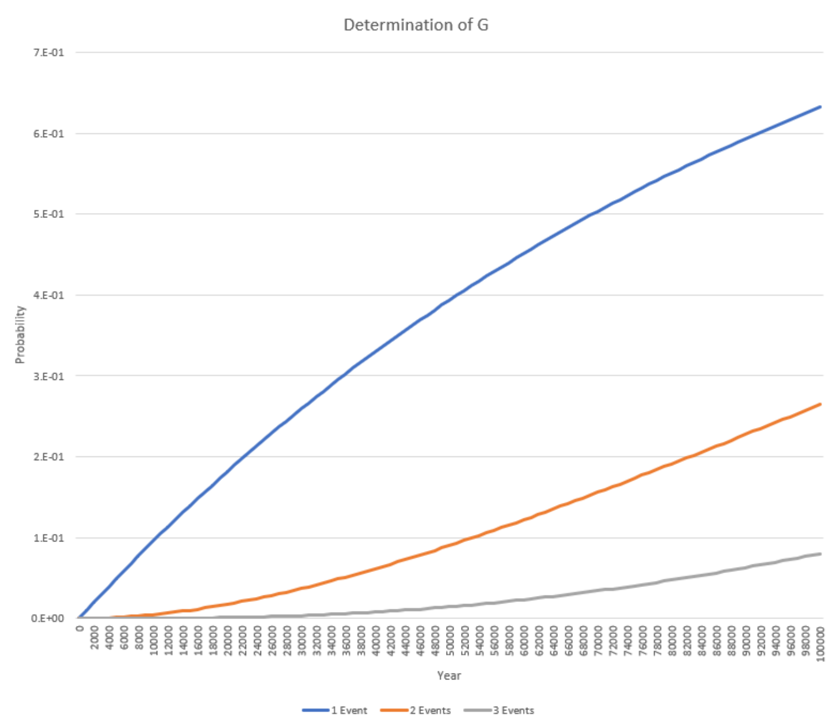

FIGURE 2. Determination of G

These derived values were then used to inform the GoldSim simulation logic in Section II.C. In accordance with step 4 of the methodology, it was assumed that G events occur randomly within the focus period, while the remaining $B - G$ events occur at uniformly spaced intervals during the non-Focus Period.

II.C. Practical application and verification with GoldSim

GoldSim was utilized in this research to estimate the levels of radionuclide release and exposure, which are influenced by incidents occurring near the disposal site. It was also applied to derive the likelihood of various scenarios. As a modeling tool, GoldSim enables the simulation of both actual and theoretical systems, making it particularly useful for scenario analysis in waste disposal facilities. It can replicate the release and movement of radioactive materials from waste, and is widely recognized for its role in evaluating the safety of low- and high-level radioactive waste repositories both domestically and internationally.

The repository simulation model was created using GoldSim, based on multiple hypothetical assumptions. The primary aim of the study was to demonstrate the modeling approach rather than to derive precise numerical outcomes. This repository model includes components such as radionuclide inventory, waste canisters, buffer/backfill materials, the Excavated Damaged Zone (EDZ), natural barriers, and the surrounding ecosystem. For each component, adsorption and precipitation processes were considered. The model assumed that radioactive materials are leached by groundwater entering the canister due to degradation, and then transported through advection and diffusion mechanisms. The canister is assumed to fail after $10^4 years$, with radionuclides being released at a defined rate from the point of failure.

Each component's parameters were derived from SKB's report [2], and in cases where data ranges were provided, values were modeled using triangular distributions due to limited available data [3].

Based on the generalized methodology presented earlier, a GoldSim simulation was conducted to derive the corresponding risk plot. Among various abnormal scenarios, an earthquake was selected as a representative example. The total mission time for the simulation was set to $10^7\ years$, with an assumed earthquake frequency of 10^{-5}events/year.

To carry out step 2 and identify the appropriate focus period, a baseline simulation assuming no seismic events was first conducted using GoldSim. The resulting plot from this normal scenario is presented below:

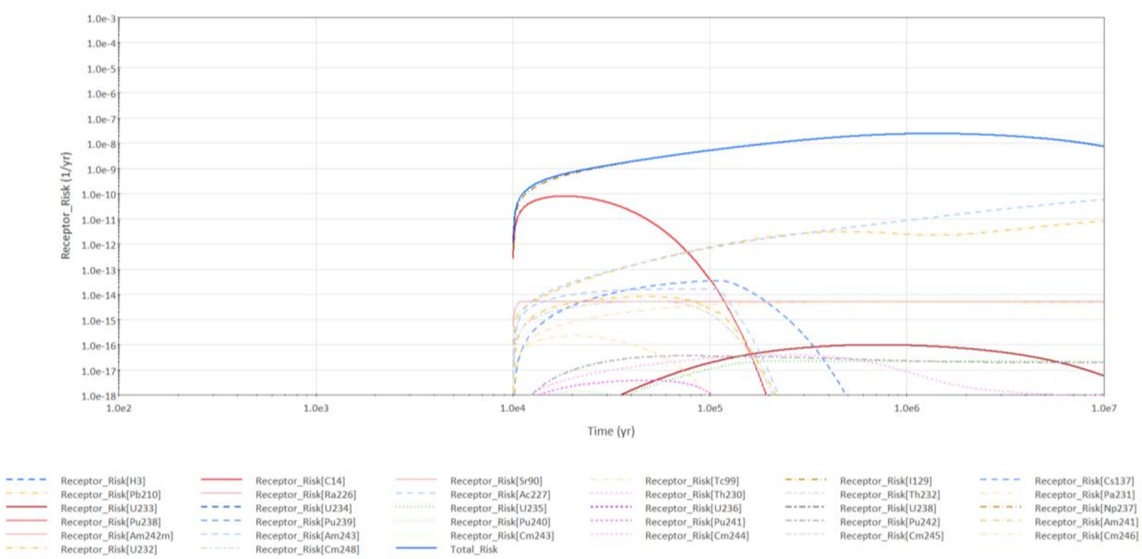

FIGURE 3. Normal scenario Risk Plot

From this plot, the time period during which the maximum consequence occurs under normal conditions can be identified. Assuming a focus period of $10^{-5} years$, multiple earthquake events were introduced in accordance with the methodology. Utilizing the values of G and $(B - G)$ calculated in the accompanying spreadsheet, step 5 of the proposed methodology was applied. The resulting outcomes are illustrated in the following plot:

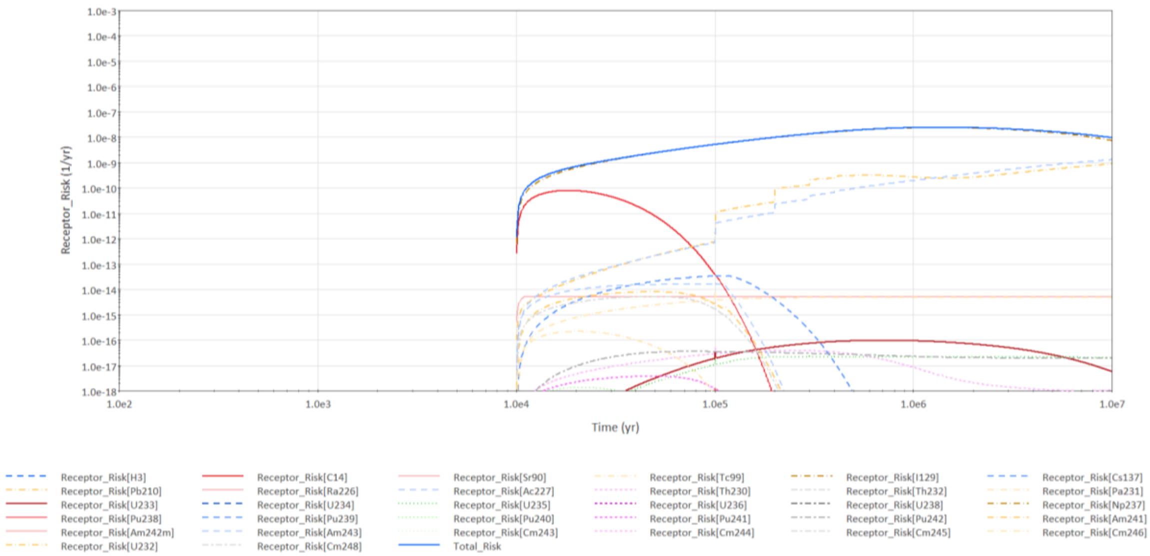

FIGURE 3. Multi Earthquake scenario Risk Plot

III. Conclusion

This study proposed a generalized methodology for conducting risk assessments of abnormal event scenarios in deep geological repositories, with a particular focus on computational efficiency and probabilistic rigor. The methodology integrates statistical modeling using Poisson and Gamma distributions to quantify the frequency and temporal distribution of events and identifies a focus period with the highest consequence for further analysis.

Input parameters for GoldSim simulations were derived through a structured spreadsheet-based process, allowing for flexible and reproducible implementation of event-based risk profiles. By applying a conservative scenario involving multiple earthquakes, the study demonstrated how probabilistic thresholds and event allocations could be used to generate time-dependent risk plots. The resulting profiles reflect both the uncertainty and dynamic nature of long-term safety assessments in geological disposal systems.

Through practical application and verification using GoldSim, the proposed approach was shown to offer a realistic and efficient framework for simulating the impact of arbitrary abnormal events. This enhances the robustness of risk assessments under generalized conditions, especially in regulatory environments that require comprehensive evaluation of both dose and risk criteria.

Future work will focus on automating data transfer between spreadsheet tools and simulation software to further streamline the process and expand the applicability of the methodology to a broader range of event types and repository configurations.

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