AN INTEGRATED APPROACH TO RISK-BASED POST-CLOSURE SAFETY EVALUATION OF COMPLEX RADIATION EXPOSURE SITUATIONS IN RADIOACTIVE WASTE DISPOSAL

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Embodying the safety of radioactive waste disposal requires the relevant safety criteria and the corresponding stylized methods to demonstrate its compliance with the criteria. This paper proposes a conceptual model of risk-based safety evaluation for integrating complex potential radiation exposure situations in radioactive waste disposal. For demonstrating compliance with a risk constraint, the approach deals with important exposure scenarios from the viewpoint of the receptor to estimate the resulting risk. For respective exposure situations, it considers the occurrence probabilities of the relevant exposure scenarios as their probability of giving rise to doses to estimate the total risk to a representative person by aggregating the respective risks. In this model, an exposure scenario is simply constructed with three components: radionuclide release, radionuclide migration and environment contamination, and interaction between the contaminated media and the receptor. A set of exposure scenarios and the representative person are established from reasonable combinations of the components, based on a balance of their occurrence probabilities and the consequences. In addition, the probability of an exposure scenario is estimated on the assumption that the initiating external factors influence release mechanisms and transport pathways, and its effect on the interaction between the environment and the receptor may be covered in terms of the representative person. This integrated approach enables a systematic risk assessment for complex exposure situations of radioactive waste disposal and facilitates the evaluation of compliance with risk constraints.

Keywords : Risk Assessment, Radioactive Waste Disposal, Exposure Scenarios, Dose-Likelihood Aggregation, Conceptual Model

1. INTRODUCTION

The post-closure safety assessment of a radioactive waste disposal system needs to consider the various possibilities for human radiation exposure on the site specific basis[1]. Some normal natural processes such as the degradation of the engineering barriers and transport of radionuclides by groundwater may result in a gradual release of radionuclides into the environment, which could lead to human exposure some time in the future. Other, less likely, natural disruptive events such as earthquakes or faulting may affect the performance of the disposal system. In addition, human actions, so called "human intrusions", in the future may also disrupt a disposal system. Since the evolution of a disposal system and the future status of the biosphere are very uncertain over long time periods, there may exist a number of potential exposure situations[2].

For achieving radiological protection of the public or future generations from the disposal of radioactive waste in the long term, the individual source related safety criteria, in the form of dose and/or risk constraints, shall be established for the post-closure phase of the disposal system. In this context, risk is defined as the product of the probability of receiving a radiation dose and the probability that the dose will give rise to a deleterious health effect[3]. The same degree of protection can be achieved by using either a risk constraint or a dose constraint in consideration of the likelihood that the doses would be incurred. The safety criteria may be set up separately by categories of exposure situations (e.g., normal natural processes, probabilistic natural events, and human intrusions) or overall for all the situations. Table 1 shows some national safety criteria for the post-closure phase of radioactive waste disposal[4].

Embodying the radiological safety of a waste disposal

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Table 1. National Dose and Risk Constraints for Post-Closure Safety of Radioactive Waste Disposal Facilities in Some Selected Countries[4].

Country	Low and Intermediate Level Waste (LILW)	High-Level Waste (HLW)
Finland	▪ As an expectation value, 0.1 mSvy^{-1} from normal evolution ▪ 5 mSvy^{-1} for accidental conditions	▪ 0.1 mSvy^{-1} for normal evolution ▪ As an expectation value, 0.1 mSvy^{-1} from unlikely events
France	(refer to the ICRP recommendation)	▪ 0.25 mSvy^{-1} for normal evolution
Germany	▪ 0.3 mSvy^{-1} for all scenarios	▪ 10^{-6} risky^{-1} from situations with probabilities more than 10^{-7}y^{-1} ▪ 10^{-5} risky^{-1} from situations with probabilities more than 10^{-8}/y
Japan	▪ 0.01 mSvy^{-1} for normal scenarios ▪ 0.3 mSvy^{-1} for scenarios with low probability ▪ 10 mSvy^{-1} for accidental situations	Under development: ▪ Considering 0.3 mSvy^{-1} for all scenarios as a basic criterion
Korea	▪ 0.1 mSvy^{-1} for normal evolution ▪ 10^{-6} risky^{-1} from all natural probabilistic scenarios ▪ 1 mSvy^{-1} for human intrusion	Under development: ▪ Considering 5×10^{-6} risky^{-1} from all scenarios with 5 mSvy^{-1} for an individual scenario
Sweden	▪ 10^{-6} risky^{-1} from all scenarios	▪ 10^{-6} risky^{-1} from all scenarios
Switzerland	▪ 0.1 mSvy^{-1} for normal scenarios ▪ 10^{-6} risky^{-1} from all probabilistic scenarios	▪ 0.1 mSvy^{-1} for situations with high probabilities ▪ 10^{-6} risky^{-1} from all situations with low probabilities
United Kingdom	▪ 10^{-6} risky^{-1} from all scenarios	▪ 10^{-6} risky^{-1} from all scenarios
USA	▪ 0.25 mSvy^{-1} for natural scenarios	▪ 0.15 mSvy^{-1} for natural scenarios for 104 yrs ▪ 1 mSvy^{-1} for natural scenarios beyond 104 yrs
IAEA (ICRP)	▪ 0.3 mSvy^{-1} for natural scenarios; or ▪ 10^{-5} risky^{-1} from all natural scenarios	▪ 0.3 mSvy^{-1} for natural scenarios; or ▪ 10^{-5} risky^{-1} from all natural scenarios

system requires not only the relevant safety criteria but also the corresponding stylized methods to demonstrate its compliance with the criteria. The approaches taken to show whether constraints are satisfied can be classified broadly into two types in connection with the form of constraints[3]: (1) a disaggregated approach considering the dose and its corresponding likelihood of occurrence separately for each exposure situations and (2) an aggregated approach combining doses and probabilities to estimate risk. In a disaggregated approach, likely release scenarios are identified and the doses calculated, usually by using a deterministic analysis, from these scenarios are compared with the dose constraint. The significance of other less likely scenarios can be examined from separate consideration of the resultant doses and their likelihood of occurrence. In other words, this approach does not need strict treatment of the probability of such scenarios but rather an appreciation of their radiological consequences balanced against the estimated level of their likelihood. On the other hand, the aggregated approach, or risk-based approach, calculates the total risk from all credible processes involving the relevant waste disposal system which may give rise to doses to future individuals and compares it with the risk constraint. This approach is conceptually perfect in that it integrates the effects of all types of scenarios. However, the concept of risk is not easy to grasp and the approach requires an overall analysis of all relevant exposure situations and their associated probabilities within the assessment time frame under consideration[5].

Although recent remarkable development in the probabilistic safety assessment (PSA) methodology based on event tree or fault tree analysis has been successfully grafted into nuclear systems analysis[6,7], a serious model has not been introduced yet for a comprehensive risk evaluation of radioactive waste disposal systems. Unlike the other cases of nuclear facilities, the post-closure safety assessment of a radioactive waste disposal system involves different types of potential exposure situations over a much longer period which tend to depend upon natural evolutions with time, difficult to quantify, rather than upon current engineering features relatively easy to analyze. Due to such difficulties, some efforts has been restricted to elaborating a probabilistic model for individual exposure scenarios[8,9] and the risk assessment has remained on an elementary level for radioactive waste disposal in which a traditional performance assessment calculated the doses fragmentarily for a few exposure situations to convert them into risk by rote.

In this paper, the authors try to develop a risk assessment model easily applicable to integrating complex potential exposure situations from radioactive waste disposal.

2. MODEL DEVELOPMENT

The whole exposure pathway from radioactive waste disposed of to a radiation receptor may be simplified in a chain of release, transport and contamination, and radiation exposure, as shown in Fig. 1. We try to integrate the overall exposure situations to evaluate compliance with a relevant risk constraint. For this purpose, we should start with the receptor's standpoint to address them rather than with the source. Then a total risk R to an individual is expressed in a continuous form of expectancy over a dose distribution from possible exposure situations as:

$$R \equiv \gamma \cdot E(D) = \gamma \int_{D} p(D)\, D\, dD \ \ (< risk\ constraint) \qquad (1)$$

where $p(D)$ is the annual probability of receiving a radiation dose in the range (D, $D+dD$), γ denotes the risk coefficient representing the chance of contracting a radiation induced deleterious health effect per unit dose (e.g., $5\times10^{-2}Sv^{-1}$)[10], and $E(D)$ is the expected value of D. Since the dose will be caused from a significantly uncertain mixture of various situations, it is practically not possible to integrate this expression to yield an exact risk, but the risk may be estimated in a discrete way from probable important exposure situations contributing to the total risk as:

$$R \ \approx \ \gamma \sum_{k=1}^{n} p_k D_k = \gamma \sum_{k=1}^{n} p_k C_k F_k \qquad (2)$$

where p_k is the annual probability of exposure situation k giving rise to annual dose D_k to the individual, C_k the radiological level of contaminated media (e.g., Bqg^{-1}), and F_k the dose coefficient linking the contamination level to dose (e.g., $[Svy^{-1}]/[Bqg^{-1}]$) with interactions between the media and the receptor.

To derive exposure situations and p_k for a waste disposal system, it is necessary to begin with the waste from which they originate. In other words, the risk must be assessed from the risk scenarios referring to a relevant combinations of probabilities and consequences for probable exposure scenarios which give a full picture of the risks attributable to the radioactive waste disposal. In order to compose the scenarios, we should identify important components on the pathways from release to contamination to combine them into exposure scenarios, based on a logical structure reflecting both the system-specific properties and the individual characteristics of the pathways. While their composition and level of details depend on the system and available information, the pathways may in general be constructed largely of the release and the transfer. Conceptually, we can suppose a whole system as various potential phenomena of radionuclide migration from a number of sources and scenarios to the environmental media domain of exposures are piled one upon another with time in a topological frame of transfer pathways bounded by the release and the biosphere. Then we may describe the whole potential transfer phenomena from the source to the environmental media in terms of an expected level of radioactivity in the media via a combination of release and transfer: i.e.,

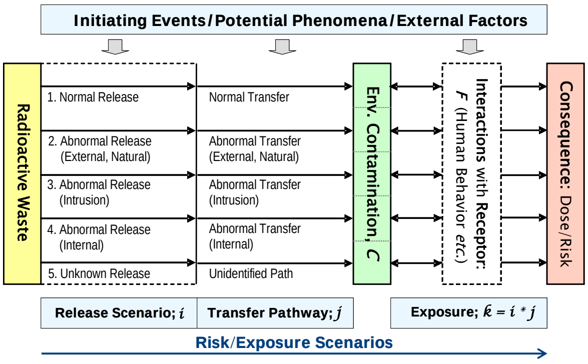

Fig. 1. Abstraction of complex exposure situations for the risk assessment of radioactive waste disposal system.

$$\sum_{i=1}^{l} p(i) \left[\sum_{j=1}^{m} p(j|i)\, C_{ij} \right] = \sum_{i=1}^{l} \sum_{j=1}^{m} p_{ij}\, C_{ij} \qquad (3)$$

where $p(i)$ is the annual probability of release scenario i and $p(j|i)$ is the conditional probability that the radionuclide flux due to release scenario i goes through pathway j to result in the radiological level C_{ij} in the environmental media. Since γ and F are coefficients unrelated to the migration phenomena, Eq. (3) may be connected with (2) pivoting on some proper contaminated media as

$$\gamma \sum_{i=1}^{l} \sum_{j=1}^{m} p_{ij}\, C_{ij} F_{ij} = \gamma \sum_{k=1}^{n} p_k\, C_k F_k \ \approx \ \gamma \int_{D} p(D)\, D\, dD$$

$$\equiv R \ \ (i, j = k;\ lm = n) \qquad (4)$$

where F_{ij} is the dose coefficient related to C_{ij}. In this way, exposure situation k in view of the receptor in Eq. (2) may be converted basically into release scenario i and transfer pathway j in view of the source term, and p_{ij} represents an overall probability of the risk scenario. More rigorously, this implies that there may exist some F_{ij} approximating the probability of receiving a dose to the probability of the risk scenario in a given disposal system. For the purpose of risk limitation, we can deal with F_{ij} in terms of the receptor or the representative person[11]. In the context of the risk constraint system, the representative person may be defined as an individual exposed to a risk that is representative of individuals at the higher risk in the population influenced by the waste disposal. The radiological protection of the public is assumed to be achieved when the value of risk to the representative person is less than the risk constraint.

For embodying this conceptual model mathematically, we should define the release scenarios and the transfer

Table 2. Basic Radionuclide Release Scenarios and Transfer Pathways for the Post-Closure Risk Assessment of Radioactive Waste Repository.

No.	Release Scenario	Transfer Pathway
1	Normal release ▪ gradually occurs along with the system degradation	Normal transfer ▪ gradually occurs with natural processes with time
2	Abnormal release (external, natural) ▪ due to external abrupt events (i.e., seismic activity and faulting)	Abnormal transfer (external, natural) ▪ along new paths formed by external abrupt events
3	Abnormal release (intrusion) ▪ originates from human intrusion	Abnormal transfer (intrusion) ▪ along new paths formed by human intrusion
4	Abnormal release (internal) ▪ from internal defects of the engineering system	Abnormal transfer (internal) ▪ along paths specific or related to abnormal release 4
5	Unknown release ▪ attributable to incomplete understanding of the system	Unidentified path ▪ attributable to incomplete survey or understanding on the geosphere

pathways in harmony with the disposal system. The two sets of five items, respectively illustrated in Fig. 1 and described in Table 2, may provide a basis for stylizing this work. The five release scenarios cover typical release patterns or origins of most waste repositories: i.e., normal release processes which gradually occur along with the system degradation or natural evolution with time, abnormal releases due to external abrupt events such as seismic activity and faulting, abnormal releases originated from human intrusion, abnormal releases from internal defects of the engineering system, and the other releases attributable to incomplete understanding on the system. The transfer pathways may also be classified in a similar way, as shown in Fig. 1 and Table 2, in connection with the release scenarios. In this matrix, a release may take five paths with respective probabilities at that time and conversely, a path may also receive five releases over time.

3. APPLICATION

The conceptual model established above can be materialized for the post-closure risk assessment of a waste disposal system as follows. If any internal and/or external phenomena including normal natural processes influence the system's performance at a point of time or over a period of time, each release will occur with an annual probability involving the likelihood of its initiating phenomena. In most actual cases, the release at a definite time will occur in a single pattern, but two or more release patterns may occur simultaneously in some cases; for example, accompanying a special scenario such as human intrusion, in which defining the number of releases may also depend on the method taken for analysis. Unless the system is expected to recover from disruption, the corresponding probabilities of disruptive scenarios need to be considered as cumulative over the time interval from the repository closure to the time for which the estimation is carried out. For example, in an instance where the occurrence of a geological abrupt event is to be described as a Poisson process with parameter λ (e.g., average annual likelihood), the probability of the corresponding abnormal release at a time t after repository closure should be based on $1-e^{-\lambda t}$, which is the probability that the event may occur at least once during the time period[6,9], rather than on just λ. Similarly, the transfer pathways may also receive the respective releases with their own annual probabilities in response to the relevant initiating phenomena and instill their migration characteristics into the radionuclide plumes to produce the resultant radioactive contamination in the environmental media.

Considering the toxicity level of radioactive waste disposed of, we can set bounds to the risk scenario (e.g., $p_{ij} > 10^{-6}$ yr^{-1})[2]. This simplifies the analysis and allows us to avoid producing some meaningless consequences. While the patterns of interactions between the environmental media and the receptor are also much probabilistic, they are very uncertain particularly in the future. So, for the purpose of demonstrating compliance with the risk constraint, it may be practical to impose their probabilistic nature on a representative person and thus F values in Eq. (3) rather than to assign probabilities to individual behaviors in relation to natural conditions. Once we estimate the risk values with time, we can construct risk profiles suitable for the purpose of assessment to determine compliance with the risk constraint.

Through the above development, the source (i.e., the waste repository), radionuclide and the environmental media were considered as a single term, respectively, for simplification. However, it should be noted that the model does not lose its generality for their multicomponent systems. In addition, as mentioned earlier, this model may be detailed by increasing scenarios and/or pathways, and proper probability models may be employed in describing probabilistic processes. The typical PSA techniques such as event tree analysis and fault tree analysis may also be introduced in analyzing engineering system's performance or release scenarios to estimate the corresponding probabilities. These elaborations should, of course, be harmonized with the system characteristics, the amount of available data, and the purpose of assessment.

4. ILLUSTRATION

The authors demonstrate how to apply the approach described above through a simple example of the waste disposal system with five release scenarios and five transfer pathways, as Fig. 1. Suppose that the annual probability of release scenario, p_i, and the environmental contamination level weighted by the transfer pathways, C_i ($= \Sigma p(j|i) C_{ij}$, $j = 1 \sim 5$), are estimated as Fig. 2 and Fig. 3 from respective analyses. Assuming that the dose coefficient reflecting receptor's contact with the contamination, F_i, is unity for the representative person in each exposure situation, the dose contribution of each scenario (i.e., $p_i D_i = p_i C_i F_i$) may be shown as Fig. 4. The corresponding total annual risk to the representative person (i.e., $\gamma \Sigma p_i D_i$, $\gamma = 5 \times 10^{-2}$ Sv^{-1}) also appears in Fig. 4, which is a risk profile for this case. While these are the procedures and figures in terms of release scenarios, the same ones can be easily developed in terms of transfer pathways.

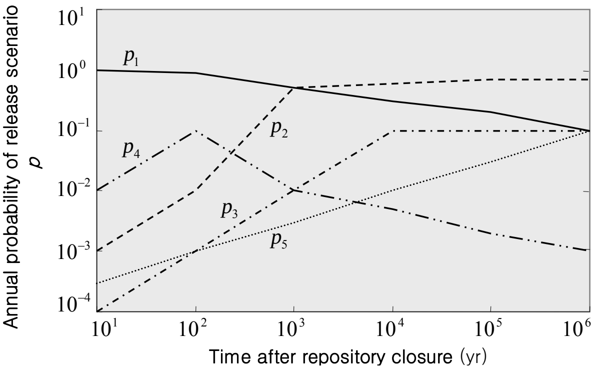

Fig. 2. Illustration for the model application: Assumed trend for annual probabilities of release scenarios (p_i).

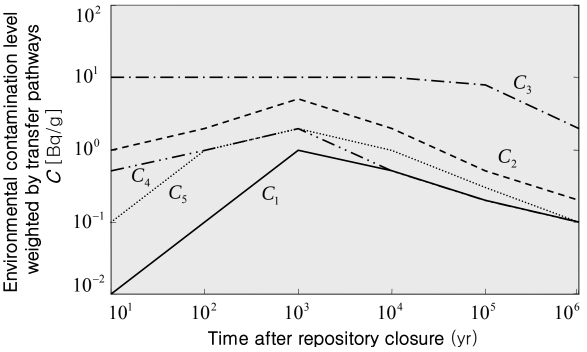

Fig. 3. Illustration for the model application: Assumed trend for the environmental contamination level weighted by the transfer pathways ($C_i = \Sigma p(j|i) C_{ij}$, $j = 1 \sim 5$).

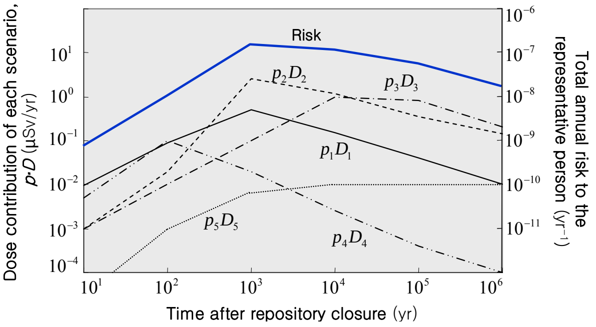

Fig. 4. Illustration for the model application: Dose contribution of each scenario ($p_i D_i = p_i C_i F_i$) and the total risk to the representative person ($\gamma \Sigma p_i D_i$).

5. CONCLUDING REMARKS

In this paper, the authors presented a conceptual model easily applicable to integrating complex potential radiation exposure situations related to the radioactive waste disposal system in terms of risk. The great advantage of the model consists in its linearly combinable function. In most cases, the risk-based safety assessment of complex systems will be accompanied with a huge amount of calculation with time. In addition, it is very difficult for the assessment to keep a consistency through analyzing and combining a variety of scenarios and situations. On the contrary, this approach effectively integrates all the risk elements, such as sources, releases, pathways, and related probabilities, from respective treatment for them, while it also allows us to extract the individual elements from the whole set by means of linear algebra. Such nice properties of the model facilitates a series of works in the risk assessment, including the total risk estimation, the sensitivity analysis, and the uncertainty analysis. Consequently, it is expected that this model may be well applied to evaluating compliance with the risk constraint in the risk-based safety case of radioactive waste disposal.

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