Integrated Risk-Weighted Radioactivity Flux Ratios as Performance Indicators of Defense-in-Depth for HLW Disposal System

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1. Introduction

The heart of safety cases for developing a high-level radioactive waste (HLW) disposal system is to construct defense-in-depth arguments supporting the disposal safety, the basic considerations of which are presented in Article 7 of the related NSSC Notice to deep geological repository [1]. In addition, the relevant safety case may need more concrete indicators of system performance in order to optimize the subsystems, to improve the system by applying Best Available Techniques, or to compare the system alternatives for protective capability. The performance may be expressed in many ways linking the related factors to the system characteristics and behaviors and according with the purpose of system development in different phases [2]. This study proposes some performance indicators supporting compliance with the disposal safety objectives in harmony with the integrative meaning of the safety case which the Article emphasizes.

2. Cumulative radiological fluxes

2.1 Cumulative expected dose

While the peak curve with time appearing as a result of disposal safety assessment has a visual forte for compliance with the safety objective, it will have large uncertainty also with, in particular, respect to time. The cumulative expected dose through time span T, $E^T(\mathrm{D})$ may show an overall system performance as a complement. In relation to the safety objective of HLW disposal [1],

$$E^T(\mathrm{D}) = \int_0^T E[D(t)]\,dt \approx \int_0^T [\sum P_k(t) D_k(t)]\,dt\,, \qquad (1)$$

where the subscript k denotes an exposure scenario or a corresponding exposure pathway through relevant scenarios [3]. The scenarios in (1) may include a proper range of potential exposure situations, as well as normal ones, to the purpose of the assessment. From (1) we can construct $E^T(\mathrm{D})$ with time, in which the values corresponding to a thousand, ten thousands and the overall performance period may have representative meanings in relation to the safety functions of main barriers. Furthermore, we may compare this trend with similar expectation of cumulative dose due to natural radionuclides, including uranium, from the disposal site.

2.2 Weighted releasing fraction of the waste

In connection with the concept of cumulative expected dose mentioned above, a disposal safety function which the waste form constructs by confining radionuclides within itself may be estimated as the following ratio of cumulative release to the original radionuclide inventory disposed of:

$$CRW(T) = \sum r_i^T\ w_i^T \,/ \sum r_i^T\ q_i^o\,, \qquad (2)$$

where w_i^T is the activity (Bq) of radionuclide i released from the waste for a period of 0~T (=$\int_0^T w_i(t)dt$); q_i^0 is the radionuclide inventory at t=0; and r_i^T is the fractional contribution of radionuclide i to the expected dose from influent to exposure pathways for a period of 0~T, defined as

$$r_i^T \equiv [E_i^T \,/\, b_i^T] \,/\, \sum\ [E_j^T \,/\, b_j^T]\ , \qquad (3)$$

where b_i^T is the influent activity (Bq) of radionuclide i to exposure pathways for a period of 0~T in relation with Expression (6) below. In this manner, the characteristics of biosphere may influence the CRW in terms of r_i.

2.3 Weighted net effluent fraction of the EBS

We may represent the capability of engineered barriers for containment of radionuclides released from the waste by the relevant fluxes ratio:

$$CRE(T) = \sum r_i^T\ e_i^T \,/ \sum r_i^T\ w_i^T\,, \qquad (4)$$

where e_i^T is the effluent activity of radionuclide i to the geosphere, or the natural barrier, for a period 0~T.

2.4 Weighted net effluent fraction of the geosphere

Similarly to the *CRE* defined above, we may represent the capability of natural barriers for isolation of radionuclides released from the engineered barriers by the relevant fluxes ratio:

$$CRG(T) = \sum r_i^T\ g_i^T\ /\ \sum r_i^T\ e_i^T, \qquad (5)$$

where g_i^T is the effluent activity of radionuclide i from the geosphere to the biosphere for a period 0~*T*.

2.5 Weighted influent fraction to exposure pathways

The fractional amount of radionuclides influent to the exposure pathways in effluent from the geosphere may be an index on radiological receptivity of the neighboring habitat: i.e.,

$$CRB(T) = \sum r_i^T\ b_i^T\ /\ \sum r_i^T\ g_i^T \qquad (6)$$

where b_i^T is the influent activity of radionuclide i to the relevant exposure pathways for a period of 0~*T*.

3. Application of the flux ratio indicators

The above-defined performance indicators of disposal system components are applicable in many ways to estimating the degree of defense-in-depth through multiple barriers or to comparing system candidates overall.

From a viewpoint of radiological protection, the overall performance of barriers in a disposal system may be expressed by combining the individual performance indicators of subsequent barrier components as:

$$CR(T) = CRW \cdot CRE \cdot CRG \cdot CRB \qquad (7)$$

For the purpose of defense in depth, we may expect the following set of conditions for a relevant period of time $T\ (\gg 1)$:

$$CRW < 1 \qquad (8)$$

$$CRE \ll 1 \qquad (9)$$

$$CRG \ll 1 \qquad (10)$$

$$CRB < 1 \qquad (11)$$

$$CR <<< 1 \qquad (12)$$

Furthermore, even if there should be some wide uncertainties in barrier performance, considering a probable range of performance and the uncertainties,

$$CRE \sim CRG. \qquad (13)$$

Fig. 1 illustrates the above-defined indicators for an imaginary disposal system. In real systems, the indicator curves may give us some useful intuition, showing various forms and trends. We can apply this information to carry out systems analysis, compare the alternatives, and optimize the system. For these purposes, we need to assess the system rather practically than to simply demonstrate the safety conservatively.

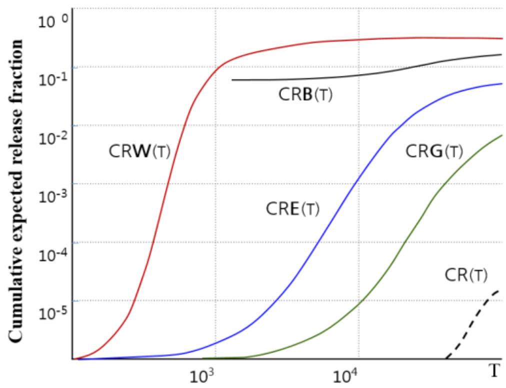

Fig. 1. An example of the cumulative flux ratios.

4. Conclusion

Safety cases of the deep geological repository for HLW, which inevitably involve broad uncertainties over time and space, shall include complementary arguments of defense in depth supporting compliance with the safety objective [1, 3]. The performance indicators proposed here which are based on cumulative radionuclide fluxes weighted in terms of exposure risk can answer this requirement, being used to estimate the defense-in-depth performances of the overall system and its barrier components.

REFERENCES

[1] NSSC Notice 2016-27, General criteria on deep disposal facility for high-level radioactive waste.

[2] IAEA TECDOC-1372, Safety Indicators for the Safety Assessment of Radioactive Waste Disposal, IAEA, 2003.

[3] KINS/RR-1221 (v.2), A Draft Guide to Constructing the Safety Case, KINS, 2015.