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Assessment Of Radionuclide Release Rates From The Engineered Barriers And The Quantification Of Their Uncertainties For A Low- And Intermediate-Level Radioactive Waste Repository

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방사성폐기물처분장 인공방벽으로 부터의 핵종유출률 평가 및 불확실도 정량화

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Abstract

The radionuclide release rates from the engineered barrier composed of concrete structure and clay-based backfill in a low and intermediate level waste repository were assessed. Four types of release pathway were considered, and the contribution of each pathway to the total release were analyzed. To quantify the effect of uncertainties of input parameter values on the assessment of radionuclide release rates, the Latin Hypercube sampling method was used, and the resulting release rate distribution were determined through a goodness-of-fit test. Finally, the ranges of maximum release rates were estimated statistically with a confidence level of 95%.

요 약

콘크리트 구조물 과 점토성 되메움재로 구성된 중저준위 방사성폐기물처분장 인공방벽으로 부터의 핵종유출률이 평가되었다. 네 종류의 유출경로가 고려되었으며, 각 유출경로가 방사성핵종의 총유출률에 미치는 영향이 분석되었다. 입력변수 값의 불확실도가 핵종유출률 분석에 미치는 영향을 정량화하기 위해 Latin Hypercube 표본추출 방법이 이용되었으며, 그 결과 얻어진 유출률 분포는 적합도검증을 통하여 결정되었다. 마지막으로 최대유출률의 범위가 통계적방법에 의해 95% 신뢰도수준으로 추정되었다.

1. Introduction

In Korea, a low and intermediate level radioactive waste repository is scheduled to be operated by the end of the 1990's, and the site selection is under way. The radioactive wastes are appreciated to be disposed of into rock caverns excavated in a host rock below ground surface. Although the detailed design concept of the repository has not been defined yet, the preliminary design concept suggested that radioactive wastes should be disposed of, depending on their radioactivity, into one of three types of cavern; Low-Level Waste(LLW) cavern for trash wastes, Solidified Concentrate Waste(SCW) cavern for solidified evaporator concentrates, and Intermediate-Level Waste(ILW) cavern for spent resins, spent filters and high activity trash wastes.[1] As SCW cavern and ILW cavern contain the major part of radionuclide inventory in the repository, the assessment of radionuclide release rates from both caverns is important from the viewpoint of radioactive waste disposal safety. Several studies have developed the generic models to assess the radionuclide release rates from the high-level waste or the spent fuel repository[2, 3], and Cho et al.[4] suggested the simplified models for the performance assessment of backfill in a low- and intermediate-level waste repository. In the present study, the radionuclide release rates from the engineered barrier composed of concrete structure and backfill in the ILW cavern with the design concept being suggested at present in Korea were assessed and their uncertainties due to the distribution of input parameter values were also quantified.

2. System Description

The concrete structure will be installed to support stacked wastes in ILW caverns. When the concrete structure is filled with the wastes, the concrete slab cover is put on the structure. As it is not supposed to seal the gap, there is an aperture between the structure and the cover, and it works as a gas vent when gas is generated from the corrosion of waste container material. The space between the concrete structure and the wall of cavern may be filled with clay or a crushed rock mixed with clay.

It is currently thought that any release of radionuclide from a repository would most probably take place in groundwater. Thus to date, most release scenarios have considered the groundwater-borne radionuclide release. The expected series of events after the closure of repository is as follows: the groundwater existing in the surrounding host rock intrudes into the cavern, and saturates the backfill and concrete structure. There are considerably empty spaces between each waste container and between concrete wall and waste containers because of the cylindrical shape of waste container, and the intruded groundwater will then fill in the voids. As time elapses, the waste container is corroded and the radionuclides will be leached out from the waste matrix into groundwater present in the void resulting in an equilibrium concentration. The leached radionuclides will be transported into the concrete structure and the backfill, and finally released to the surrounding host rock. There are four possible types of pathway for the radionuclide release into host rock that is the release through the wall, the bottom, and the top of concrete structure, and the aperture between the slab cover and the concrete structure. The radionuclide release concept is represented schematically in Fig.1. Although the waste containers will be stacked uprightly in the real repository, they are represented as being stacked horizontally in the figure to enhance understanding the proposed release concept. The barrier effects of waste container is not considered. Dense clay-based materials and concrete have a low permeability, and moreover, the hydraulic gradient in a disposal cavern deep in hard rock is expected to be relatively low. Under these conditions, diffusion will be the principal mechanism of radionuclide release from the repository.

3. Mathematical Model For Radionuclide Release

Considering the geometry of repository shown in Fig.1, the radionuclide release through concrete structure and backfill can be approximated reasonably as the diffusional transport through a composite slab. It is also common practice to consider one-dimensional diffusion of radionuclide because the longitudinal diffusion is generally greater than transverse one.

Then the transient diffusional transport of radio-

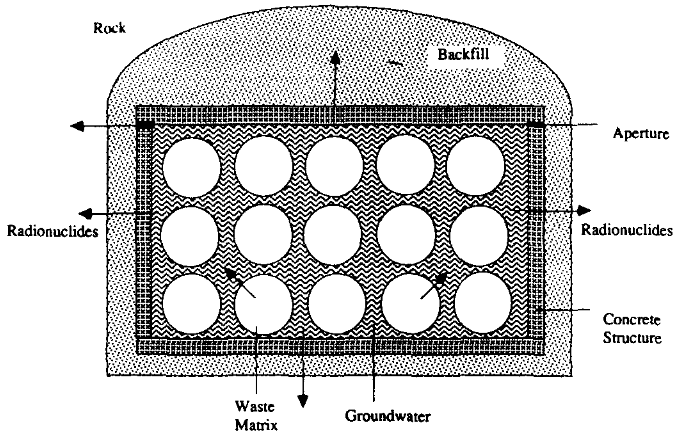

Fig. 1. Concept for the Radionuclide Release Through the Engineered Barrier in the ILW Cavern

nuclide through engineered barriers is given by

$$\partial C_{i1}/\partial t = D_{ai1}\, \partial^2 C_{i1}/\partial x^2 - \lambda_i C_{i1} \qquad -l < x < 0 \tag{1}$$

$$\partial C_{i2}/\partial t = D_{ai2}\, \partial^2 C_{i2}/\partial x^2 - \lambda_i C_{i2} \qquad x > 0$$

where C_i: solution phase concentration of nuclide i

λ_i: decay constant of nuclide i

D_a: apparent diffusion coefficient of nuclide i ($=D_{pi}/R_i$)

D_{pi}: pore diffusion coefficient of nuclide i

R_i: retardation factor of nuclide i

l: thickness of concrete structure

The subscript 1 and 2 mean the concrete structure and the backfill in the repository. The retardation factor, R_i is defined as.

$$R_i = 1 + K_d \rho_d / \theta \tag{2}$$

Here K_d is the distribution coefficient, θ is the porosity, and ρ_d is the bulk density.

The solution of Eq.(1) depends on the initial and boundary conditions. The outer boundary condition for backfill is replaced by an infinite medium boundary condition, and this approximation simplifies the mathematics considerably. The solution at an appropriate distance into the backfill is then taken to represent the concentration at the edge of the backfill, to serve as a source for migration through geosphere. For inner boundary condition, it is assumed that the leached radionuclide maintains the equilibrium concentration determined from chemical conditions in the repository [4]. As there are no radionuclides immediately after the closure of repository, the initial condition is

$$C_{i1} = C_{i2} = 0 \qquad \text{all } x,\ t = 0 \tag{3}$$

By continuity, the boundary conditions are

$$\theta_1 D_{pi1}\, \partial C_{i1}/\partial x = \theta_2 D_{pi2}\, \partial C_{i2}/\partial x \qquad x = 0,\ t > 0 \tag{4}$$

$$C_{i1} = C_{i2} \qquad x = 0,\ t > 0 \tag{5}$$

and

$$C_{i1} = C_{i0} \exp(-\lambda_i t) \qquad x = -l,\ t > 0 \tag{6}$$

$$C_{i2} = 0 \qquad x \to \infty \tag{7}$$

where C_{i0} is the equilibrium concentration of nuclide i under the near-field condition of repository.

The solution of Eq.(1) with the initial and boundary conditions from Eq.(3) to (7), is [5]

$$C_{i2}(x,t)=\frac{2C_{i_s}\exp(-\lambda_i t)}{1+\sigma}\sum_{n=0}^{\infty}\alpha^n erfc\frac{(2n+1)l+kx}{2\sqrt{D_{ai_1}t}} \quad (8)$$

where $k=\sqrt{D_{ai_1}/D_{ai_2}}$

$\sigma = (D_{pi2}k/D_{pi1})(\theta_2/\theta_1)$

$\alpha=\frac{\sigma-1}{\sigma+1}$

Then the radionuclide release rate is

$$F_{i2}(x,t)=J_{i2}(x,t)A$$

$$= -D_{p_{i2}}\theta_2 A\frac{\partial C_{i2}}{\partial X} \quad (9)$$

$$= \frac{2C_{i_s}\exp(-\lambda_i t)D_{p_{i2}}k\theta_2 A}{(1+\sigma)\sqrt{\pi D_{ai_1}t}}\sum_{n=0}^{\infty}\alpha^n\exp\left(-\frac{[(2n+1)l+kx]^2}{4D_{ai_1}t}\right)$$

where $J_{i2}(x, t)$ is the radionuclide flux through the backfill based on unit surface area, and A is the diffusional surface area of backfill.

4. Input Parameter Uncertainty Analysis

In previous section, it is assumed that the input parameters used to assess the radionuclide release rates have single values neglecting the uncertainties involved in the parameter values. In practice, the input parameter values have however considerable uncertainties and can be expressed more reasonably as the distributions rather than single values. Sometimes the considerable differences are encountered among the results of experimental measurements, and the possibility of extreme values of input parameters should be considered in the assessment of engineered barrier performance. The combination of extreme values of input parameters can cause the occurrence of results that are much more severe than those predicted by the application of typical input parameter values.

To evaluate how the assessment results are affected by the input parameter uncertainty, the following procedure is used. First, the major uncertain input parameters are selected and the ranges over which they may vary and their distribution types are defined for each parameter on the basis of the informations from various sources and current state of knowledge. Then, the values of input parameters are sampled from their ranges according to pre-specified distribution using Latin Hypercube sampling technique.

Latin Hypercube sampling was originally proposed by Mckay et al.[6], and generates a sample of size n from k random variable, $X_1, X_2, \cdots, X_k$. The range of each variable is divided into n non-overlapping intervals of equal probability. One value from each interval is selected at random. The n values thus obtained for X_1 are paired at random with the n values obtained for X_2. These n pairs are combined in a random manner with the n values for X_3 to form n triples. The process is continued until a set of k-triples is formed. This is the Latin Hypercube sample, which is used as input parameters for the calculation of radionuclide release rate. This technique is good because it samples without undue sampling size n. It is known that sample size is sufficient if $n > 2k$ [7].

For LHS, the input parameters are usually assumed to be independent of one another. However the assumption of independence among input parameters may not be appropriate for the mathematical models to calculate the radionuclide release rates from the engineered barrier in the repository, and the significant correlations are expected to be between certain parameters. To handle these dependences among the input variables, the method suggested by R.L. Iman and W.J. Conover [8] is used. It is based on rank correlations which are intended to induce the desired rank dependence among the input parameters, and its theoretical basis as follows:

- Suppose that a random row vector X has a correlation matrix I.
  That is, the elements of X are uncorrelated.
- Let C be the desired correlation matrix of some transformation of X. Because C is positive definite and symmetric, C may be written as $C=P\ P'$

where P is a lower triangular matrix. The Cholesky factorization scheme [9] may be used to obtain a lower triangular matrix P.

– Then, the transformed vactor X P' has the desired correlation matrix C.

Monte Carlo simulation with Latin Hypercube sampling yields the distributions of radionuclide release rates. From these distributions, the mean and the standard deviation are calculated, and then the confidence limits of release rates can be estimated. Since these confidence limits are however not for release rates of populations but for those of samples, it is necessary to estimate the population confidence limits from the sample parameters.

If a population distribution is normal, the confidence limits of population with confidence level C are [10, 11]

$$\mu \pm Z_c\, \sigma \qquad (10)$$

where μ: population mean

σ: population standard deviation

Z_c: confidence coefficient corresponding to confidence level C

However, the population distributions sometimes are not normal distribution and, in that case, the confidence limits should be estimated with a distribution-free approach. From the Chebycheff inequality, the following approximation of confidence limits with confidence level C for the population can be derived [10, 11]

$$\mu \pm A\, \sigma \qquad (11)$$

where

$$A = [1/(1-C)]^{0.5}$$

For the estimation of confidence limits using Eq.(10), and Eq.(11), the population mean and population standard deviation are necessary. If the sample mean is X for large sample (n > 30), then the confidence limits for estimation of the population mean in case sampling is from an infinite population, is [10, 11]

$$X \pm Z_c \frac{\sigma}{\sqrt{n}} \qquad (12)$$

where confidence coefficient Z_c depends on the particular level of confidence desired, and n is the sample size. In general the population standard deviation is unknown, so that to obtain the above confidence limits, the sample standard deviation S is used. Introducing Eq.(12) into Eq.(10) and Eq.(11) gives the following final expressions for population confidence limits.

for normal distribution

$$X \pm \left(\frac{1}{\sqrt{n}} + 1\right) Z_c S \qquad (13)$$

for non-normal distribution

$$X \pm \left(\frac{Z_c}{\sqrt{n}} + A\right) S \qquad (14)$$

To determine if an observed sample has a specified theoretical distribution, the Chi-square test[10, 11] is used. This test is based on the degree of goodness-of-fit between the frequencies of occurrence of observations in an observed sample and the expected frequencies obtained from the hypothesis distribution.

5. Nmerical Results And Discussion

5.1. Assessment of Radionuclide Release Rate

The disposal capacity of the repository was assumed to be 250,000 drums (as 200 L carbon steel drum). The wastes are composed of 110,000 drums low-level wastes, 70,000 drums solidified concentrate wastes, and 70,000 drums intermediate-level wastes [1].

The release rates were calculated for six radionuclides; C-14, Ni-63, Sr-90, Tc-99, I-129, and Cs-137. These are the principal nuclides for the safety assessment of low-and intermediate-level waste disposal because of their relatively large inventories and long half-lives. To illustrate the presented methodology for the assessment of radionuclide release rate from the engineered barrier in the waste repository, the radionuclide inventories were estimated using the Swedish SFR data [12] and are shown in Table 1. It was assumed that the 90% of total inventories are contained in SCW and ILW, and both ILW and SCW have same radionuclide concentration. The equilibrium radionuclide concentrations in the repository were estimated by the simple sorption equilibrium equation: $C_o = I_o/V\ [\theta + (1-\theta)\ \rho_s\ K_{dc}]$, where I_0 is the radionuclide inventory, V is the waste volume, θ is porosity of waste matrix, ρ_s is the real density of waste matrix, K_{dc} is the distribution coefficient of nuclide on cement. Here, θ and ρ_s are taken to be 0.5 and 2700 kg/m^3, respectively. The sorption of radionuclide on cement depends, in a complex manner, on the ingredients of the cement-based waste matrix, pore-water chemistry, nuclide speciation etc. In addition, sorption properties change with time due to chemical alternation. Here for simplicity, constant K_{dc} values were used and the K_{dc} (L/kg) values were conservatively assumed to be 100 for C-14, 0.1 for Cs-137, Sr-90, and Tc-99, 0.3 for I-129, 50 for Ni-63 [12]. Thickness of the aperture between concrete structure and slab cover was assumed to be 1 mm. The values of other important input parameters used in the calculation of radionuclide release rates from the engineered barrier are shown in Table 1 and 2 [1, 12−14].

Table 1. Input Parameters Used to Calculate the Radionuclide Release Rates From the Engineered Barrier in ILW Cavern

Radio-nuclide	λ_i (y^{-1})	I_o ++ (GBq)	C_{i0} (GBq/m^3)	D_{ai1} (m^2/y)	D_{pi1} (m^2/y)	D_{ai2} (m^2/y)	D_{pi2} (m^2/y)
C−14	1.12E−4	3.5E+3	9.3E−5	4.3E−7	6.3E−3	1.3E−2	1.3E−2
Ni−63	6.93E−3	3.3E+5	1.7E−2	8.6E−7	6.3E−3	6.3E−5	1.3E−2
Sr−90	2.41E−2	1.3E+5	2.3E+0	4.0E−4	6.3E−3	4.9E−5	1.3E−2
Tc−99	3.30E−6	1.7E+2	4.5E−5	4.3E−6	6.3E−3	2.5E−3	1.3E−2
I−129	4.33E−8	9.8E−1	7.4E−6	1.4E−4	6.3E−3	3.7E−3	1.3E−2
Cs−137	2.29E−2	2.5E+6	4.4E+1	4.0E−4	6.3E−3	6.3E−5	1.3E−2

\+ 1.0E−1 means 1.0x10^{-1}

\+ + based on the disposal capacity of 250,000 drums

Table 2. Thickness and Diffusional Surface Area of the Engineered Barriers in ILW Cavern

	wall	bottom	top	aperture
Concrete structure thickness (m)	0.5	0.3	0.3	−
Backfill thickness (m)	0.9	0.5	1.0	0.9
Diffusional surface area (m^2)	5440	6392	6392	1

The radionuclide release rates at the edge of backfill with time are shown in Fig.2, and for some important radionuclides, the contribution of each release pathway to the total release rates are presented in Fig.3 to Fig.6.

C-14 starts to release immediately after the closure of repository, and its release rate reaches to the maximum value at an early time (about 50 years). C-14 has a considerably long half-life, and strongly sorbed on concrete but not sorbed on clay-based backfill. As shown in Fig.3, C-14 is therefore released

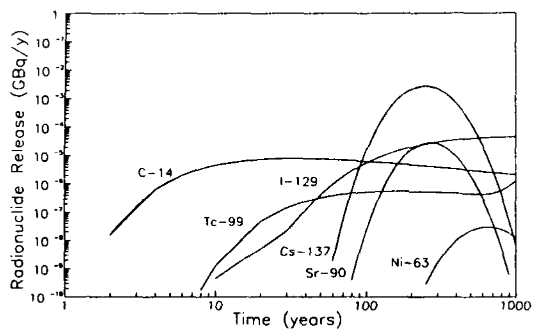

Fig. 2. Radionuclide Release Rates From the Engineered Barrier in the ILW Cavern

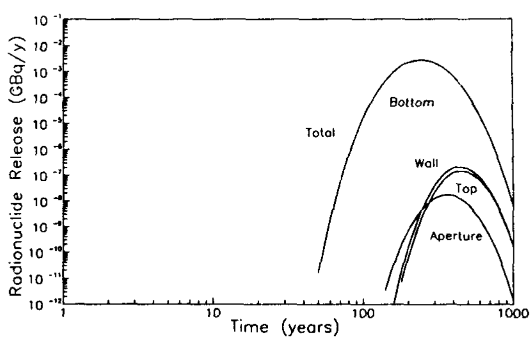

Fig. 5. Contribution of Each Release Pathway to the Total Release Rates for Cs-137

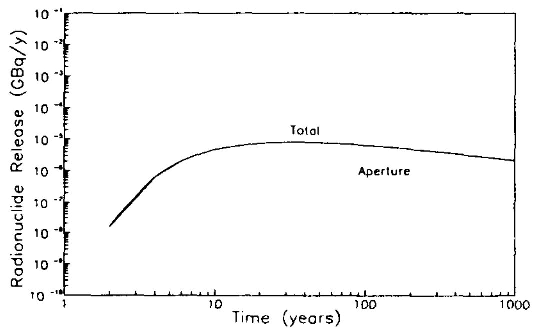

Fig. 3. Contribution of Each Release Pathway to the Total Release Rates for C-14

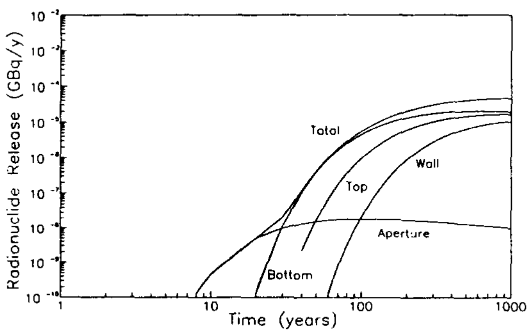

Fig. 6. Contribution of Each Release Pathway to the Total Release Rates for I-129

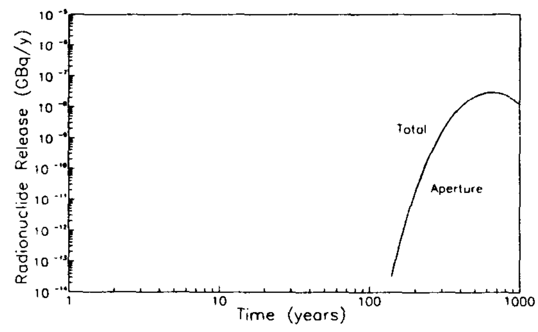

Fig. 4. Contribution of Each Release Pathway to the Total Release Rates for Ni-63

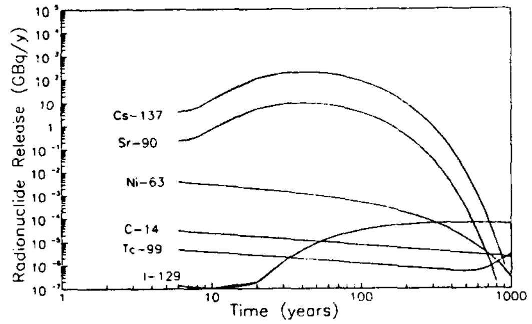

Fig. 7. Radionuclide Release Rates From the Engineered Barrier in the ILW Cavern Without Clay-Based Backfill

mainly through the aperture pathway over the whole period, and other pathways are negligible. Ni-63 is strongly sorbed on concrete and backfill so that both contribute to the retardation of release. Ni-63 is also released through the aperture but the release rates are lower because of its short half life.

Cs-137 is the most important radionuclide over the mid-term period. On the contrary to C-14, Cs-137 is not sorbed on concrete but strongly sorbed on clay-based backfill. Therefore the aperture pathway does not contribute to the release, and only after a considerable period, it starts to release and its release rate reaches the maximum value at about 250 years, and then decreases drastically because of short half-life. The important release pathways are the bottom and the wall of the concrete structure because of relatively small thickness of clay-based backfill (Fig. 5). The thickness of backfill at the top side is relatively large so that its contribution is decreased. Sr-90 shows the release behaviour similar to that of Cs-137 because of similar sorption characteristics and half-life, although the release rates are smaller than those of Cs-137. I-129 is sorbed weakly on concrete and backfill so that both do not almost work as barriers. All the three pathways of the bottom, the top and the wall of the engineered barrier are important, but the aperture pathway is not important because of its small cross sectional area (Fig.6).

To evaluate the contribution of clay-based backfill to the retardation of radionuclide release, the release rate from the concrete structure without backfill was calculated, and the results are shown in Fig.7. In this case, Cs-137 and Sr-90 are released early after closure of the repository, and their release rates are high. Because both Cs-137 and Sr-90 are strongly sorbed on clay but not on concrete, so that concrete structure does nearly not function as a barrier for these radionuclides. Therefore if the clay-based backfill is not installed in the repository, the harmful cationic nuclides such as Cs-137, and Sr-90 will be released at high rate early after closure of the repository. In the case of no concrete structure, the situation is the opposite and C-14 and Tc-99 will be released with high rate at the early stage.

These results represent the mutual aid of concrete and clay to improve the performance of engineered barrier. Namely C-14 which is a non-sorbing nuclide in clay-based backfill is released without retardation in the case of no concrete structute. As Cs-137, and Sr-90 are ,on the contrary, not nearly sorbed on concrete, but strongly sorbed on clay-based backfill, the barrier effect of backfill becomes important for these radionuclides resulting in the decrease of releases. Therefore the combination of concrete structure and clay-based backfill can improve the effects of engineered barrier in the repository.

5.2. Input Parameter Uncertainty Analysis

The several input parameters with large uncertainties for the mathematical models describing the radionuclide release are chosen and then the ranges and the distribution types of values for each parameter are defined. This definition is based on the thorough examination of the valuable informations from the various sources and the current status of knowledges [12-18]. The ranges and distribution types of input parameter values for three radionuclides, C-14, Ni-63, and Cs-137, are summerized in Table 3. Here the upper limit and lower limit of the range of parameter values are assumed to be the 0.001 quantile and the 0.999 quantile respectively. To corporate the dependence among the input parameters into sampling, the correlation coefficient matrix was made. The values of correlation coefficient were taken to be 0.9 for strong dependence, and 0.8 for intermediate dependence respectively. The assumed correlation coefficient matrices among the input parameters are shown in Table 4, and these dependences were corporated into the sampling of parameter values. The values of input parameters were sampled from their uncertainty ranges and distributions using the Latin Hypercube sampling technique, and the coresponding input par-

Table 3. Uncertainty Ranges and Types of Distribution of Input Parameters for the Assessment of Radionuclide Release From the Engineered Barrier in ILW Cavern

Parameter	Ranges			distribution
	C−14	Ni−63	Cs−137	
$D_{ai1}(m^2/y)$	6.3E−8⁺−6.3E−5	1.3E−7−1.3E−4	1.6E−4−1.6E−3	lognormal
$D_{pi1}(m^2/y)$	6.3E−4−1.6E−2	6.3E−4−1.6E−2	6.3E−3−1.6E−2	lognormal
$D_{ai2}(m^2/y)$	6.3E−4−1.6E−2	1.6E−5−1.6E−4	3.2E−6−1.6E−2	lognormal
$D_{pi2}(m^2/y)$	6.3E−3−1.6E−2	1.6E−3−1.6E−2	1.6E−3−1.6E−2	lognormal
$K_{dc}(Mg/m^3)$	100−5000	50−1000	0.1−2.0	lognormal
θ_1	0.2−0.3	0.2−0.3	0.2−0.3	normal
θ_2	0.15−0.2	0.15−0.2	0.15−0.2	uniform

+ 1.0E−1 means 1.0×10^{-1}

Table 4. Correlation Coefficient Matrix of Input Parameters for the Assessment of Radionuclide Release

	D_{ai1}	D_{pi1}	D_{ai2}	D_{pi2}	K_{dc}	θ_1	θ_2
D_{ai1}	1						
D_{pi1}	0.9	1					
D_{ai2}	0	0	1				
D_{pi2}	0	0	0.9	1			
K_{dc}	0	0	0	0	1		
θ_1	0.9	0.8	0	0	0	1	
θ_2	0	0	0.9	0.8	0	0	1

ameter sets were obtained.

The distributions of maximum radionuclide release rates due to the input parameter uncertainties are shown in Fig.8 through Fig.10. These frequency histograms are from 50 Monte Carlo simulations. From these figures, it may be seen that the uncertainty ranges of maximum release rates cover several orders of magnitude. To estimate the upper and the lower limits of maximum release rates, it is necessary to determine whether the observed release rates have a specified theoretical distribution. For this purpose, the Chi-Square test at 0.05 significance level was used. Then, the upper and the lower limits of the maximum release rates were estimated with 95% confidence level by Eq. (13) because the release

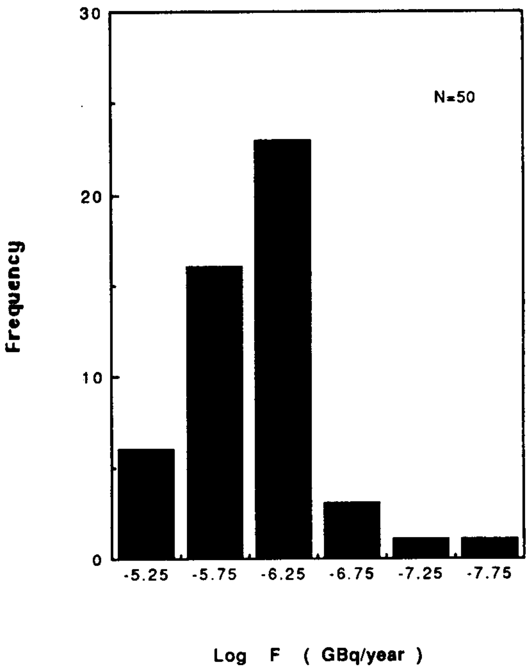

Fig. 8. Distribution of the Maximum Radionuclide Release Rates From the Engineered Barrier for C−14

rates for all radionuclides show log-normal distribution, and the results are also presented in Table 5. As shown in this table, the maximum release rates of Cs-137, and Ni-63 are distributed over wide range (several order of magnitude), and that of C-14

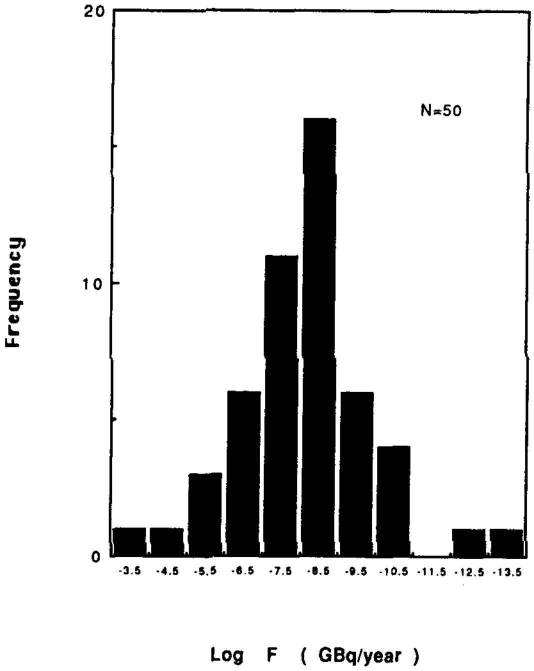

Fig. 9. Distribution of the Maximum Radionuclide Release Rates From the Engineered Barrier for Cs−137

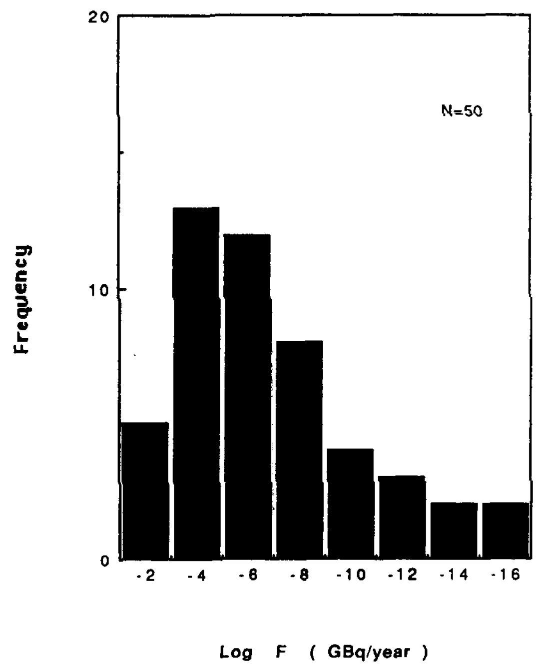

Fig. 10. Distribution of the Maximum Radionuclide Release Rates From the Engineered Barrier for Ni−63

covers relatively narrow range. These differences are mainly due to the degree of uncertainties involved in the values of diffusion coefficients. For Cs-137, the values of diffusion coefficient in clay reported in the literatures [14-18] cover wide range and the half-life is relatively short resulting in a large uncertainty in the release rates. Therefore the careful measurements of diffusion coefficients in clay for sorbing nuclides such as Cs-137, Sr-90, and Ni-63 can reduce the uncertainties involved in the assessment results for the performance of engineered barrier in the repository.

6. Summary And Conclusions

The radionuclide release rates from the engineered barrier composed of the concrete structure and the clay-based backfill in the low- and intermediate level waste repository were assessed. To quantify the effect of uncertainties involved in the input parameter values to the assessment results of radionuclide release rates, the Latin Hypercube sampling method and the statistical estimation were used. The results show that C-14, Sr-90, and Cs-137 are important nuclides on the view point of release rates. The radionuclides are released early from the concrete structure without clay-based backfill and their release rates are much higher. Therefore the combinational use of the concrete structure and the clay-based backfill can improve greatly the performance of engineered barrier in the repository. The uncertainties of the assessment results of maximum release rate due to the input parameter uncertainty are larger in case of the sorbing nuclides such as Cs-137, and the careful experiments to measure the diffusion coefficients can contribute to reduce the uncertainties involved in the assessment results.

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Table 5. 95% Confidence Intervals for the Maximum Radionuclide Release Rates Rrom the Engineered Barrier in ILW Cavern

nuclide	X[a]	S[b]	95% Confidence Interval (GBq/y)		time(y)
			lower limit	upper limit	
C−14	−0.65	0.53	5.69E−8	1.40E−5	50
Ni−63	−8.18	1.98	2.48E−13	1.76E−4	600
Cs−137	−6.67	3.49	3.22E−15	1.44E−1	250

[a]X: mean of log(release rate)
[b]S: standard deviation of log(release rate)

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