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■ 論 文 ■

Probabilistic Safety Assessment for High Level Nuclear Waste Repository System

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ABSTRACT

An integrated model is developed in this paper for the performance assessment of high level radioactive waste repository. This integrated model consists of two simple mathematical models. One is a multiple-barrier failure model of the repository system based on constant failure rates which provides source terms to biosphere. The other is a biosphere model which has multiple pathways for radionuclides to reach to human.

For the parametric uncertainty and sensitivity analysis for the risk assessment of high level radioactive waste repository, Latin hypercube sampling and rank correlation techniques are applied to this model. The former is cost-effective for large computer programs because it gives smaller error in estimating output distribution even with smaller number of runs compared to crude Monte Carlo technique. The latter is good for generating dependence structure among samples of input parameters. It is also used to find out the most sensitive, or important, parameter groups among given input parameters.

The methodology of the mathematical modelling with statistical analysis will provide useful insights to the decision-making of radioactive waste repository selection and future researches related to uncertain and sensitive input parameters.

INTRODUCTION

Nuclear energy has played an important role of electricity generation in Korea. Therefore it is necessary to set up appropriate systems for the management of the increasing radioactive wastes generated by nuclear power plants. These wastes vary greatly in physical/chemical form and isotopic content. Generally, the radioactive wastes can be classified into high, intermediate, and low levels according to radioactivity. Currently, several waste management techniques have been proposed to achieve the goal of permanent and safe disposal, depending on the radioactive content and quantity of the wastes. Management options for high level reprocessing wastes or spent fuel include seabed disposal and emplacement in a deep geological repository (>500m). Management options for intermediate and low level wastes include land burial at intermediate (<300m) and shallow (>50m) depth, respectively. It is generally agreed that underground disposal, with the wastes appropriately immobilized, is a good choice to protect human and environment. Here, underground disposal means the emplacement of radioactive waste in the terrestrial subsurface without intention of future retrieval.

Safely assessments are necessary to estimate the performance of an underground disposal system for radioactive wastes and to compare the results with qualitative or quantitative regulatory acceptance criteria. And also, they are useful to identify the possible areas of system improvement. Safety assessments are performed from generic to site-specific. Generic safety assessment is useful for programmatic decision making for the choice of a disposal option and for the appropriate use of available resources. Generic assessment is also helpful in acquiring the understanding on the feasibility of proposed disposal concept. Site-specific assessments are necessary for decision making which affects the siting, design, construction, operation, closure and sealing of a repository[1,2]. It is clear that the safety assessment of nuclear waste repository systems is one of the key elements in establishing the overall acceptability of nuclear power. However, there are no recommended procedures for carrying out such assessments and hence many scientific discussions are underway.

At present, two kinds of methodology for the safety assessment of underground disposal are being developed. One is deterministic safety analysis which considers the worst cases hypothetically and demonstrates that the consequences are acceptable even under such extreme cases. The other is probabilistic safety analysis which accounts for all kinds of possible failures using logical schemes such as fault trees and event trees and determines the probabilities of their occurrence as well as their consequences. The probabilistic safety analysis has the advantage of imposing a conceptual effort to organize all potential causes of failure into comprehensive logical schemes which can be tractable mathematically, when confronted with deterministic safety analysis.

Various methods to assess the probabilistic safety for radioactive waste disposal options have been proposed. Prizker and Gassmann [3] suggested a multiple-barrier failure model for the probabilistic analysis of high level radioactive waste repository system. S.Chang and W.Cho[4] expanded this model to the case in which the failure rate of each barrier is time-dependent. They also considered the geosphere as another barrier for radionuclide to reach biosphere. P.Kim *et al.* [5] developed a similar model for the shallow land buried low level radioactive waste reposistory system. Bertozzi and D'Alessandro [6] discussed the probabilistic approach for risk evaluation of high level radioactive waste repositories and the methodology of handling the uncertanty in input data used in the probabilistic evaluation. T. Kim *et al.* [7,8,9] developed some uncertainty and sensitivity analysis methods for the probabilistic safety assessment of a high level radioactive waste repository. Bertozzi *et al.* [10] conducted a probabilistic risk analysis for the disposal of high level radioactive waste in salt mine repositories. D'Alessandro *et al.* [11] analyzed geologic events probabilistically based on the historical data. Using this result they estimated the probability of geological isolation failure for a high level repository constructed in clay stratum.

All the above studies were focused on the repository failure model or geosphere transport model of radioactive nuclides which simulates the probable release rate of radionuclides to the geosphere or to the biosphere. The inpact of released radionuclides to human, so called, consequences, are not assessed yet. W. Park *et al.* [12] developed a biosphere transport model of radionuclides considering ingestion and inhalation of human. In this paper, an integrated model which combines the repository failure model, the geosphere model, and the biosphere model is developed to analyze the long-term probable release rate and transfer rate of radionuclides from the reprocessed high level waste repository to the biosphere and to estimate the consequences (radiation doses) to human. The parametric uncertainty and sensitivity analyses are also performed to identify the propagated uncertainties of assessed output measures and to identify the most contributing input parameter groups. The nuclides considered in this paper are Tc-99, Cs-137, and Np-237. These nuclides (Tc-99 and Np-237) have very long half-lives and are the most contributing elements in human's ingestion of foods.

METHODS OF UNCERTAINTY AND SENSITIVITY ANALYSIS

Uncertainties in the prediction of the long-term behavior of a repository arise from the posibility that important scenarios have not been considered, from incompleteness in the models used to estimate probabilities and consequences, and from uncertainty in the values of the parameters which enter into these models. These three types of uncertainties may be referred to as scenario uncertainty, model uncertainty, and parametric uncertainty, respectively[6,7,10-13].

The scenario uncertainty is the extent to which the analyzer can recognize the nature of the system and can be reduced by careful selection and description of relevent scenarios. The model uncertainty may result from;first, some phenomena are not correctly described by the model, second, approximations are introduced to facilitate the calculations. The first type uncertainty can be evaluated by model validations and the second type uncertainty, the effect of approximations and simplifications on the models, should be estimated in separate sensitivity studies in respect to validated detail models. The parametric uncertainty is the one propagated from the uncertianties of the system parameter itself and can be evaluated through appropiate mathematical and statistical methodologies. Most work aimed at assessing uncertainties in repository performance has focused on this parametric uncertainty.

For the parametric uncertainty analysis, probability density functions are assigned to the input parameters taking account of the range and characteristics of data aggregated. In case that direct evidence is not available, expert opinions may be used to describe the probability density functions. The reliability of the results will then tend to be more limited by the accuracy of the probability distributions assigned to input parameters than by any calculational limitations.

Uncertainty Propagation Analysis

To figure out the uncertainties of output variables, uncetainty propagation methods are used reflecting the uncertainties of input parameters. There are two basic sampling methods used. One is simple random sampling to the input parameters (crude Monte Carlo method) and the other is Latin Hypercube Sampling strategy which needs a smaller number of samples compared to crude Monte carlo method to obtain the same accuracy. Crude Monte Carlo (CMC) method is the most primitive but the most powerful method in uncertainty propagation analysis [14-16]. Latin Hypercube Sampling (LHS), which was originally proposed by Iman, *et al.* [20-25], is a kind of variance reduction technique to generate a sample set of size n from k random variables. This technique is aimed at optimizing the sample selection in order to ensure that all relevant parameter values and their combinations are included in the calculations even for a relatively small number of runs.

Sensitivity and Importance Analysis

The objective of sensitivity analysis is to investigate how the output is influenced by unit variation of each input parameter. It is also used to evaluate the importance of input parameters when the number of input parameters are large and they have uncertainties. There are several sensitivity analysis techniques used. The performance of each technique is very much model dependent and a choice has to be made between effectiveness and robustness. A more systematic technique is needed sometimes.

Two correlation coefficients are used to assess dependency between two random variables. The one is Pearson correlation coefficient which is mainly used to check linearity and the other is Spearman rank correlation coefficient which is mainly used to check monotonicity between two random variables [25, 26]. The strength of a simple linear relationship between two variables is usually measured with r, so called, Peason's product moment correlation coefficient, or correlation coefficient for short. The strength of a monotonic relationship between two variables, as opposed to a linear relationship, is usually measured using r, but computed on the ranks of the sample values instead of the sample values themselves.
It is customary to use either r or ρ (rho) to denote the rank correlation coefficient, sometimes called Spearman's rho. This rank correlation coefficient may be used to test the hypothesis of independence, without requiring any distributional assumptions. This rank correlation coefficient is also used to generate dependency structure of the input variables. A method is developed by Iman and Conover for eliminating spurious correlation among the input variables [23, 24]. This method is based on rank correlation which is intended to induce the desired rank dependence among the input variables. The procedure and desirable properties of this method are described in the thesis of K. Woo[13].

Therefore, Spearman rank corrlation coefficient, known to be preferred to Pearson's product moment correlation coefficient for non-linear models, is used in this study as a measure of correlations between variables.

MODELS

Repository Failure Model

Water Intrusion Scenario of Radiation Release

Radioactive waste repository must be located in a geological formation which is quite stable tectonically. Therefore, the probabilities of the occurrence of an earthquake and a fault at waste repository are very low. The waste disposal stratum is located about 600m below the ground surface and the type of stratum is, in general, hard rock to prevent the intrusion of the ground water.

The waste repository is composed of parallel disposal tunnels for the emplacement of waste and shafts for the linkage to the ground surface. On the ground of the disposal tunnel, many vertical holes are dirlled for the disposal of high level waste canisters. The space between the wall of the hole and the canister is packed with backfill materials such as bentonite, zeolite, etc. After the canisters are put in all the holes in the tunnels, the disposal tunnels are packed with buffer material such as a mixture of quartz sand and bentonite, etc. When the entire repository is filled the shaft and other spaces are also packed with the same buffer materials.(see Figures 1 and 2).

The underground radioactive waste repository consists of five barriers to isolate the high level radioactive waste from the biosphere.(see Figure 3).

1) barrier A : host rock(rock salt or crystalline rock, etc.)
2) barrier B : waste canister(Ti-Pb container)
3) barrier C : waste glass(borosilicate glass)
4) barrier D : backfill (bentonite)
5) barrier E : geological structure between repository and biosphere (granite)

At the beginning of the release, host rock (barrier A) where the waste repository is located, is failed by artificial or natural events (drilling, earthquake, etc.) and some groundwater in the geological stratum surrounding the host rock intrudes into the waste repository. The space between the host rock and the wall of the waste canister is filled with backfill materials such as bentonite. After the saturation of backfill with grou-

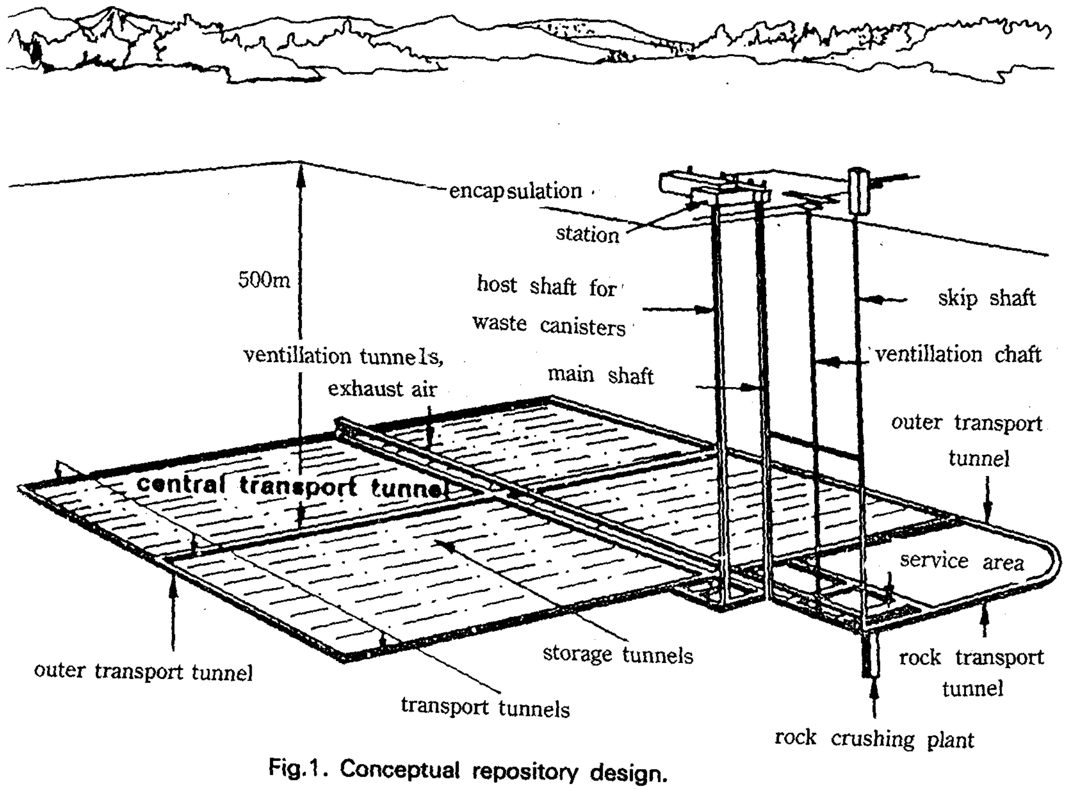

Fig.1. Conceptual repository design.

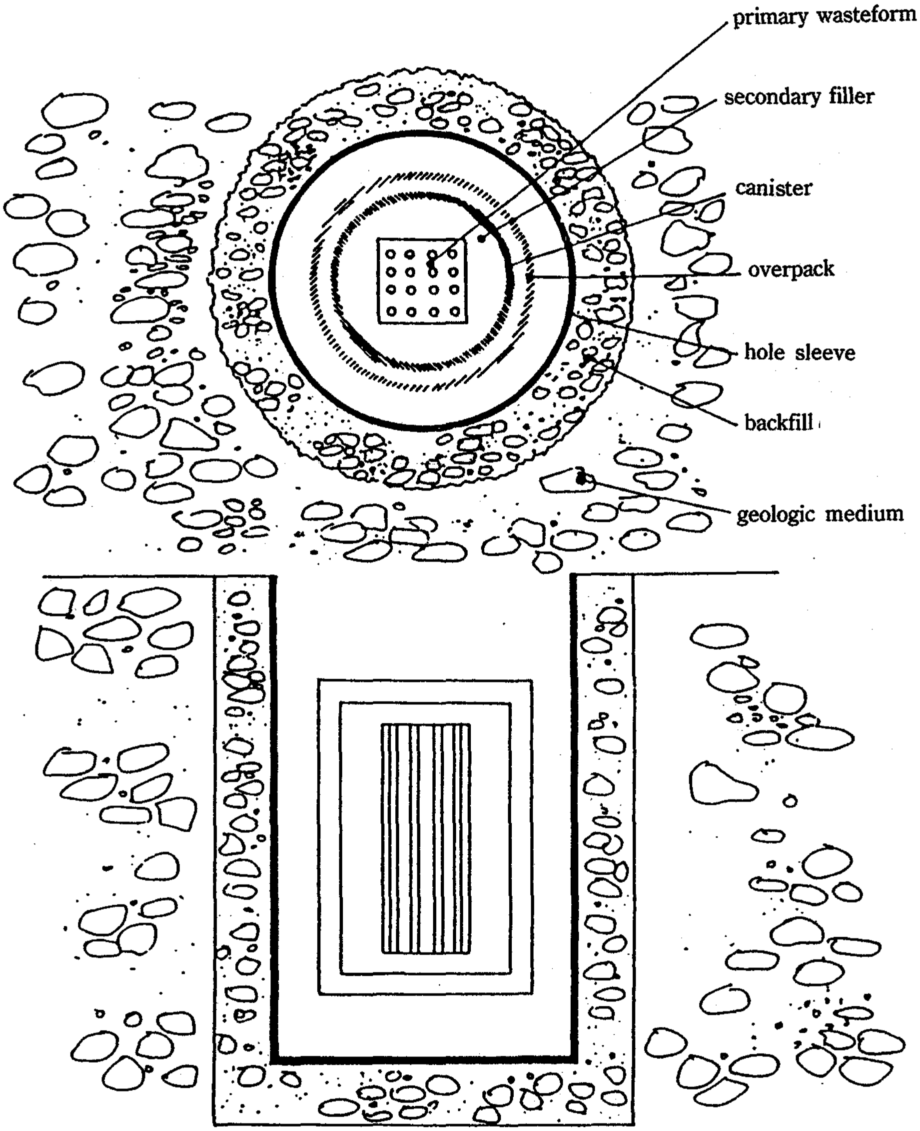

Fig.2. Schematic representation of the principal elements of the waste package.

ndwater, groundwater contacts with and corrodes the waste canister (barrier B). As corrosion proceeds, groundwater will eventually come into contact with the waste glass (barrier C). High level waste glass is a homogeneous glass so-called "Borosilicate". In case of long contact with groundwater, the waste glass is leached out at a very slow rate. The nuclides leached from the waste glass are retarded for a considerable period by adsorption as they pass through the backfill (barrier D). After passing through backfill, this groundwater reaches the ground surface or surface water through geological structure (barrier E), while the radioactive nuclides along the same path but

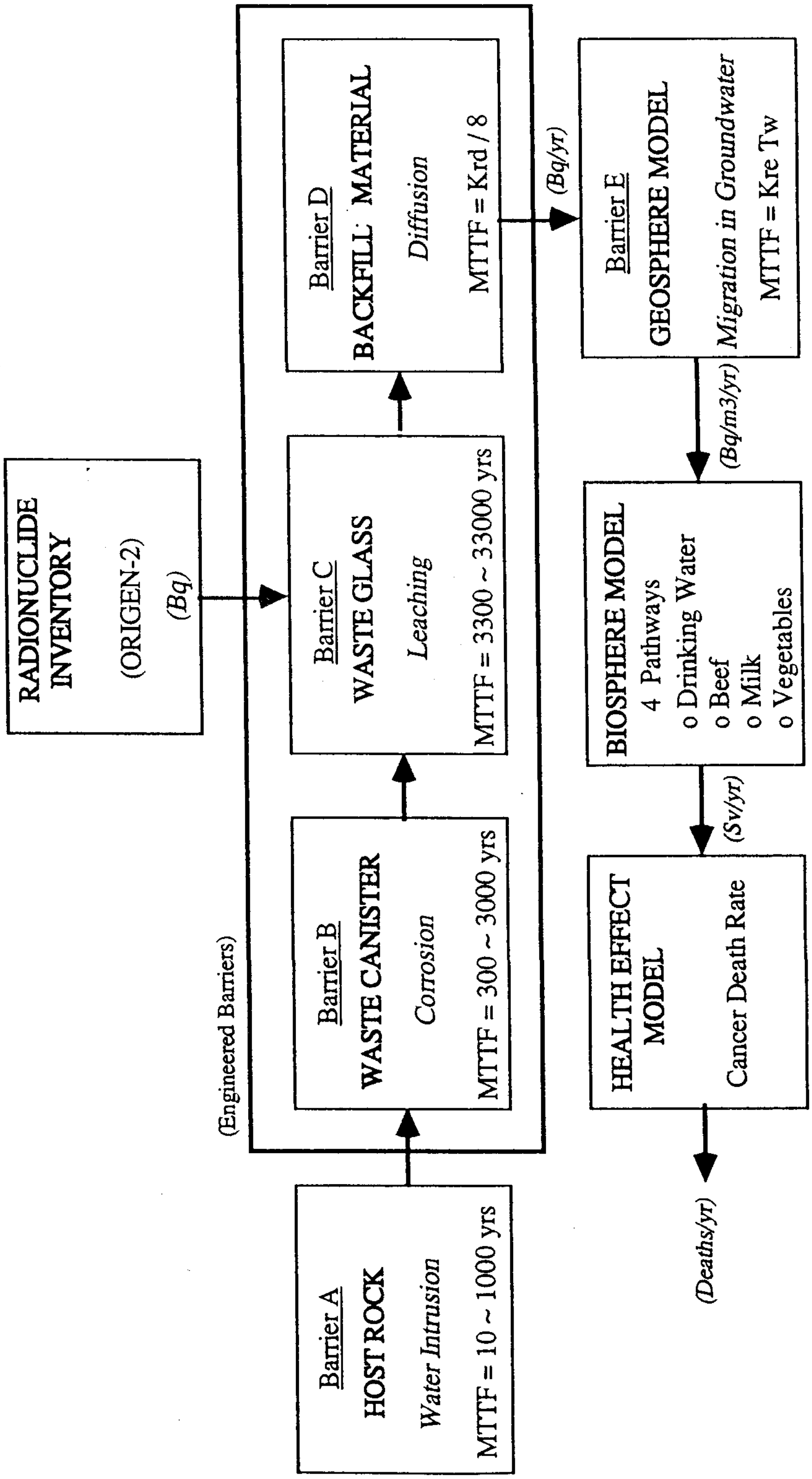

Fig.3. Risk assessment scheme for radioactive waste repository system.

are retarded by adsorption.

Reilability Assessment Model

In the system in continuous operation without repair, the failure probability density function f(t) is [27],

$$f(t) = \lambda(t)\exp\left[-\int_0^t \lambda(t')dt'\right] \qquad (1)$$

and the mean-time-to-failure(MTTF) is,

$$\mathrm{MTTF} = \int_0^\infty t f(t)\,dt \qquad (2)$$

where,

$\lambda(t)$ = hazard rate or conditional failure rate.

If the failure of the system occurs randomly, then

$$\lambda(t) = \lambda \qquad (3)$$

$$f(t) = \lambda\exp(-\lambda t) \qquad (4)$$

$$\mathrm{MTTF} = \frac{1}{\lambda} \qquad (5)$$

For the system in which components are sequential in operation in such a way that the only one unit of the system is in operation at a time [27],

$$f_{sys}(t) = \int_0^t f_1(t_1)\int_{t_1}^t f_2(t_2 - t_1)\cdots\int_{t_{N-2}}^t f_{N-1}(t_{N-1} - t_{N-2})$$

$$\times f_N(t - t_{N-1})dt_{N-1}dt_{N-2}\cdots dt_1 \qquad (6)$$

If the hazard rate is assumed constant in time, then

$$f_{sys}(t) = \left[\prod_{i=1}^{N}\lambda_i\right]\sum_{i=1}^{N}\frac{e^{-\lambda_i t}}{\prod_{j\neq 1}(\lambda - \lambda_j)} \qquad (7)$$

The rate of the radioactivity release from the waste repository can be represented by

$$R_k(t) = A_k(t)f_{sys}(t)$$

$$A_k(0)\ \exp\ (-\lambda_k t)f_{sys}(t) \qquad (8)$$

where,

$R_k(t)$ = probable release rate of radioactive nuclide k at time t (Ci/yr),

$A_k(0) = \lambda_k(0)N_k(0)$ = initial activity of the nuclide k (Ci),

$N_k(0)$ = inventory of the nuclide k at time t=0, when the waste is disposed of in the repository,

λ_k = decay constant of the nuclide k (1/yr).

Failure Rate of Each Barrier

As described in the previous sections, the release rate of radioactive nuclides to biosphere by the groundwater is only considered. The waste repository is considered as a system in continuous operation, whereby five units are in a sequential operation mode. At first, we consider the reliability of the single barrier. In the second step, we consider the overall reliabilities of the waste repository using the reliability of the single barrier. The failure mechanisms of each barrier is described in references 4, 7, 8 and 9. The MTTF, which is inverse of the failure rate, of each barrier can be summarized as follows :

MTTF of barrier A (host rock) is 10-1,000years [7,28,29].

MTTF of barrier B (waste canister) is 300-3,000 years [30,31].

MTTF of barrier C (waste glass) is 3,300-33,000 years [3,4,31].

MTTF of barrier D (backfill) is represented by [3,4],

$$\mathrm{MTTFd} = K_{rd}/8. \qquad (9)$$

MTTF of barrier E(Geological Structure) can be represented by

$$MTTFe = K_{re}\ T_w \qquad (10)$$

where,

T_w=travel time of groundwater=200-2,000 years [3],

K_{re}=retardation factor of barrier E for each nuclide.

Biosphere Model

If radioactive substances are carried from the repository to the biosphere by the groundwater, individuals in the environment can be exposed to radiation. The radioactive substances can reach human via ingestion of water and foodstuffs. The release rate of the radioactive nuclides from the waste repository to the biosphere is calculated by the geosphere model described above. The surface water which is a reception point from the geosphere may be wells, lakes, or rivers. In this paper, river is assumed to be used as a source of drinking water and irrigation water.

The pathways through which radioactive nuclides in the surface water are dispersed and finally reach to man are very complex and site-dependent. To obtain a more precise estimation of the dose to man, the site-specific biosphere model should be established. But in this study, the pathways which are generic, not site-specific, and contribute significantly to the total dose were selected and modelled.

Water from a contaminated river, lake, or well is used primarily as drinking water for the population and the cattle and as irrigation water. Also, the radionuclides are taken up by the fish in the river and lake. Then the cattle, the crops and the fish are contaminated and men are affected by ingesting these products. The soil contaminated by irrigation water is the source of the air contamination and the direct irradiation to man. Among these biosphere pathways the pathways considered in this study are ingestion of drinking water, milk, beef, and vegetables which result in the major portion of total individual dose for most radionuclides. Figure 4 shows the pathways considered in the biosphere model.

In the case of the normal evolution scenario for a repository, the releases of radionuclides last for several hundred thousands of years. The variations of the amount of radionuclides entering the biosphere are relatively small during time periods considered in the biosphere model. Therefore equilibrium states are assumed for the concentrations in the surface water and in the soil. The concentration in the soil is estimated by the following formula based on a mass balance for the root zone of the soil [36] ;

$$Cs=\frac{Q_{ir}}{Q_n+Q_{ir}}\quad (K_d+\frac{\eta}{\rho})C_w \qquad (11)$$

where, the notations of the parameters are shown in Table 1.

For each pathway, the annual dose to an individual is calculated by the following equations and the total annual dose is obtained by taking the sum of the doses resulting from the different pathways. The notations used are defined in Table 1.

- Pathway 1 : drinking water

$$D_w= C_wU_{mw}DCF_{ing} \qquad (12)$$

- Pathway 2 : milk

$$D_m= (D_cF_m)\ U_{mm}DCF_{ing} \qquad (13)$$

- Pathway 3 : beef

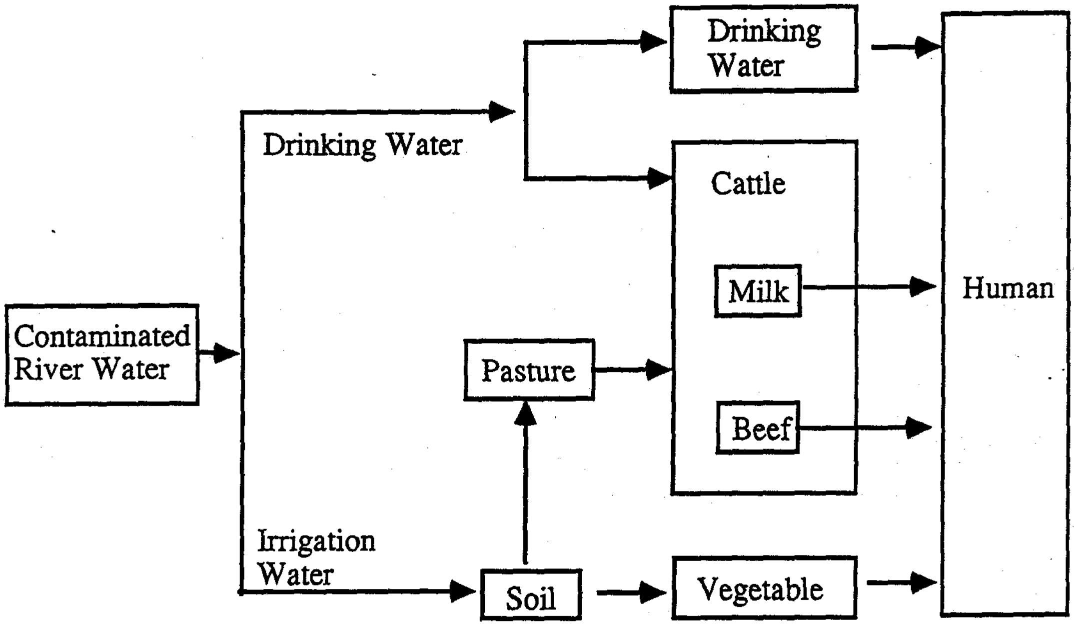

Fig.4. Pathways considered in the biosphere model.

$$D_b = (D_c F_b)\ U_{mb} DCF_{ing} \qquad (14)$$

- Pathway 4 : vegetables (direct deposition is not considered)

$$D_v = (C_s B_v)\ U_{mv} DCF_{ing} \qquad (15)$$

where, the dose ingested by cattle is estimated as

$$D_c = C_w U_{cw} + C_s (U_{cp}\ B_p + U_{cs}) \qquad (16)$$

Intergration of Repository Failure Model and Biosphere Model

The release rate of radionuclides from the repository to the surface water divided by the volume flow rate of the surface water becomes the concentration of radionuclides in the surface water. And from the biosphere model, the annual individual dose by the unit concentration ($1\ Bq/m^3$) of radionuclides in the surface water is obtained. Therefore, the annual dose to human is calculated by the following equation :

$$Dose = \sum_i 3.7 \times 10^{10} \frac{R_i}{V} \sum_p DR_{i,p} \qquad (17)$$

where,

Dose = the annual dose to man (Sv/yr),

3.7×10^{10} = the unit conversion constant,

R_i = the release rate of radionuclide i from the repository to the surface water (Ci/yr),

V = the volume flow rate of the surface water (m^3/yr),

$DR_{i,p}$ = the annual dose through biosphere pathway p per unit concentration of nuclide i ($Sv/yr/Bq/m^3$).

Table 1. Parameters of the biosphere model.

Notation	Definition (unit)
B_v	Soil-to-plant concentration ratio for vegetables
B_p	Soil-to-plant concentration ratio for pasture
C_s	Concentration in the root zone of the soil(Bq/kg)
C_w	Concentration in the surface water(Bq/m^3)
D_w	Dose from drinking water pathway (Sv/yr)
D_m	Dose from milk pathway (Sv/yr)
D_b	Dose from beef pathway (Sv/yr)
D_v	Dose from vegetable pathway (Sv/yr)
DCF_{ing}	Dose conversion factor for ingestion (Sv/ Bq)
D_c	Dose ingested by cattle (Sv/yr)
f_{pv}	Ratio for pasture-vegetables transfer factor($=B_p/B_v$)
F_b	Concentration factor for beef (yr/kg)
F_m	Concentration factor for milk (yr/m^3)
K_d	Distribution coefficient for the root zone (m$_3$/kg)
Q_{ir}	Irrigation rate (m/yr)
Q_n	Net precipitation rate (m/yr)
U_{cp}	Pasture consumption rate by cattle (kg/yr)
U_{cs}	Soil consumption rate by cattle (kg/yr) (during intaking the pasture)
U_{cw}	Water consumption rate by cattle (m^3/yr)
U_{mw}	Water consumption rate by man (m^3/yr)
U_{mm}	Milk consumption rate by man (m^3/yr)
U_{mb}	Beef consumption rate by man (kg/yr)
U_{mv}	Vegetable consumption rate by man (kg/yr)
η	Void fraction in the root zone
ρ	Bulk density of the ary soil (kg/m^3)

CALCULATION

Calculation Flowchart

Three FORTRAN programs are written for this study, which are URSAMP, URISK, and URPLOT, respectively, as shown in Fig. 5. The functions of these programs are as follows.

(1) URSAMP : This program generates sampling matrix of input parameters using the informations of distribution types and pairwise correla-

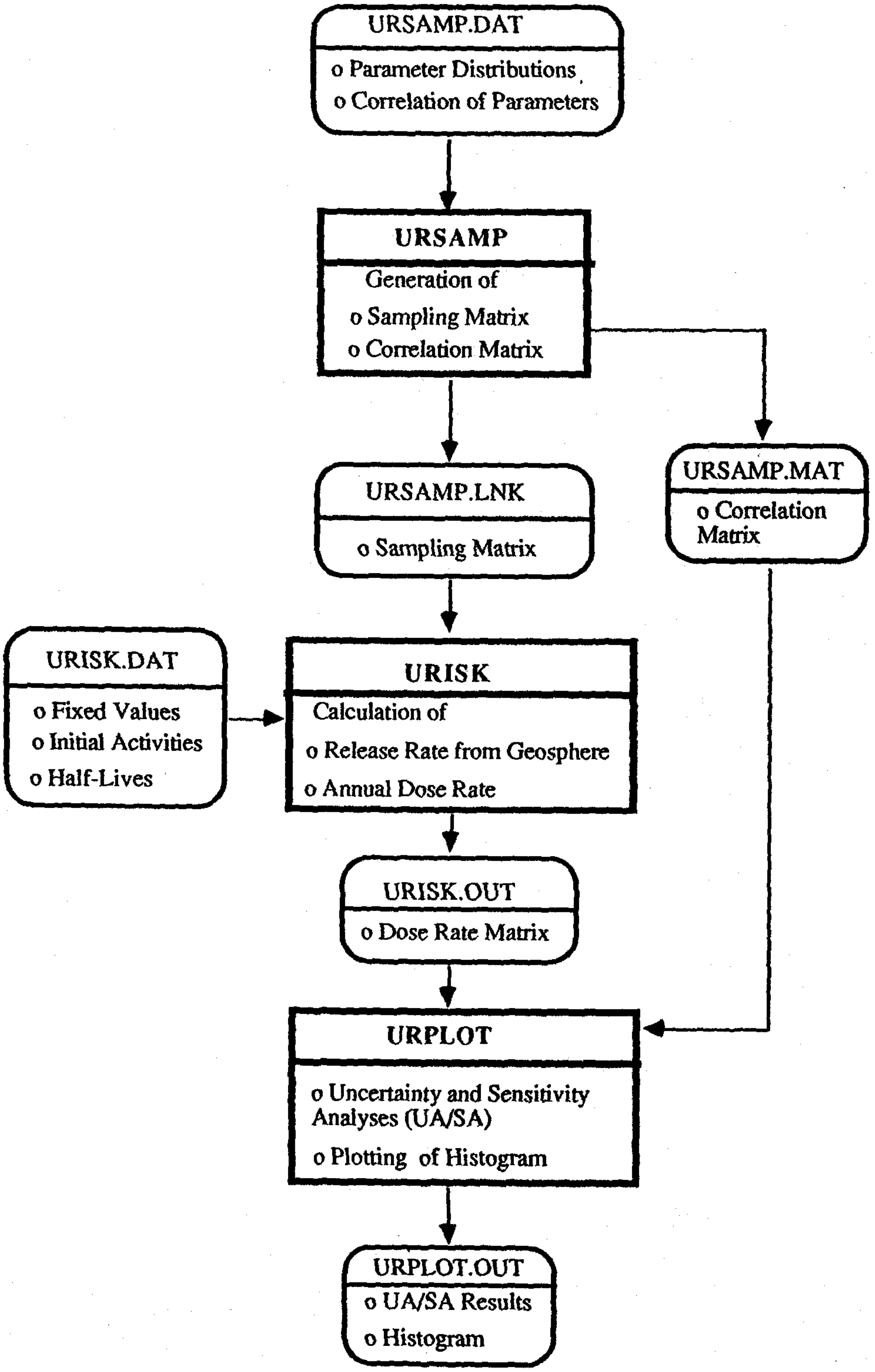

Fig.5. Flow chart of computer calculation.

tion coefficients of input parameters.

(2) URISK : This program calculates dose rates of each radionuclide as a function of time based on the input parameter set transferred from URSAMP and fixed values.

(3) URPOLT : This program generates various statistical parameters of output variable using the dose rate set transferred from URISK. It also generates rank correlation coefficients between each input parameter and output variable using the rank correlation matrix transferred from URSAMP. These correlation coefficients are used as a measure of importance ranking of parameters.

Radionuclide Inventory in the Repository

The radionuclide inventories in high level radioactive waste from the reprocessing of spent fuel disposed in the waste repository are varied with time after burial. These inventories can be calculated as a function of time after the removal of fuel from the reactor. These calculations were carried out by the use of ORIGEN2 code [37]. The reactor parameters used in these calculations are as follows : 3.2% U-235 enrichment of a fuel, average burnup of 30 MWd/MTU, exposed time of 1,100 days. It is assumed that spent fuel is reprocessed 160 days after removal from the reactor and the total inventories based on 10 PWRs with 1 GWe and 40 years operation are disposed at a time. Assuming that 30 tons of spent fuel are generated per reactor-year, the inventory amounts to 12,000 ton Uranium. Among numerous radionuclides contained in high level waste , the important nuclides for ingestion (Cs-137, Tc-99, Np-237) are considered in this study and they are listed in Table 4.1. with their half lives and initial inventories.

Table 2. Important nuclides for ingestion.

Nuclides	Half Life(yr)	Initial Activity (Ci)
Tc-99	2.14×110^5	1.562×10^5
Cs-137	30.2	1.483×10^9
Np-237	2.14×10^6	5.184×10^3

Input Data for Calculation

To account for the uncertainties on the model parameters which have uncertainties, parameter distribution types are assigned to these parameters. And these parameters are regarded as imput variables. For each parameter, the distribution type is chosen among uniform, loguniform, normal, and lognormal distributions according to its range and characteristics. Tables 3. and 4. show the uncertainty ranges and the distribution types of the input variables used for this calculation [5, 36]. The assumption of loguniform distribution gives more conservative results than that of lognormal distribution.

The other parameter values are fixed as given in Tables 5. and 6. These values are based on mean consumptions estimated for Korean habits style and data from references [36,38~41]. The soil-to-plant concentration ratio for pasture, B_p, is assumed to be proportional to the concentration ratio for vegetables B_v : $B_p=f_{pv}B_v$.

Because K_d and B_v are correlated [41], a correlation coeficient of -0.5 is introduced for these parameters in the sampling matrix by using Iman's correlation method [23]. This correlation allows to remove unrealistic combinations of parameter values from the sampling matrix.

RESULTS AND CONCLUSIONS

The minimum, mean, and maximum values of annual dose rates of the three nuclides under

Table 3. Uncertainty distribution of common parameters.

Parameter		Uncertainty Range	Distribution Type
X_1	(Vol.Flow Rate)	10^8~10^{10}m^3/yr)	LU(8,10)
X_2	(MTTFa)	10~1000 yr	LU(1,3)
X_3	(MTTFb)	300~3000 yr	LU(2.48,3.48)
X_4	(MTTFc)	3300~33000 yr	LU(3.52,4.52)
X_5	(T_w)	200~2000 yr	LU(2.30, 3.30)
X_6	(Q_{ir})	0.04~0.4 m/yr	LU(-1.60, -0.60)

* Loguniform Distribution(lower limit ; 8, upper limit ; 10, with base 10)

Table 4. Uncertainty distribution of nuclide-dependent parameters.

Parameter	Tc-99	Cs-137	Np-237
X_7 (K_{rd})	LU(1~100)*	LU(100~10000)	LU(200~800)
X_8 (K_{re})	LU(1~10)	LU(100~1000)	LU(100~300)
X_9 (K_d)	LN(-2.770, 0.21)	LN(-0.409, 0.50)	LN(-0.276, 0.52)
X_{10} (B_v)	LN(0.568, 0.25)	LN(-2.051, 0.59)	LN(-2.194, 0.61)
X_{11} (F_m)	LN(-1.398, 0.75)	LN(-1.721, 0.75)	LN(-6.149, 0.75)
X_{12} (F_b)	LN(-4.796, 0.60)	LN(-4.292, 0.60)	LN(-6.523, 0.60)

* LU=loguniform distribution with lower bound=1 and upper bound=100

* * LN=lognormal distribution μ=-2.770, σ=0.21

Table 5. Values of fixed parameters.

Parameter	Value	Parameter	Value
U_{cp}	20,000 kg/yr	U_{mb}	30 kg/yr
U_{cs}	180 kg/yr	U_{mv}	330 kg/yr
U_{cw}	2.9 m^3/yr	Q_n	0.25 m/yr
U_{mw}	0.37m^3/yr	η	0.3
U_{mm}	0.11m^3/yr	ρ	1,650 kg/m^3

Table 6. Values of nuclide-dependent fixed parameters.

Parameter	Tc-99	Cs-137	Np-237
$DCF_{ing(Sv/Bq)}$	3.4×10^{-10}	9.0×10^{-9}	1.2×10^{-6}
f_{pv}	3.78	1	1

consideration are presented as a function of time for the case of 100 sample runs in Figures 6. through 8. The uncertainties of the parameter values under consideration give rise to the uncertainties on the calculated annual dose rates of about three orders of magnitude for the three nuclides

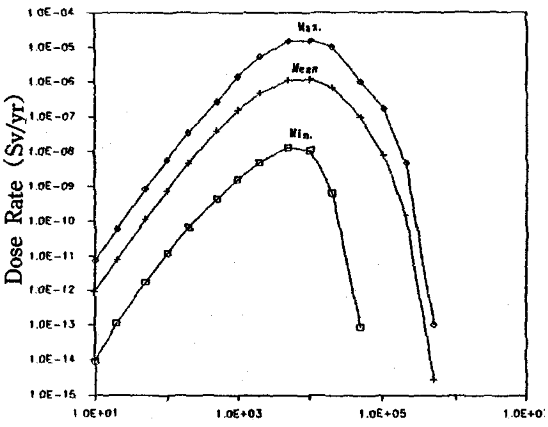

Fig.6. Annual dose rate of Tc-99.

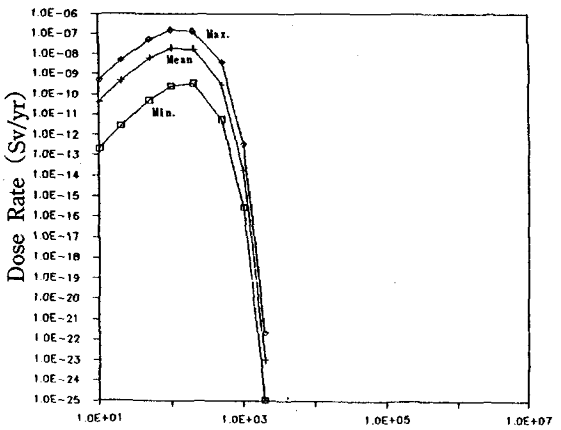

Fig.7. Annual dose rate of Cs-137.

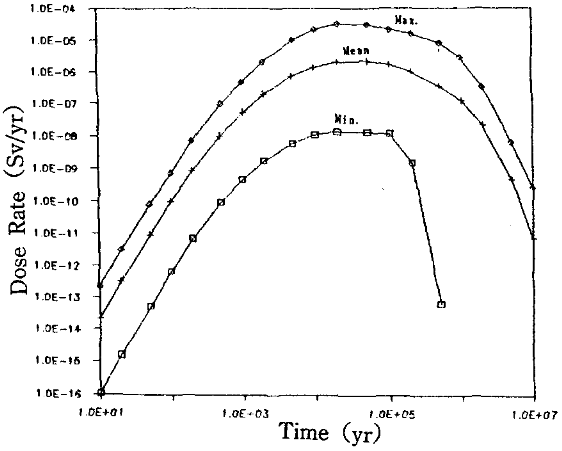

Fig.8. Annual dose rate of Np-237.

(the gap between maximum and minimum values).

Figure 9. shows for the comparison of the annual dose rate of each nuclide with the total dose rate (mean values). The peak value of the total dose rate is 2.65×10^{-6} Sv/yr (0.265 mrem/yr) at about 20,000 years after disposal. This peak value is smaller than 2.5×10^{-4} Sv/yr (25 mrem/yr), which is determined as the annual individual dose limit to the whole body for the safe disposal of radioactive waste by U. S. Environmental Protection Agency [42]. When the uncertainty is considered for total annual dose rate, the maximum peak value is a little bit less than 2.5×10^{-4} Sv/yr (25 mrem/yr). If some other radionuclides are included in the calculation, the peak annual dose rate may be larger than this value. However, it would be decreased if the uncertainties on some input parameters are reduced.

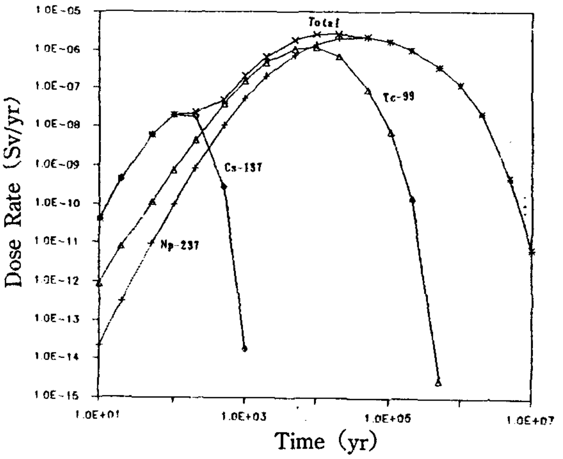

Fig.9. Total dose rate and annual dose rates (mean values) of the three nuclides.

Cesium-137, whose half life is shortist among three radionuclides considered in this study, is important for time periods up to 200 years and becomes negligible after 500 years. Technetium-99 is inportant for the time period between 200 years and 10,000 years. It diminishes after 2×10^5 years. After 10,000 years, Np-237 is the dominant nuclide. The peak times are mianly dependent on the half lives and retardation factors of radionuclides.

The results of rank correlation coefficients between the parameters and the dose rate of each radionuclide are illustrated in Fig. 10 through 12, which show the sensitive parameters for each nuclide. (1) In case of Tc-99, it is found in Fig. 10 that the volume flow rate of the surface

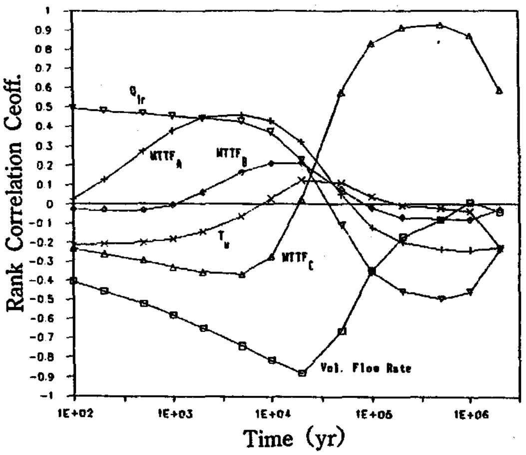

Fig.10(a) Rank correlation coefficient between each common parameter and the dose rate ; Tc-99, 100 sample runs.

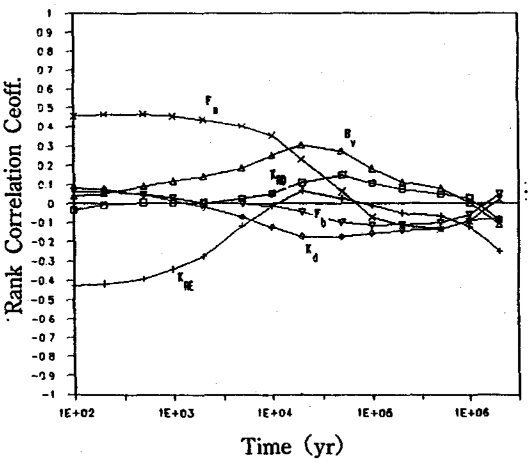

Fig.10(b) Rank correlation coefficient between each nuclide-dependent parameter and the dose rate ; Tc-99, 100 sample runs.

water is the most influential parameter throughout all the periods. Mean-Time-to-Failure of barrier A (host rock) MTTFa, irrigation rate Q_{ir}, concentration factor for milk F_m, are also found as sensitive (important) parameters.

(2) For Cs-137 in Fig. 11. , retardation factor for barrier D (backfill) K_{rd} is strongly correlated with the dose rate. This is attributed to the large retardation factor of Cs-137. The volume flow rate of the surface water is also a sensitive parameter.

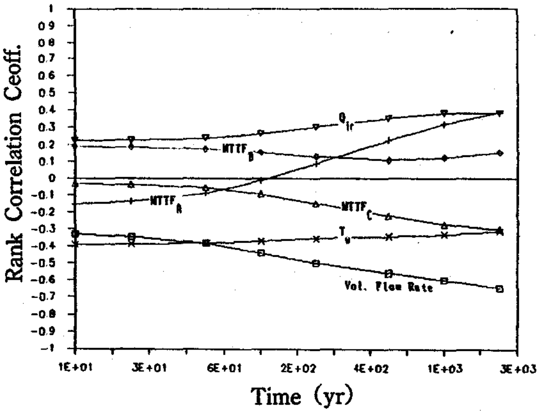

Fig.11(a) Rank correlation coefficient between each common parameter and the dose rate ; Cs-137, 100 sample runs.

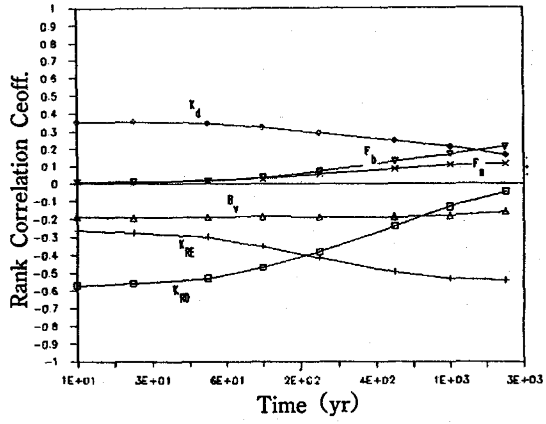

Fig.11(b) Rank correlation coefficient between each nuclide-dependent parameter and the dose rate ; Cs-137, 100 sample runs.

(3) For Np-237 in Fig. 12., the volume flow rate of the surface water is most strongly correlated throughout all the periods. K_{re} is also a sensitive parameter.

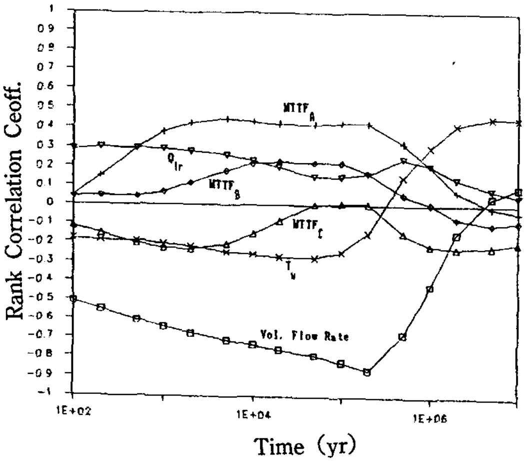

Fig.12(a) Rank correlation coefficient between each common parameter and the dose rate ; Np-237, 100 sample runs.

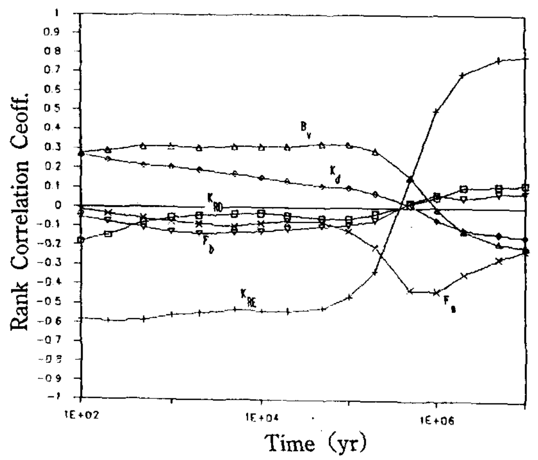

Fig.12(b) Rank correlation coefficient between each nuclide-dependent parameter and the dose rate ; Np-237, 100 sample runs.

(4) As the size of sample increases (50, 100, 300), it is found that the rank correlation coefficients of insensitive parameters converge while there are littlle changes in those of strongly correlated parameters [13].

The following conclusions are drawn from this study.

(1) The integrated model for the safety assessment of radioactive waste repository, which consists of the geosphere model for probabilistic risk analysis and the biosphere model with only the important pathways for ingestion of radionuclides, is developed. This model can be useful for the safety assessments in site evaluation or conceptual design stage of radioactive waste repository.

(2) The modified Monte Carlo simulation method using Latin Hypercube sampling can be a good method for the uncertainty analysis of the highly uncertain system.

(3) The rank correlation coefficient seems to be good for generating the dependence structure between samples of input parameters and a proper sensitivity estimator for the nonlinear system.

(4) The methodology of mathematical modelling with statistical analysis is effective for the decision-making of radioactive waste repository selection and future research area related to uncertain and sensitive input parameters.

The followings are recommended for the future work in this area.

(1) A lot of works must be done in development of radionuclide release scenarios from waste repository for the completeness of probabilistic safety assessment.

(2) The suggested integrated model in this study can be improved using site-specific informations, if specific site is determined.

(3) Much effort is required for reducing uncertainties of the input parameter values used in various models, such as, geology, hydrology, and

radition biology models.

(4) Finally, modelling uncertainties must be explored among various models used to describe each phenomena.

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