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Development of the Safety Assessment Code (CALM) for the Disposal of Low-and Intermediate-Level Radioactive Waste

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중 · 저준위 방사성폐기물 처분안정성 평가코드(CALM) 개발

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Abstract

A safety assessment computer code CALM (Computer program of Assessment for LILW Management) is developed for the theoretical prediction of long-term safety of low-and intermediate-level radioactive waste disposal. CALM is composed of three submodels, which are the resaturation model, the geosphere migration model, and the radiation dose model. For the verification of its usefulness, the safety assessment of an assumed waste repository is performed. The results show that the computer code, CALM developed through this study can be a useful tool for the safety assessment of low- and intermediate-level radioactive waste repository.

요 약

중 · 저준위 방사성폐기물 처분의 장기 안전성을 이론적으로 예측하기 위한 처분안전성평가 전산코드인 CALM이 개발되었다. 이 CALM은 처분장 재포화모델, 처분장에서의 지하 핵종 이동모델, 생태계에서의 핵종이동 및 방사선피폭선량 모델로 구성되어 있다. 개발된 평가코드의 유용성을 확인하기 위해 가상처분장에 대한 안전성 평가를 수행하였다. 그 결과 이 연구를 통해 개발된 CALM은 중 · 저준위 방사성폐기물 처분 안전성 평가에 유용하게 사용될 수 있음이 확인되었다.

1. Introduction

In Korea, the low-and intermediate-level radioactive waste repository is scheduled to be operated early 1996, and the site investigations for selection of a radioactive waste disposal site are under way. As the radioactive waste disposal project has proceeded, people have taken a growing interest in the safety of radioactive waste disposal and the development of a computer code for the safety assessment of radioactive waste disposal has become more important.

To meet the nation's need, CALM that is the first safety assessment code for low-and intermediate-level radioactive waste disposal in Korea is developed.

CALM inends to assess the radiation exposure to the neighbors of disposal site due to the radionuclides released by groundwater from a waste repository constructed in underground host rock. CALM is composed of three-submodels, which are the model for repository resaturation time, the model for radionuclide migration through geosphere, and the model for radionuclide transport in biosphere and radiation dose.

In this paper, the structure and theoretical modelings of CALM are described and the results of preliminary safety assessment for an assumed repository are presented to illustrate the usefulness of the code.

2. Structure

CALM is composed of three submodels comprising the resaturation model REMORE, the radionuclide migration model MIMOSA, and the radiation dose model RADDOSE [Fig. 1]

REMORE is to estimate the resaturation time of repository. After the closure of waste repository, the groundwater that exists in the surrounding host rock will intrude into the repository and saturate the backfill materials. This phemomenon is called as resaturation. The resaturation time is important on the viewpoint of safety assessment because it determines the starting point of radionuclide release.

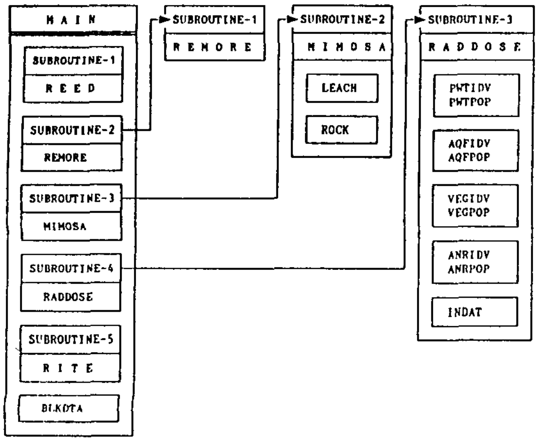

Fig. 1. Schematic Diagram of Structure of CALM code

MIMOSA is to simulate the far-field migration of radionuclides leached from waste through geosphere. Radionuclides are transported through rock matrix to the biosphere by groundwater. In MIMOSA, the tansportation of radionuclide by advection and diffusion in groundeater, chemical interaction between radionuclides and rock matrix and the radioactive decay are considered. An analytic solution is used to describe the radionuclide migration through a single fissure of rock.

RADDOSE is to calculate the individual and population dose due to the radionuclide release to biosphere. The radionuclides released into biosphere can be transported to human through various pathways, and cause radiation exposure to man. In RADDOSE, 4 pathways which are the potable water, the aquatic foods, the vegetation, and the animal products are considered.

3. Theoretical Modeling

3.1. Resaturation Model

The assumptions for the estimation of resaturation time are as follows:[1]

- The lateral flow of groundwater around waste repository is ignored.
- The repository is located in host rock below water table and there are aquifers with high permeability above and below the repository, respectively.
- The spaces between the wall of repository and the disposed waste are packed with backfill materials.
- The repository maintains the dry condition immediately after closure.

After the closure of repository, the intrusion rate of ground water into repository from the upper and the lower aquifers is given as[1]

$$Q_o = 2K_V \cdot \frac{H}{D} \cdot A \tag{1}$$

where

Q_o: groundwater intrusion rate (m^3/sec)

A : floor area of repository (m^2)

H : hydraulic head difference between repository and aquifer (m)

D : distance from repository to aquifer (m)

K_V: vertical hydraulic conductivity of surrounding rock (m/sec),

and the void volume of repository (V_m) is

$$V_m = L \cdot e \cdot n \cdot A \tag{2}$$

where

L: height of repository cavern

n: porosity of backfill

e: extraction ratio

$$= \frac{\text{floor area of disposal tunnel and corridor}}{\text{total bottom area of repository.}}$$

Then the resaturation time of void volume in the repository is

$$t_m = \frac{V_m}{Q_o} = \frac{L \cdot e \cdot n \cdot D}{2 \cdot K_V \cdot H.} \tag{3}$$

The water volume required to achieve the re-equilibrium of pressure boundary in the surrounding rock (V_r) is given as

$$V_r = D \cdot A \cdot H \cdot S_s \tag{4}$$

where S_s: specific storage of rock (m^{-1}),

and the time required for re-equilibrium of pressure in the surrounding rock (t_r) is

$$t_r = \frac{2V_r}{Q_o} = \frac{D^2 \cdot S_s}{K_V} \tag{5}$$

Therefore, the resaturation time to of repository is

$$\begin{aligned} t_o = t_m + t_r &= \frac{L \cdot e \cdot n \cdot D}{2\,K_V \cdot H} + \frac{D^2 \cdot S_s}{K_V} \\ &= \frac{L \cdot D}{2\,K_V \cdot H}\left(e \cdot n + \frac{2D \cdot S_s \cdot H}{L}\right). \end{aligned} \tag{6}$$

In this study, it is assumed that aquifer is located only above the repository and groundwater intrusion rate through backfill of repository flows constantly. Then, resaturation time is derived considering the effect of abackfill in repository. The groundwater intrusion rate into backfill from surrounding rock is given as,

$$Q_b = K_b \cdot \frac{H_r}{D_b} \cdot A \tag{7}$$

Q_b: groundwater intrusion rate into backfill (m^3/sec)

H_r: hydraulic head difference between repository and surrounding rock (m)

D_b: thickness of backfill (m)

K_b: hydraulic conductivity of backfill (m/sec)

The void volume of repository (V_m) is equal to equation (2). The resatiration time of void volume in repository is

$$t_m = \frac{V_m}{Q_b} = \frac{L.e.n.D_b}{K_b \cdot H_r} \tag{8}$$

Therefore, the resaturation time of repository is obtained by adding equation (5) and (8).

$$t_o = t_m + t_r = \frac{L.e.n.D_b}{K_b \cdot H_r} + \frac{D^2 \cdot S_s}{K_V} \tag{9}$$

3.2. Radionuclide migration model in the far-filed

After resaturation of repository, groundwater corrodes the waste container and comes into eventually contact with waste matrix. Then the radionuclides are leached out from the waste matrix into groundwater. Because of the low water flow rate through the repository, radionuclides concentration in groundwater is assumed to be in equilibrium with that in waste matrix, which is a conservative assumption.

The host rock where the repository is to be located is mainly the crystalline rock such as granite, and its hydraulic conductivity and permeability are very low. There are, however, many fissures and fractures in the crystalline rock and the radionuclides are transported by groundwater through these fissures in rock.

For the mathematical modeling the groundwater flow is assumed to be one-dimensional along the Z-direction through fissure (Fig. 2).[2]

The governing equation for radionuclide migration through fissure is[2,3]

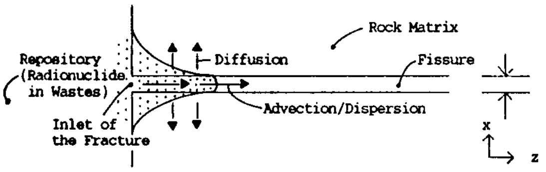

Fig. 2. Radionuclide migration through the fissure in rock and diffusion in rock matrix

$$\frac{\partial C_f}{\partial t}=\frac{D_f}{R_f}\frac{\partial^2 C_f}{\partial Z^2}-\frac{V}{R_f}\frac{\partial C_f}{\partial Z}-\lambda C_f-\frac{q}{bR_f} \qquad (10)$$

where

V : velocity of groundwater in fissure (m/yr)

Df: dispersion coefficient in fissure (m^2/yr)

Rf: retardation factor of nuclide on the wall of fissure

λ : decay constant ($year^{-1}$).

Since the concentration of radionuclide in groundwater is low, the linear sorption isotherm is usually assumed. Then the retardation factor of nuclide, Rf is given by[4]

$$R_f=1+\frac{K_a}{b} \qquad (11)$$

where

Ka: distribution coefficient of nuclide defined as the mass of solute absorbed per unit area of surface divided by the concentration of solute in solution [m]

b : a half of fracture width [m].

The fissure can be considered as a vertically expanded unit area strip and the mass balance of radionuclides in the porous rock matrix is as follows:

$$\frac{\partial C_P}{\partial_t}=\frac{R_P}{D_P}\frac{\partial^2 C_P}{\partial X^2}-\lambda C_P \qquad (12)$$

where

Cp: radionuclide concentration in rock matrix (Ci/m^3)

Dp: diffusion coefficient of nuclide in rock matrix (m^2/yr)

Rp: retardation factor of nuclide in rock matrix

The flux of nuclide q describing the loss by diffusion from the fissure to the rock matrix is given according to the Fick's law

$$q=-\phi_d D_p\frac{\partial C_P}{\partial X}\bigg|_{Z=b} \qquad (13)$$

where ϕ_d is the porosity of rock. Assuming again linear isotherm the retardation factor of nuclide in porous rock matrix is as follows:

$$R_P=1+\frac{\rho_b K_d}{\phi_d} \qquad (14)$$

where

b: bullk density of rock (g/cm^3)

Kd: distribution coefficient of nuclide based on the rock mass

The initial condition and the boundary conditions for Eq. (10) are

$$C_f(Z,0)=0 \qquad (15a)$$
$$C_f(0,t)=C_0e^{-\lambda t} \qquad (15b)$$
$$C_f(\infty,t)=0 \qquad (15c)$$

and for Eq. (12)

$$C_P(X,Z,0)=0 \qquad (16a)$$
$$C_P(X,b,t)=C_f(Z,t) \qquad (16b)$$
$$C_P(\infty,Z,t)=0 \qquad (16c)$$

where Co is the initial concentration of nuclide. Eq (11) expresses the coupling of the porous rock matrixk to the fissure.

Applying the Laplace transform technique to Eqs. (10), (12) with these initial and boundary conditions, the following solutions for fissure and rock matrixk are obtained:[5]

$$C_f(z,t)=\frac{2}{\sqrt{\pi}}C_0\exp\left(\frac{V_z}{2D_f}\right)\exp(-\lambda t)\times \int_{\sqrt{\frac{Z}{2}\left(\frac{R_f}{D_f t}\right)}}^{\infty}\exp\left\{-\xi^2-\left(\frac{Vz}{4\xi D_f}\right)^2\right\}\times \operatorname{erfc}\left\{\frac{Z^2\phi_d D_P\sqrt{\frac{R_P}{D_P}}}{8\xi^2 D_f b\sqrt{\left(t-\frac{Z^2R_f}{4\xi^2 D_f}\right)}}\right\}d\xi \qquad (17)$$

$$C_p(x,z,t)=\frac{2}{\sqrt{\pi}}C_0\exp\left(\frac{V_z}{2D_f}\right)\exp(-\lambda t)\times \int_{\sqrt{\frac{Z}{2}\left(\frac{R_f}{D_f t}\right)}}^{\infty}\exp\left\{-\xi^2-\left(\frac{Vz}{4\xi D_f}\right)^2\right\}\times \operatorname{erfc}\left\{\frac{Z^2\phi_d D_P\sqrt{\frac{R_P}{D_P}}+\frac{1}{2}(x-b)\sqrt{\frac{R_p}{D_P}}}{8\xi^2 D_f b\sqrt{\left(t-\frac{Z^2R_f}{4\xi^2 D_f}\right)}}\right\}d\xi \qquad (18)$$

3.3. Model for annual dose to man from the radionuclide release

The radiation exposure pathway considered in the RADDOSE are the potable water, the vegetations, the aquatic food, and the animal product. The schematic diagram for the pathway of radiation exposure to neighbor population is shown in Fig. 3.

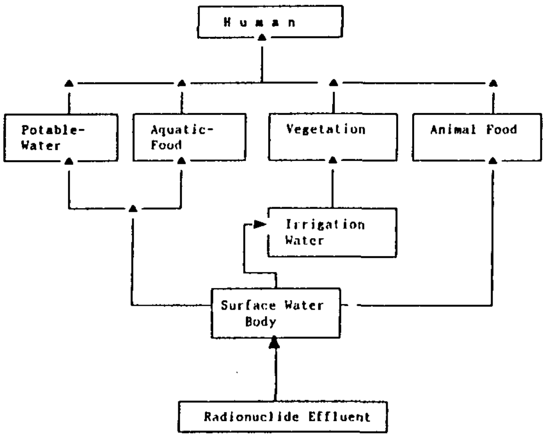

Fig. 3. Schematic representation of RADDOSE

1) Radiation exposure pathway

i) Potable water

The annual internal dose from ingestion of contaminated water is

$$R_{apj}=\frac{M_p\cdot U_{ap}}{F}\sum_i Q_i\cdot D_{aipj}\cdot \exp(-\lambda_i\cdot t_p) \tag{19}$$

where

Uap : exposure time or intake rate (usage) associated with pathway p for age group a [kg/yr or l/yr]

Daipj: dose factor [mrem/pCi] (age group a, radionuclide i, pathway p, and organ j)

Rapj : annual individual radiation dose (mrem/yr)

Mp : mixing ratio

Qi : release amounts of radionuclide (Ci/yr) (=Cf*Gf) (Gf: underground water flow rate)

F : flow rate of groundwater (m^3/yr)

λi : decay constant of nuclide i (1/yr)

tp : transit time (yr)

The expression (Qi*Mp/F).exp(−λi*tp) yields the concentration of nuclide i at the time the water is consumed in pCi/l. As a minimum, the transit time tp may be set equal to 12 hours to allow for radionuclide transport through the water purification plant and the water distribution system. The transit time should be increased as appropriate to allow for travel from the point of effluent release to the water purification plant intake.

ii) Aquatic Foods

The annual internal dose from consumption of aquatic foods produced from the contaminated rivers is

$$R_{apj}=\frac{M_p\cdot U_{ap}}{F}\sum_i Q_i\cdot B_{ip}\cdot D_{aipj}\cdot \exp(-\lambda_i t_p) \tag{20}$$

where Bip: bioaccumulation factor (l/kg)

The concentration of radionuclide in aquatic foods are assumed to be directly related to the concentrations of the nuclides in water. Equilibrium ratios between the two concentrations called bioaccumulation factors (Bip) can be found in the literature.[6]

The transit time tp may be set equal to 24 hours to follows for radionuclide decay during transit through the food chain, as well as during food preparation.

iii) Vegetation

The annual internal dose from consumption of vegetation irrigated by contaminated water is

$$R_{apj}=U_{ap}\sum C_{iv}\cdot D_{aipj} \tag{21}$$

where Civ is the concentration of radionuclides in the edible portion of crop species v and is given below in two different forms according to the type of radionuclides.

The concentration of radioactive material in vegetation results from deposition onto the plant foliage and from uptake from the soil of activity deposited on the ground.

The model used for estimating the transfer of radionuclides from irrigation water to crops through water deposited on leaves and uptake from soil was derived for a study of the potential dose to people from a nuclear power complex in the year 2000.

The first term in brackets relates to the concentration derived from direct foliar deposition during the growing season. The second term relates to uptake from soil and reflects the long-term deposition during operation of the nuclear facility.

- For all radionuclides except tritium

$$C_{iv} = d_i \left[\frac{r\,(1-\exp(-\lambda_{ei} \cdot t_e))}{Y_v \cdot \lambda_{ei}} + \frac{f_i \cdot B_{iv}\,[1-\exp(-\lambda_i \cdot t_b)]}{p \cdot \lambda_i} \right] \cdot \exp(-\lambda_i \cdot t_h) \qquad (22)$$

where

di : deposition rate from irrigated water (pCi/m2 per hr) = Ciw * I

I : average irrigation rate during the growing season (l/m^2/hr)

r : fraction of deposited activity retained on crops, leafy vegetables or pasture grass

λei : effective removal rate constant (1/hr = λi + λw

λw : removal rate constant (l/h^2)

te : period of crop, leafy vegetable, or pasture grass exposure during growing season (yr)

Yv : agricultural productivity by unit area (measured in wet weight)

fi : fraction of the year that crops are irrigated

Biv: concentration factor for uptake of radionuclide from soil by edible parts of crops, pCi/kg (wet weight) per pCi/kg dry soil

tb : period of time of which soil is exposed to the contaminated water (hrs)

: effective surface density of soil, kg (dry soil)/m^2

th : hold-up time that represents the time interval between harvest and consumption of the food (hrs)

- For tritium

$$Civ = Ciw \qquad (23)$$

where Ciw is radionuclide concentration in irrigated water (pCi/l)

iv) Animal Foods

The annual internal dose from consumption of animal products such as meat or milk from the animals that are grown by contaminated feed or forage is

$$R_{apj} = U_{ap} \sum_i C_{ia} \cdot D_{aipj} \qquad (24)$$

where Cia is the radionuclide concentration in animal products and is given below in two different forms according to the type of radionuclides.

- For all radionuclides except tritium

$$C_{ia} = F_{ai} \cdot [C_{iF} \cdot Q_F + C_{iaw} \cdot Q_{aw}] \qquad (25)$$

where

Fai : stable element coefficient

Cif : radionuclide concentration in feed or forage (pCi/kg)

Ciaw : radionuclide concentration in animals drinking water (pCi/l)

Qf : animal consumption rate of feed or forage (kg/day)

QAW: animal consumption rate of water (l/day)

- For tritium

$$C_{ia} = F_a \cdot C_w [Q_F + Q_{aw}] \qquad (26)$$

The radionuclide concentration in an animal product such as meat or milk is dependent on the amount of contaminated feed or forage eaten by the animal and its intake of contaminated water.

2) Total Dose

Total annual dose to man is the summation of the internal dose from all pathways mentioned above.

$$R_{aj} = \sum_j R_{apj} \qquad (27)$$

4. Safety Assessment for Assumed Low-and Intermediate-Level Radioactive Waste Repository

4.1. Assumed Repository and Radionuclide Release Scenario

To assess the usefulness of CALM, it is applied to the safety assessment of assumed radioactive waste repository. The repository is assumed to be a engineered rock cavern type repository that is located

Table 1. Assumed hydrological characteristics of aquifer, rock and backfill

	Aquifer (unconsolidated sand)	Repository layer	Backfill (silty sand)
permeability (m^2)	10^{-11}	10–×∯	—
hyraulic conductivity (m/sec)	10^{-4}	10^{-11}	10^{-10}
porosity	0.3	0.001	0.25
specific sotorage (1/m)	—	10^{-7}	—

in homogeneous and massive rock matrix. There is an aquifer above the repository rock matrix and the backfill material is assumed to be a silty sand. The hydrological characteristics of aquifer and rock are shown in Table 1.[4, 7-8] The disposal capacity and the total excavated volume of repository are assumed to be 500,000 drums and 2,000,000 m^3 respectively. [Fig. 4] The radionuclide inventories to be disposed of into repository are represented in Table 2.[5] For the illustration, the maximum individual total body doses to the neighbor due to the release of H-3 and Tc-99 are calculated.

For radionuclide release scenario, only well scenario is considered because it gives the most conservative results. Then the radionuclides leached from wastes are migrated through a single long fissure in rock medium and released into a well located in the vicinity of repository. The migration length is assumed to be 150 m.

The values of parameters used to calculate the resaturation time of repository are shown in Table 1. The hydraulic head difference Hr between repository and surrounding rock and the thickness of backfill Db are assumed to be 50 m and 2 m, respectively.

The parameters used to calculate the migration of radionuclide through rock matrix are presented in Table 3 and for dose model the values of parameters suggested in NRC Reg. Guide 1.109[9] are used.

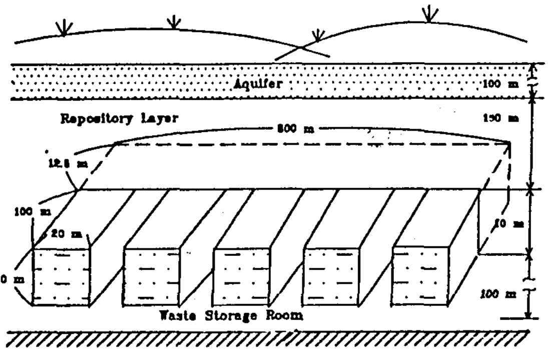

Fig. 4. Schematic representation of assumed repository

Table 2. Radionuclide-related parameter

Nuclide	Inventory ($Ci/10^5m^3$)	K_d (g/cm^3)	K_a (m)	$K_{d,con}$ (g/cm^3)
H_3	1.080×10^4	0.0	0.0	0.5
Tc^{99}	2.880	0.0	0.0	0.5

Table 3. Parameters used to calculate the radionuclide migration through rock media

Parameter	Value
Half width of the fissure, b	0.0001 [m]
Porosity of the rock matrix, ε_p	0.005
Tortuosity factor, τ	0.1
Molecular diffusivity, D^*	0.05 [m^2/year]
Bulk density of the rock, P_p	2.62 [g/cm^3]
Axial dispersion length, α_L	0.1 [m]
Groundeater velocity, v	10.0 [m/year]

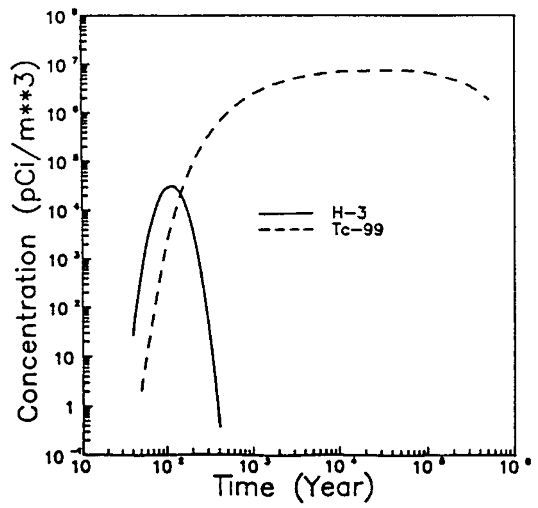

Fig. 5. **Breakthrough curves of Tc-99 and H-3 released into the well located in the vicinity of assumed repository**

4.2. Results and Discussion

The results of safety assessment for the assumed repository show that the resaturation time of repository is about 10 years and the radionuclide concentration in groundeater flowed into the wellc an be represented by a breakthrough curve (Fig. 5) and a function of time after the release from the repository.

As shown in the figure, the maximum values of radionuclide conentration in groundwater flowed into the well will be obtained at 120 year for H-3 and at 6 x 10^4 years for Tc-99 after the beginning of release respectively, and the maximum concentrations are 3.634 x 10^4 pCi/m^3 and 7.411 x 10^6 pCi/m^3 respectively.

The radiation doses to neighbors of the waste repository due to the contaminated well are estimated for the various pathways and the parameters of Reg. Guide 1.109 are used in the calculation. For consevatism, it is assumed that man ingests the well water as potable water, and consumes the vegetation and crops irrigated by contaminated water and the animal products from the animals that are grown by contaminated feed and contaminated water.

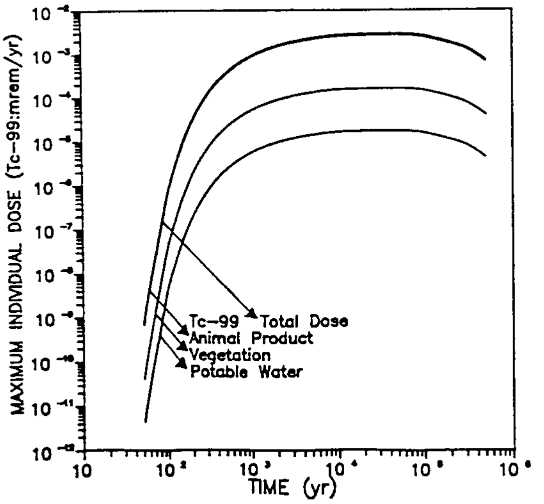

Fig. 6. **Maximum annual dose (total body) to man due to the release of Tc-99**

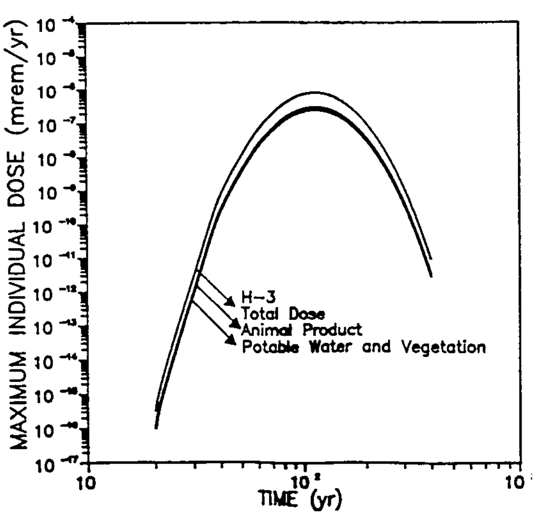

Fig. 7. **Maximum annual dose (total body) to man due to the release of H-3**

The maximum individual doses for total body after the closure of repository are represented in Fig. 6 and 7. As shown in the figures, the maximum doses are 8.03 x 10^{-7} mrem/year at 120 years for H-3 and 2.87 x 10^{-3} mrem/year at 6 x 10^4 years for Tc-99 after the closure of repository.

These value are very low in comparison with 500 mrem/year that is the maximum permissible dose for public in the case of in nuclear power plant operation.

5. Conclusion

For the successful imprementation of the low- and intermediate-level radiocative waste disposal project, the assurance of the disposal safety is essential. The prediction of long-term disposal safety can be performed using the safety assessment computer code.

In this paper, CALM, a integrated safety assessment computer code for low- and intermediate-level radioactive waste disposal is developed. To assure its effectiveness the safety assessment of an assumed repository was peformed for numerical illustrations and the results show that the computer cold CALM can be used for the safety assessment of low- and intermediate-level radioactive waste repository.

For the specific assessment, however, the performance of near-field barrier in repository such as backfill might be considered. Therefore the studies on the simulation of near-field migration of radionuclides and the adoption of numerical solution with FDM using Crank-Nicolson sheme to simulate radionuclide migration through geosphere are underway.

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