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A GENERIC SAFETY ASSESSMENT CODE FOR GEOLOGIC DISPOSAL
OF RADIOACTIVE WASTE : GSRW COMPUTER CODE USER'S MANUAL

November 1992

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A Generic Safety Assessment Code For Geologic Disposal of
Radioactive Waste: GSRW Computer Code User's Manual

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The computer code system GSRW (Generic Safety assessment code for geologic disposal of Radioactive Waste) was developed as an interim version of safety assessment methodology for geologic disposal of high-level radioactive waste. Scenarios used here are based on normal evolution scenarios which assume that the performance of a disposal system is not affected by probabilistic events. The code consists of three parts. The first part evaluates a source term from a disposal facility which consists mainly of a vitrified waste, a metallic container and a buffer zone. Two kinds of source term models are provided: Model 1 which simulates the dissolution of silicate component of glass and the diffusive transport of radionuclides in the buffer zone, and Model 2 which assumes that the concentration of a radionuclide is limited by the solubility of its specific chemical form at the interface between the buffer and a vitrified waste. The second part analyses the transport of radionuclides in the geosphere, which is based on analytical solutions or numerical solutions of a mass transport equation involving the advection, dispersion, linear sorption and decay chain. The third part assesses the transport of radionuclides in the biosphere and the resulting radiological consequences to the man, which is based on a dynamic compartment model for the biosphere and a dose factor method for dose calculations. This report describes mathematical models used, the structure of the

code system, and user information and instructions for execution of the code.

Keywords: Geologic Disposal, High-level Radioactive Waste, Safety Assessment, Computer Code, User's Manual, Geosphere, Source Term, Biosphere, Dose Calculation, Transport, Diffusion, Dispersion, Sorption, Decay Chain

放射性廃棄物地層処分の一般的安全評価コード：
GSRW計算コードのユーザズマニュアル

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計算コードGSRWは、高レベル放射性廃棄物地層処分安全評価手法の中間バージョンとして開発されたものである。本手法で用いられた評価シナリオは、処分システムの性能が確率論的事象によって影響を受けないと仮定した通常シナリオに基づいている。本コードは3部分により構成されている。最初の部分は、固化体、金属容器及び緩衝材で構成される処分施設からのソースタームを評価するものである。ここでは以下の2種類のモデルが用いられている：ガラス固化体のシリカ成分の溶解及び緩衝材中の拡散移行を考慮する（モデル1）、固化体－緩衝材境界において核種濃度はその化学形の溶解度で拘束される（モデル2）。2番目の部分は地層中での核種移行を解析解及び数値解に基づき解析するもので、移流、分散、線形吸着及び崩壊連鎖を考慮している。3番目の部分は生態圏中における核種移行及び人間の被曝線量を解析するもので、動的コンパートメントモデル及び線量換算係数法に基づいている。本報告書は、本コードの数学モデル、コード構造及び使用法を記述したものである。

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1. INTRODUCTION

The safety of radioactive waste disposal is one of the essential subjects of all countries engaged in nuclear energy production. In particular, a high-level radioactive waste (HLW) which contains an significant amount of long-lived radionuclides will be disposed of into deep geologic disposal system consisting of a series of engineered and natural barriers, so as to isolate it effectively and to ensure radiation protection of human and his environment even in the far future. Nuclear facilities are subjected to, before their constructions and operations, safety review by the national regulatory body to demonstrate through safety assessment that the facilities will not cause any unacceptable level of radiological consequences on the public.

The Japan Atomic Energy Research Institute (JAERI) is developing a safety assessment methodology for geologic disposal of HLW, in accordance with the Long-Term Yearly Program for Safety Study on High-Level Radioactive Wastes (1991 - 1995) established by the Atomic Energy Safety Commission of Japan. Objectives of the development of the methodology are;

- to demonstrate a generic feasibility of HLW disposal in Japan,
- to extract the important pathways and parameters,
- to identify the major uncertainties involved in the results of assessment,
- to indicate the effects of various barriers to be involved in a disposal system,
- to assign a priority of future research,
- to provide information which will be used to derive criteria and guidelines for safety regulation, and
- to establish the methodology for licensing procedures.

As a part of this activity, we have developed a computer code system GSRW (Generic Safety assessment code for geologic disposal of Radioactive Waste) as an interim version of deterministic safety assessment methodology. The GSRW code intends to evaluate radiological consequences to an individual or a population due to radioactivity released from deep geologic radioactive waste repositories by groundwater. A series of barriers provided with a disposal system will prevent the release of radionuclides from a repository, and retard the subsequent transportation of them in the geosphere.

The most complex part of a repository performance assessment is the analysis of the transport of radionuclides by groundwater in and through the repository and the geosphere. In the GSRW code, these computations are based on simplified models which incorporate only the major mechanisms and components, both of which will be potentially involved in the disposal system. Among the mechanisms whose effects are involved in the computation are;

- dissolution and leaching of the waste matrix,

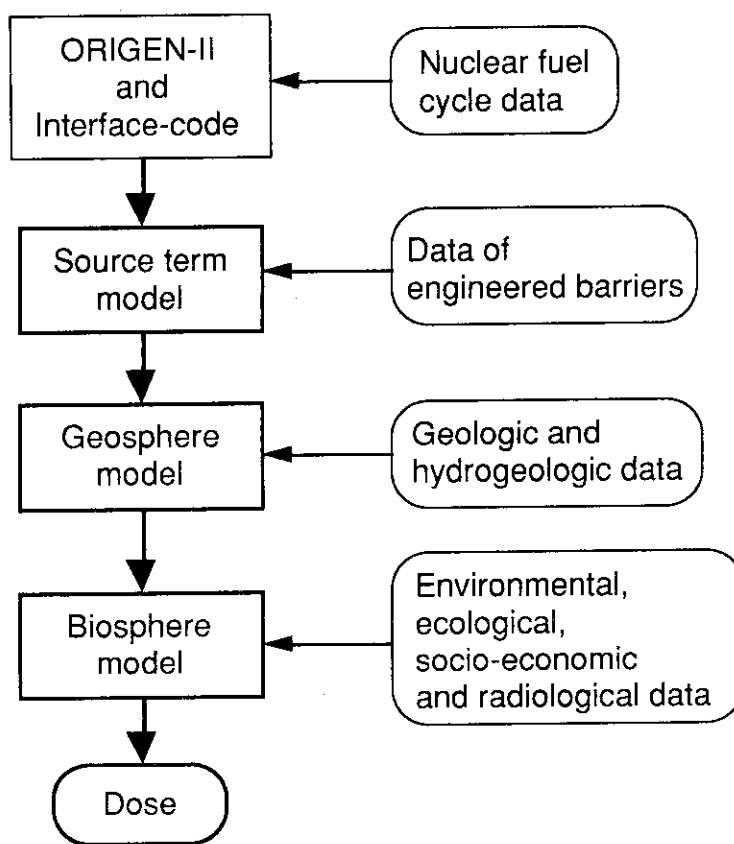


Fig. 1 Sub-models in the GSRW code

- dissolution of the elements in the waste,
- diffusive transport of radionuclides through a buffer material,
- advective and dispersive transport by groundwater in the geosphere,
- sorption equilibrium of radionuclides in the buffer and geologic media,
- dilution of the radionuclides transported to adjacent aquifers by a large volume of water,
- transport of the radionuclides in the biosphere consisting of terrestrial and aquatic ecosystems,
- and
- exposure to the public.

This simplified approach makes a large number of computer execution more practical, simplifies interpretation of analytical results, and permits a generic safety assessment, in particular where a candidate disposal site is not decided yet.

The GSRW code is composed of three interlinked models, a source term, a geosphere and a biosphere model, as illustrated in Fig. 1. The ORIGEN-II and interface codes are used to evaluate the inventory of radionuclides in HLW as a function of time. The first model evaluates a source term from a disposal facility which consists mainly of a vitrified waste form, a metallic container and a

buffer material. Two kinds of source term models are provided: Model-1 which simulate the dissolution of silicate component of glass and assumes that the radionuclides in the vitrified wastes are released in proportion to the leaching rate of silicate component, and Model-2 which assumes that the concentration of a radionuclide is limited by the solubility of its specific chemical form at the interface between the buffer and a vitrified waste. The second model analyses the transport of radionuclides in the geosphere, which is based on analytical solutions or numerical solutions of a mass transport equation involving an one-dimensional advection, a three or one-dimensional dispersion, a linear sorption and a decay chain. The third model assesses the transport of radionuclides in the biosphere and the resulting radiological consequences to the man, which is based on a dynamic compartment model for the biosphere and a dose factor method for dose calculations.

1.1 Basic descriptions of a disposal system and scenarios

The safety of the disposal system depends on the performance of engineered barriers (a waste matrix, a container, a buffer zone and repository structures) to confine radionuclides in the repository, and the ability of natural barriers to retard and dilute radionuclides during the transport in the geosphere and the biosphere. In the GSRW code, the safety of the repository is assumed to be controlled by this multi-barrier concept, as shown in Fig. 2. The concept of the disposal system assumed here consists of;

- the container plays as a barrier to protect the waste contained therein from the contact with groundwater during a certain initial period of the time after the closure of the repository, and then determines the initiation of radionuclide release,
- the vitrified matrix confines radionuclides, however, once the container failed significantly the matrix will be subjected to a dissolution process by groundwater, which is controlled by the dissolution rate of the matrix and also by the solubility of the elements involved,
- the buffer zone, in which radionuclides are transported by the diffusion and retention mechanisms, retards the release of radionuclides from the repository,
- the repository structure consisting of cementitious materials will keep the chemical environment of groundwater favorable to reduce the solubility of the elements for a certain period of the time depending on the rate of corrosion process by which alkali components of cementitious materials are released,
- the geosphere, where most portions of the radionuclides released from the repository are effectively retained and delayed by various retention mechanisms, retards the transport of the radionuclides to the biosphere, and
- the radionuclides finally entered into the biosphere will be diluted with a large volume of groundwater in adjacent aquifers, and with surface water bodies such as ocean, river, lake and

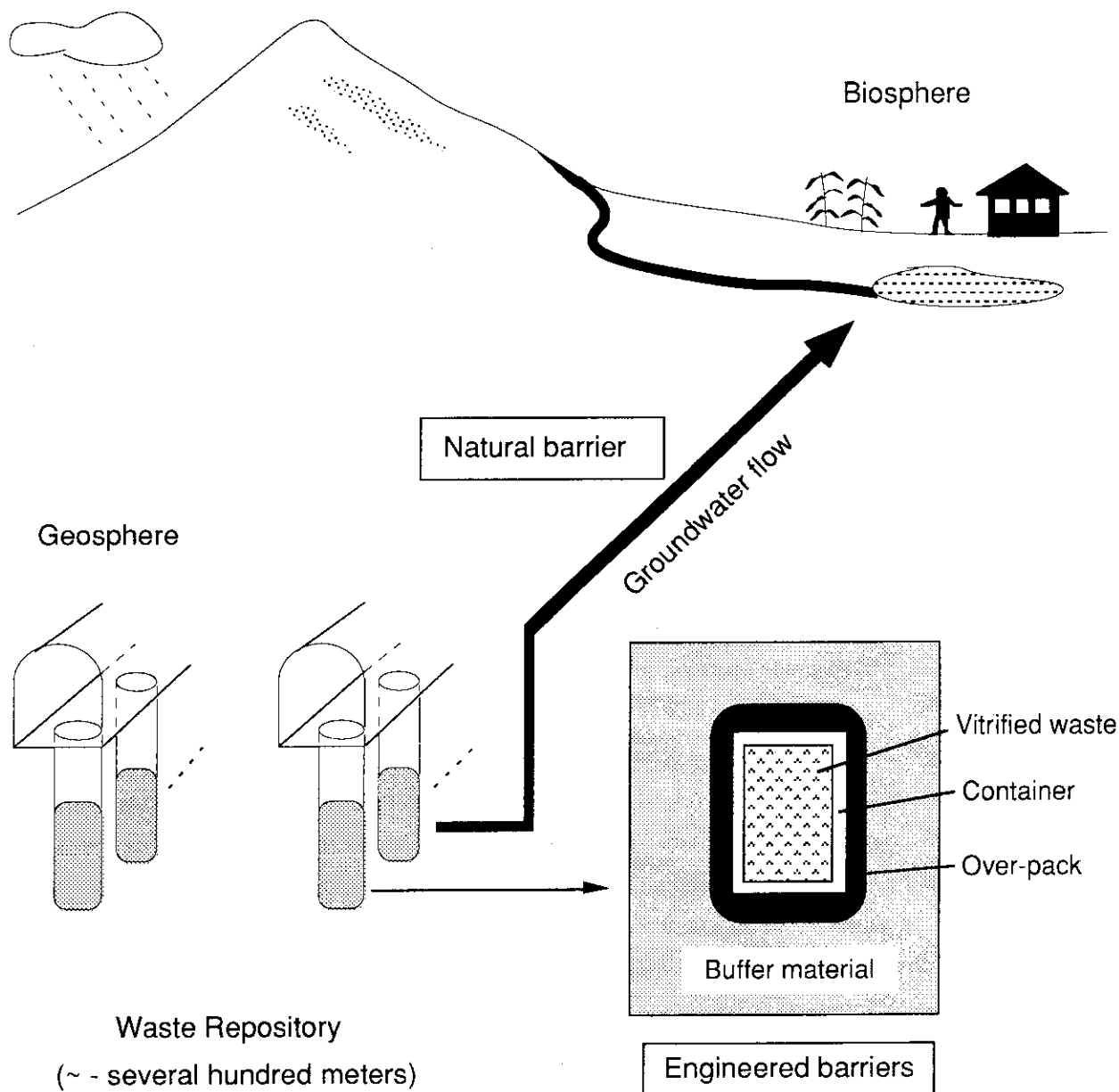


Fig. 2 Multi-barrier concept for high-level radioactive waste disposal

so on, before coming into contact with the man.

This concept which is reflected in the modelling scheme adopted in the GSRW code may realize the isolation of most of the radionuclides in the waste during a long time, allow the reduction of radionuclide concentrations at the biosphere, and finally maintain radiological consequences to individuals or populations at an acceptable level, even in the case where the ability of some of barri-

ers would be reduced.

The scenarios considered in the development of the methodology are based on groundwater migration scenarios, assuming that the performance of the disposal system is not affected by probabilistic events as is the case of normal evolution scenarios. It is assumed in the scenarios that all of the components involved in the repository are resaturated eventually with groundwater, after the closure of the repository. Degradation with groundwater thus contacted of the components occurs resulting in corrosion of the container and then dissolution of the vitrified matrix. These processes lead to the release of radionuclides into the buffer zone. Since the advection in the zone may be negligible small, the transport in the low permeable zone is mainly controlled by the diffusion mechanism. The subsequent transport in the geosphere is mediated by groundwater through fractures and porosity. The control processes of the transport are the advection, the dispersion including molecular diffusion and mechanical dispersion, the retention with mineral components of a rock, and the radioactive decay. Radionuclides entered into adjacent aquifers are diluted with a large volume of groundwater and further by surface water bodies.

1.2 Basic descriptions of modeling

The safety assessment methodology involves models to predict a long-term behavior of the disposal system and to evaluate radiological consequences associated with the disposal. A schematic flow of a generic modeling procedure is shown in Fig. 3. The first step in the modelling is to understand physicochemically the features, events and processes which will be potentially involved in the disposal system considered. The second step is to construct a conceptual model based on the identification of significant mechanisms and their relationships, which are required for the description of the disposal system abstractly, among a variety of them to be potentially involved in the system. The third step is to convert the conceptual model to a mathematical model by formulating the mechanisms and the relationships quantitatively. During this procedure, simplifications and approximations are introduced to keep the practicality in implementations of model applications. Ideally, however, the mechanisms and relationships are described in forms testable in a model validation process. The mathematical model is then converted to a computer code by using an analytical or numerical solutions of the mathematical formulations used. Final step is to verify and validate the model in the form of computer code, to ensure that it pertinently predicts the behavior of radionuclides in each sub-system. Verification of the code intends to assure that it executes the calculation exactly as intended in the mathematical model. This is achieved through the implementation of a set of test problems designed to compare results calculated by the code in question with known, analytic solutions if the code employs numerical solutions, and with results calculated by similar codes. Validation of the model aims at the confirmation that the model represents the system pertinently for which it is in-

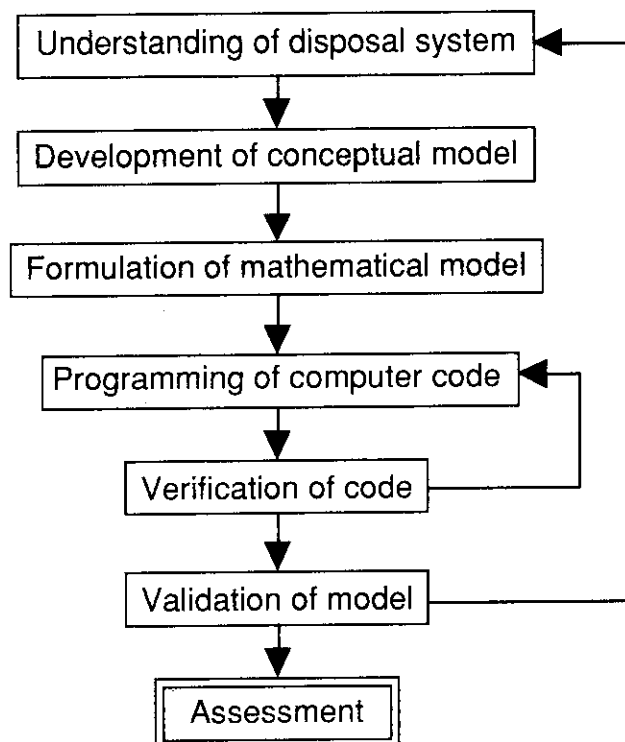


Fig. 3 Modeling procedure

tended. This is usually carried out by comparing results calculated by the code with experimental observations. The GSRW code was applied to the test case 1 (Earth Trench Case) proposed by the IAEA Co-operative Research Programme on the Safety Assessment of Near-Surface Radioactive Waste Disposal Facilities (NSARS). It was found that the geosphere model involved in the GSRW code analyzed the transport of radionuclides adequately¹⁾.

A basic consideration adopted in the development of the GSRW code was to provide a flexible and practically used analytical tool for the assessment of long-term radiological consequences from repositories. The code has been designed, therefore, to incorporate as many as the major mechanisms which may significantly affect the consequences, among all of the potential mechanisms that will take place in a disposal system. The mechanisms which are identified to be important from safety assessment point of view are modeled to the extent possible, at a level of detail appropriate to the accuracy with which it is considered to describe them, taking into account the current availability of data required to execute the code. This approach will provide the code which will give analytical results being as accurate as is possible without unnecessary impracticality and complexity. In addition, the GSRW code has been constructed in a modular form. It is therefore possible to develop alternative versions of individual modules, corresponding to the increase and enhancement in scientific knowledge required for understanding of a disposal system, and then substitute them for

the version incorporated in the code system.

The assessment models incorporated into the GSRW code are as shown in Fig. 1;

- a source term model for the repository
- a geosphere model, and
- a biosphere model.

Brief descriptions of each model are given the bellow.

1.2.1 Source term models

The source term model analyses the physical and chemical containment of radionuclides and defines the flux of the radionuclides released from the repository into the surrounding rock formation. The repository (engineered barrier) may involve such components as the vitrified product encapsulated in the metallic container, and a buffer material (e.g., bentonite.). The source term model, therefore, includes the following processes:

- the corrosion of the metallic container to determine the pint of time when the dissolution of the matrix initiates,
- the flux of a specific radionuclide at the interface between the vitrified waste and the buffer material is determined by the dissolution of the vitrified matrix controlled by a diffusion in an infinite medium and a specific solubility of silicate component, or the leaching of the radionuclide controlled by a diffusion through the buffer material and a specific solubility of the radionuclide,
- the diffusion-controlled transport of radionuclides through the buffer material, taking into account retardation processes, to determine the source term to the geosphere.

The repository after the closure will be gradually refilled with water and reached an equilibrium hydraulic pressure, during this course a water flow at a very slow rate goes toward into the repository and no radioactivity can be diffused out of the repository until the equilibrium pressure has been realized. The estimation of the time needed for this process requires a complex transient water-flow analysis, and the result should depend on a repository design and geohydraulic conditions specific to a site. The methodology developed here does not involve this transient analysis, taking into account that it intends to perform a generic safety assessment of repositories.

No radioactivity can be leached out of the waste form which is encapsulated in a container until the container has failed and the form has begun to contact with water. The time required for this process, the container failure time, depends on the degradation rate specific to electrochemical environment to which the container is exposed. In this model, the container is taken as a factor determining an delay time to onset of radionuclide leaching from the waste form. A user of the code may input this delay time which can be estimated from the corrosion rate of a specific metal used as a container

material.

It is assumed that, upon container failure, the waste form comes into contact with water and radionuclides would be leached out of the form depending either on the dissolution rate of the waste form which is modeled here as a sphere or a prolate spheroid (Model-1) or on their solubility limits (Model-2). In the first model, radionuclides are assumed to dissolve congruently with the waste form (SiO_2) in which they are homogeneously distributed on a macroscopic scale. The release of SiO_2 is modeled by a diffusion mechanism in an infinite medium. The second model does not involve the dissolution process of the waste form, but assumes that the concentration of a specific radionuclide in water at the boundary between the waste form and the buffer material is controlled by its solubility limit. The choice of model is entrusted to a user's physico-chemical understanding of the system to be solved.

The subsequent transport of radionuclides through the buffer zone is modeled by an one-dimensional diffusion through a finite medium in the Cartesian coordinates (Model-1), or it is solved including the leaching behavior of radionuclide in the spherical coordinates (Model-2). In the both models, the concentration of a specific radionuclide is governed by its sorption equilibrium between water and the buffer material.

1.2.2 Geosphere model

Geologic media assumed here are homogeneous porous media connected with several dominant fractures which further connect directly with groundwater in a sedimentary soil layer or with ocean. The groundwater-mediated migration of radionuclides in the homogeneous porous media surrounding the repository is simulated by an analytical solution of a mass transport equation involving one-dimensional advection, three-dimensional dispersion, retention and decay chains. The transport of radionuclides through the fractures modeled as a pipe is analyzed by the analytical solution of the mass transport equation containing one-dimensional advection, one-dimensional dispersion, retention and decay chains. Although the retention involves a number of physico-chemical mechanisms such as reversible and irreversible chemical adsorption, physical adsorption, molecular diffusion into immobile water, filtration, precipitation, aggregation and so on, the identification of all of the mechanisms that take place, however, is so far still worked out. Even if each potential mechanism is successfully identified and modeled precisely, the computation with such the model requires much greater variety of database than that currently available (e.g., radiochemical speciation data, kinetic parameters corresponding to each interaction mechanism, geochemical equilibrium data, a complete mineralogical composition of the geologic media, and also the local variation of these data). Therefore, the basic retention mechanisms were not specifically distinguished in the model used here, but their total effects that retard the migration of radionuclides were assumed to be empirically repre-

sented by a distribution coefficient, K_d , defined as the ratio of the amount of radionuclide retained on the media to the amount in the solution. The use of K_d in the model is based on the following assumptions that K_d is independent of the concentration of the radionuclide, that each radionuclide migrates independently of the others, and that each retention occurs instantaneously and reversibly.

Although the geosphere model used in the safety assessment methodology is rather simple, the following models have been developed to support the analysis with the simplified model⁽²⁻⁶⁾:

- two-dimensional water flow model in the porous media (2DSEEP, SPMIX),
- three-dimensional water flow model in the porous media (3DSEEP),
- two-dimensional solute transport model in the porous media (MIG2DF), - two-dimensional solute transport model in the fractured media (DBP), and
- three-dimensional solute transport model (MIG3D).

1.2.3 Biosphere model

Finally, once radionuclides emerge from the geosphere, they enter into the environment and cause radiological consequences to man through a variety of exposure pathways. The long-term safety assessment for the future generation may require consideration of the alteration of environmental conditions associated with the cycling of ice age. Due to the vast uncertainty about future environmental conditions, the basis of model structures for times far into the future should not depend on detailed environmental features reflecting from a specific site, taking into account that a candidate site for HLW disposal is not decided yet in Japan. The basic philosophy adopted in the development of the GSRW code is to evaluate the consequences due to radionuclide release under environmental conditions not too far differed from those currently and commonly experienced in Japan.

The biosphere model combined with a dosimetry submodel, which is based on a time-dependent compartment model, simulates the transport of radionuclides through the environment. The model evaluates the internal doses in a term of the committed effective dose equivalent resulting from both inhalation of contaminated suspended materials and ingestion of contaminated food and drinking water, and the external doses in a term of the effective dose equivalent due to the immersion in gamma radiation fields. As shown in Fig. 4, the exposure pathways assumed here include:

- internal exposure from inhalation of suspended materials,
- internal exposure from ingestion of food (farm products, aquatic products) and drinking water, and
- external exposure from radionuclides deposited on the surface.

A dosimetry submodel evaluates the committed effective dose equivalent (internal exposures) and the effective dose equivalent (external exposures) for an individual. In addition, the sub-

model calculate "postulated" population doses (the committed effective dose equivalent for a population) assuming that the annually accumulated radioactivity passing through a vertical section at a certain distance from the repository is all ingested by a local population. This index would be useful particularly for a case where a large number of sensitivity analyses are performed to extract the important pathways and parameters and to identify the relative importance of various barriers involved in a disposal system.

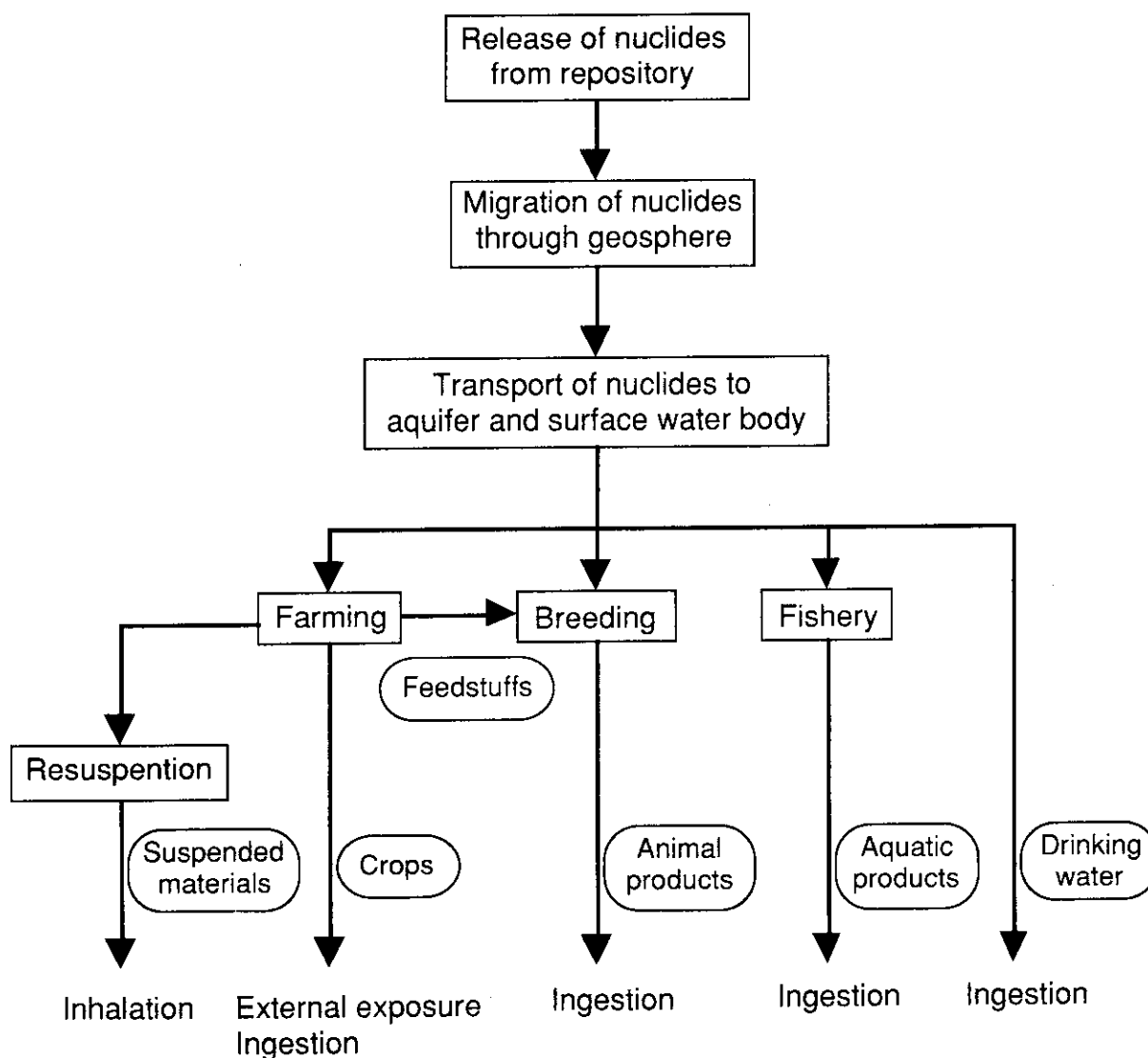


Fig. 4 Transport and exposure pathways involved in the groundwater scenario

2. SOURCE TERM MODEL

The source-term in the GSRW code is defined as the time-dependent rate of radionuclide release from the boundary of disposal units (buffer - rock interface). The disposal unit is assumed to be composed of vitrified waste, container and buffer material in this model (see Fig. 5).

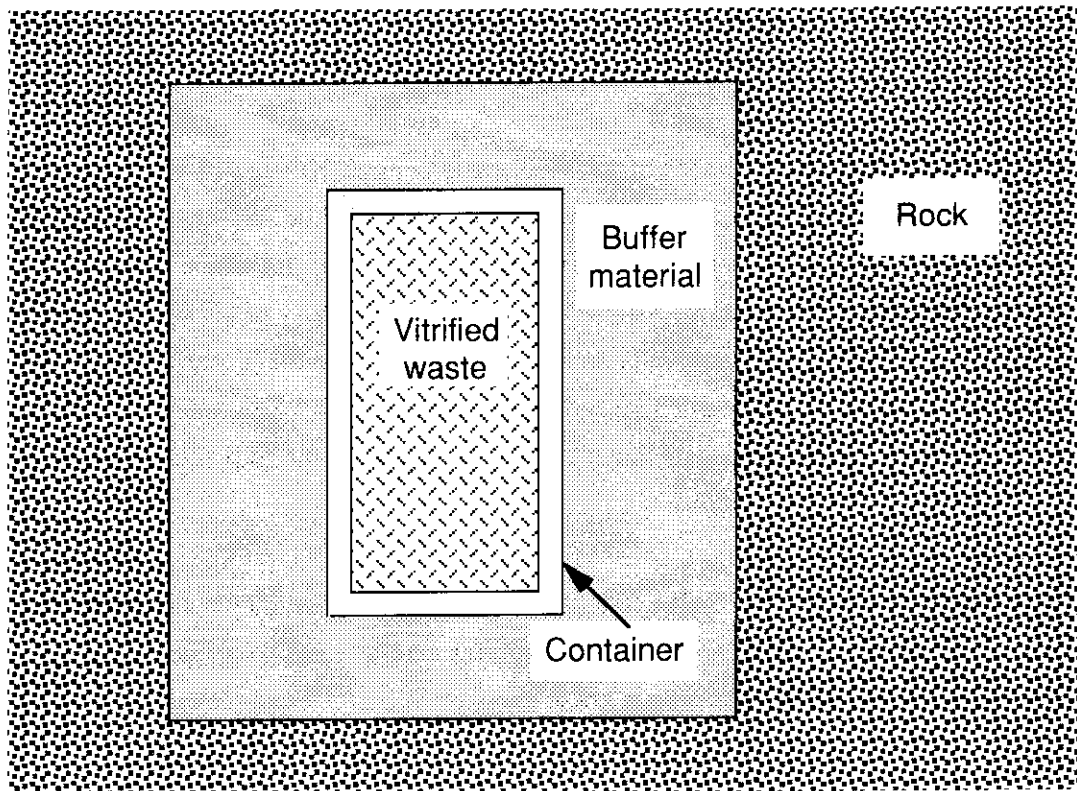


Fig. 5 Conceptual model of the disposal unit in this methodology

Releases of radionuclides from the vitrified wastes will be initiated by failures of the containers. The degradations of the containers are mainly induced by corrosion of a metal which contacts with groundwater. In this model, the following simplified approach is adopted : the effect of container-degradation is taken into account as the container failure time which is equal to an delay time to the onset of radionuclide releases. Because a great uncertainty is involved in predicting corrosion phenomena from incompletely understood geochemical data. This simple modeling approach is not predictive about the failure time of the containers : the failure time should be subjected to sensitivity analysis, taking into account the distribution of relevant corrosion data currently available. The containers are assumed to fail completely, and provide no inhibition to radionuclide releases after the failure time.

The vitrified waste comes into contact with groundwater after the failure of container, and the radionuclides will be released from the waste glass. The releases of radionuclides from the vitrified wastes are simulated by the following two different models : 1) the radionuclides in the vitrified wastes are assumed to be released in proportion to the leaching rate of SiO_2 which is a main component of waste glass (model-1), 2) the concentration of the radionuclides is assumed to be solubility-limit of its chemical form at the boundary of waste glass and buffer material, and the release rate of the radionuclides depends on a diffusive flux through the buffer material (model-2).

2.1 Model-1

In this model, the finite cylinder of vitrified waste is approximated by a sphere or a prolate spheroid in order to obtain compact analytical solutions. Radionuclide migration through the buffer material is modeled as a one-dimensional diffusive transport, and the shape of waste form only influences the leaching rate of SiO_2 from the waste glass. The boundary of the waste form and buffer material is restricted by the prescribed nuclide flux which is equal to the product of the leaching rate of SiO_2 and the existing ratio of the nuclide, and the concentration of the nuclide at another boundary is assumed to be zero because the advection should be dominant in the rock region^{7), 8)}.

2.1.1 Sphere

The leach time T is defined as the time interval between the beginning of dissolution and the completion of dissolution of the waste form. Assuming here a waste form consisting of SiO_2 , the time-dependent waste form volume $V(t)$ is given by

$$\frac{d}{dt} \rho V(t) = -m(t) \quad (1)$$

where ρ : waste form density (g/m^3),

$V(t)$: waste form volume at time t (m^3), and

$m(t)$: mass-loss rate at time t (g/sec).

We assume that the concentration of SiO_2 in the groundwater is set at the surface of the waste glass at the solubility limit and is zero on an infinite spherical surface enclosing the waste glass, and that at any time t the dissolution rate can be approximated by the steady-state solutions of the surface mass flux. Then the steady-state concentration of SiO_2 $N_s(R)$ is given as follows

$$N_s(R) = \frac{r}{R} N_s^{\text{sat}} \quad (R \geq r) \quad (2)$$

where r : sphere radius of waste glass (m),

R : radial distance (m),

N_s^{sat} : solubility limit in groundwater (g/m^3),

and time-dependence of the sphere radius r is neglected in eq. (2). Then the mass-loss rate $m(t)$ is given by

$$\begin{aligned} m(t) &= 4\pi r^2 \left[-D_e \frac{\partial}{\partial R} \left(\frac{r}{R} N_s^{\text{sat}} \right) \right]_{R=r} \\ &= 4\pi r D_e N_s^{\text{sat}} \end{aligned} \quad (3)$$

where D_e : effective diffusivity of SiO_2 (m^2/sec).

Substituting eq. (3) into eq. (1) yields

$$\rho \frac{d}{dt} \left[\frac{4\pi}{3} r(t)^3 \right] = -4\pi r D_e N_s^{\text{sat}} \quad (4)$$

$$\text{with the initial condition } r(0) = r_0. \quad (5)$$

We have the following solution about $r(t)$

$$r(t) = \sqrt{r_0^2 - \frac{2D_e N_s^{\text{sat}}}{\rho} t}. \quad (6)$$

From definition of the leach time T we have that

$$T \equiv \frac{\rho r_0^2}{2D_e N_s^{\text{sat}}}, \quad (7)$$

and the mass-loss rate is

$$m(t) = m(0) \sqrt{1 - t/T}, \quad (8)$$

$$\text{where } m(0) \equiv 4\pi r_0 D_e N_s^{\text{sat}}. \quad (9)$$

2.1.2 Prolate spheroid

In deriving the leach time and mass-loss rate of the prolate spheroid it is assumed that the ratio of the minor axis to the major axis is constant during the leaching process. The volume of a prolate

spheroid is given as follows

$$V = \frac{4\pi}{3}ab^2 \quad (a > b) \quad (7)$$

$$a = f \cosh \alpha \quad (8)$$

$$b = f \sinh \alpha \quad (9)$$

where a : semi-major axis of the prolate spheroid,
 b : semi-minor axis of the prolate spheroid,
 f : focal distance of the prolate spheroid, and
 α : geometric factor of the prolate spheroid.

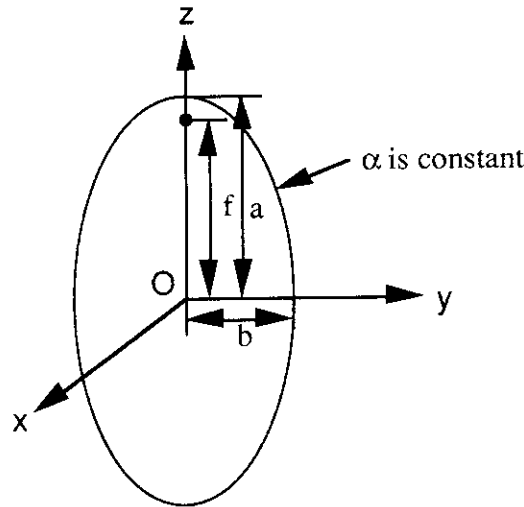


Fig. 6 Prolate spheroidal waste form

At steady state the mass transfer rate per unit area (surface mass flux) is nonuniform for the prolate spheroid and depends on the position on the surface. The mass flux has a maximum at the poles and a minimum at the equatorial plane (see Fig. 6). The total rate of dissolution $m(t)$ of SiO_2 of the effective surface concentration N_s^{sat} is obtained by integrating the surface mass flux over the surface area of the prolate spheroid, and is given by

$$m(t) = \frac{4\pi D_c N_s^{\text{sat}} f}{\ln(\coth \frac{\alpha}{2})} \quad (10)$$

We assume that the shape of the prolate spheroid is unchanged during the leaching process. Then the focal distance f is only a time-dependent parameter. Substituting eq. (7) and (10) into eq. (1) yields

$$\frac{4\pi}{3}\rho \frac{d}{dt}[f(t)^3 \sinh^2 \alpha \cdot \cosh \alpha] = -\frac{4\pi D_e N_s^{\text{sat}} f}{\ln(\coth \frac{\alpha}{2})}. \quad (11)$$

We have the following solutions about $f(t)$ and $m(t)$

$$f(t) = \sqrt{f(0)^2 - \frac{2D_e N_s^{\text{sat}}}{\rho \sinh^2 \alpha \cdot \cosh \alpha \cdot \ln(\coth \frac{\alpha}{2})} t}, \quad (12)$$

$$m(t) = m(0) \sqrt{1 - t/T}, \quad (13)$$

where $m(0) \equiv \frac{4\pi D_e N_s^{\text{sat}} f(0)}{\ln(\coth \frac{\alpha}{2})}, \quad (14)$

$$T \equiv \frac{f(0)^2 \rho \sinh^2 \alpha \cdot \cosh \alpha \cdot \ln(\coth \frac{\alpha}{2})}{2D_e N_s^{\text{sat}}}. \quad (15)$$

We also assume that the prolate spheroid has the same volume and surface area as the cylindrical waste form. Thus, equating their volumes,

$$\frac{4\pi}{3}ab^2 = \pi r^2 H \equiv V \quad (16)$$

and equating their surface areas

$$2\pi b \left\{ b + \frac{a^2}{\sqrt{a^2 - b^2}} \sin^{-1} \frac{\sqrt{a^2 - b^2}}{a} \right\} = 2\pi r(r + H) \equiv S. \quad (17)$$

Solution of eq. (16) and (17) for a and b defines the desired prolate spheroid. As is seen from the above equations, a closed-form mathematical solution for a and b cannot be obtained, so a numerical analysis is required.

2.1.3 Radionuclide transport through the buffer material

The leaching rate of each radionuclide from the waste glass $S_i(t)$ is given as the product of the mass-loss rate of SiO_2 and the existing ratio of the radionuclide $R_i(t)$.

$$S_i(t) = R_i(t)m(t) \quad (18)$$

The exiting ratio of radionuclide i is given by the Bateman's equation.

$$\frac{dR_i}{dt} = -\lambda_i R_i + \lambda_{i-1} R_{i-1} \quad (19)$$

where λ_i is the decay constant (1/yr) of radionuclide i .

The leaching rate $S_i(t)$ is used as a prescribed nuclide flux at the boundary of the waste form and buffer material. The transport equation considering diffusion and a linear sorption in the buffer material is

$$\frac{\partial N_i}{\partial t} = D_i \frac{\partial^2 N_i}{\partial x^2} - \lambda_i N_i + \frac{\lambda_{i-1} K_{i-1}}{K_i} N_{i-1} \quad (20)$$

$$D_i \equiv \frac{D_{f,i}}{K_i} \quad (21)$$

where N_i : the concentration of radionuclide i in the groundwater (g/m^3),

K_i : the retardation factor of radionuclide i (-), and

$D_{f,i}$: the diffusion coefficient in the groundwater (m^2/yr).

The boundary conditions are respectively

$$-\epsilon D_{f,i} \left. \frac{\partial N_i}{\partial x} \right|_{x=0} = S_i(t)/S \quad (22)$$

on the boundary of the waste form and buffer material, ϵ is the porosity of the buffer material and

$$N_i(L, t) = 0 \quad (23)$$

on the boundary of the buffer material and rock. Prior to the time $t = 0$ the diffusing nuclide has zero concentration in the buffer material. The analytical solutions of eq. (20) are given as follows

$$N_i(x, t) = \int_0^t \frac{S_i(t-\tau)}{\epsilon D_{f,i}} e^{-\lambda_i \tau} v_i(x, \tau) d\tau \quad \text{for 1-st nuclide} \quad (24)$$

$$\begin{aligned}
N_2(x, t) = & \int_0^t \frac{S_2(t-\tau)}{\epsilon D_{f,2}} e^{-\lambda_2 \tau} v_2(x, \tau) d\tau && \text{for 2-nd nuclide} \\
& + \frac{\lambda_1 D_1}{D_2 - D_1} \frac{K_1}{K_2} \int_0^t \frac{S_1(t-\tau)}{\epsilon D_{f,1}} \phi_{2,1}(x, \tau) d\tau
\end{aligned} \quad (25)$$

$$\begin{aligned}
N_3(x, t) = & \int_0^t \frac{S_3(t-\tau)}{\epsilon D_{f,3}} e^{-\lambda_3 \tau} v_3(x, \tau) d\tau && \text{for 3-rd nuclide} \\
& + \frac{\lambda_2 D_2}{D_3 - D_2} \frac{K_2}{K_3} \int_0^t \frac{S_2(t-\tau)}{\epsilon D_{f,2}} \phi_{3,2}(x, \tau) d\tau \\
& + \frac{\lambda_1 \lambda_2}{D_2 D_3 \omega} \frac{K_1}{K_3} \int_0^t \frac{S_1(t-\tau)}{\epsilon D_{f,1}} \{\phi_{3,1}(x, \tau) - \phi_{3,2}(x, \tau) - \phi_{2,1}(x, \tau)\} d\tau
\end{aligned} \quad (26)$$

where

$$e^{-\lambda_i t} v_i(x, t) \equiv \frac{2D_i}{L} \sum_{n=0}^{\infty} (-1)^n e^{-(D_i p_n^2 + \lambda_i)t} \cdot \sin p_n(L-x) \quad (27)$$

$$\phi_{i,j}(x, t) \equiv \phi_{i,j,i}(x, t) - \phi_{i,j,j}(x, t) \quad (28)$$

$$\phi_{i,j,k}(x, t) \equiv \frac{2D_k}{L} \sum_{n=0}^{\infty} (-1)^n \sin p_n(L-x) \cdot \left\{ \frac{e^{-(\lambda_k + D_k p_n^2)t} - e^{-\alpha_{i,j} t}}{\alpha_{i,j} - \lambda_k - D_k p_n^2} \right\} \quad (29)$$

$$p_n \equiv \frac{(2n+1)\pi}{2L} \quad (30)$$

$$\alpha_{i,j} \equiv \frac{D_i \lambda_j - D_j \lambda_i}{D_i - D_j} \quad (31)$$

$$\omega \equiv \frac{(D_2 - D_3)\lambda_1 + (D_3 - D_1)\lambda_2 + (D_1 - D_2)\lambda_3}{D_1 D_2 D_3} \quad (32)$$

From these equations, the nuclide fluxes on the boundary of the buffer material and rock ($x = L$) are given as follows

$$-\epsilon D_{f,1} \frac{\partial N_1}{\partial x} \Big|_{x=L} = -\int_0^t S_1(t-\tau) e^{-\lambda_1 \tau} v'_1(L, \tau) d\tau \quad (33)$$

$$\begin{aligned} -\epsilon D_{f,2} \frac{\partial N_2}{\partial x} \Big|_{x=L} &= -\int_0^t S_2(t-\tau) e^{-\lambda_2 \tau} v'_2(L, \tau) d\tau \\ &\quad - \frac{\lambda_1 D_2}{D_2 - D_1} \int_0^t S_1(t-\tau) \phi'_{2,1}(L, \tau) d\tau \end{aligned} \quad (34)$$

$$\begin{aligned} -\epsilon D_{f,3} \frac{\partial N_3}{\partial x} \Big|_{x=L} &= -\int_0^t S_3(t-\tau) e^{-\lambda_3 \tau} v'_3(L, \tau) d\tau \\ &\quad - \frac{\lambda_2 D_3}{D_3 - D_2} \int_0^t S_2(t-\tau) \phi'_{3,2}(L, \tau) d\tau \\ &\quad - \frac{\lambda_1 \lambda_2}{D_1 D_2 \omega} \int_0^t S_1(t-\tau) \{ \phi'_{3,1}(L, \tau) - \phi'_{3,2}(L, \tau) - \phi'_{2,1}(L, \tau) \} d\tau \end{aligned} \quad (35)$$

where
$$e^{-\lambda_i t} v'_i(L, t) \equiv -\frac{2D_i}{L} \sum_{n=0}^{\infty} (-1)^n p_n e^{-(D_i p_n^2 + \lambda_i)t} \quad (36)$$

$$\phi'_{i,j}(L, t) \equiv \frac{2(D_i - D_j)}{L} \sum_{n=0}^{\infty} (-1)^n p_n \frac{e^{-(D_i p_n^2 + \lambda_i)t} - e^{-(D_j p_n^2 + \lambda_j)t}}{\lambda_i - \lambda_j + (D_i - D_j) p_n^2} \quad (37)$$

The integrals in the eqs. (32), (33) and (34) are expressed as series of the error functions, if the solutions of eq. (18) are substituted into the integrals.

2.2 Model-2

A finite cylinder of the vitrified waste is approximated by a sphere in this model to obtain analytical solutions of a decay chain transport in the buffer material. Radionuclide migration through the buffer material is modeled as a one-dimensional diffusive transport in the spherical coordinates. The concentration of the radionuclide is assumed to be the solubility-limit of its specific chemical form on the surface of the waste form, and to be zero at another boundary because the advection is dominant in the rock region. The release rate of the radionuclide from the buffer material depends on the diffusive flux through the buffer material.

The diffusive transport equation in the buffer material is given as follows

$$\frac{\partial N_i}{\partial t} = D_i \frac{1}{r} \frac{\partial^2}{\partial r^2} (r N_i) - \lambda_i N_i + \frac{\lambda_{i-1} K_{i-1}}{K_i} N_{i-1}. \quad (38)$$

The boundary conditions are respectively

$$N_i(R_0, t) = N_{s,i}(t) \quad (39)$$

on the surface of the spherical waste form ($r = R_0$), $N_{s,i}(t)$ is the solubility-limit of radionuclide i and

$$N_i(R_1, t) = 0 \quad (40)$$

at the boundary of the buffer material and rock ($r = R_1$). The diffusing nuclide has zero initial concentration in the buffer material. The analytical solutions of eq. (37) are given as follows

$$N_1(r, t) = \frac{R_0}{r} \int_0^t N_{s,1}(t - \tau) e^{-\lambda_1 \tau} u_1(r, \tau) d\tau \quad \text{for 1-st nuclide} \quad (41)$$

$$N_2(r, t) = \frac{R_0}{r} \left[\int_0^t N_{s,2}(t - \tau) e^{-\lambda_2 \tau} u_2(r, \tau) d\tau \right. \\ \left. + \frac{\lambda_1 D_2}{D_2 - D_1} \int_0^t N_{s,1}(t - \tau) \Psi_{2,1}(r, \tau) d\tau \right] \quad \text{for 2-nd nuclide} \quad (42)$$

$$\begin{aligned}
N_3(r, t) = & \frac{R_0}{r} \left[\int_0^t N_{s,3}(t-\tau) e^{-\lambda_3 \tau} u_3(r, \tau) d\tau \right. & \text{for 3-rd nuclide} \\
& + \frac{\lambda_2 D_3}{D_3 - D_2} \int_0^t N_{s,2}(t-\tau) \Psi_{3,2}(r, \tau) d\tau \\
& \left. + \frac{\lambda_1 \lambda_2}{D_1 D_2 \omega} \int_0^t N_{s,1}(t-\tau) \{ \Psi_{3,1}(r, \tau) - \Psi_{3,2}(r, \tau) - \Psi_{2,1}(r, \tau) \} d\tau \right] \quad (43)
\end{aligned}$$

where

$$e^{-\lambda_i t} u_i(r, t) \equiv \frac{D_i}{iL} \sum_{n=-\infty}^{\infty} k_n e^{i k_n (r - R_0) - (D_i k_n + \lambda_i) t} \quad (44)$$

$$\begin{aligned}
\Psi_{i,j}(r, t) & \equiv \Psi_{i,j,i}(r, t) - \Psi_{i,j,j}(r, t) \\
& = \frac{D_i - D_j}{L} \sum_{n=-\infty}^{\infty} (-1)^n \cdot \frac{k_n^2 \sin k_n (R_1 - r)}{\lambda_i - \lambda_j + (D_i - D_j) k_n^2} \cdot \\
& \quad \{ \exp[-(\lambda_i + D_i k_n^2) t] - \exp[-(\lambda_j + D_j k_n^2) t] \} \quad (45)
\end{aligned}$$

$$\begin{aligned}
\Psi_{i,j,k}(r, t) & \equiv \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin k_n (R_1 - r) \cdot \\
& \quad \left\{ \frac{D_k k_n^2 \exp[-(\lambda_k + D_k k_n^2) t] + (\lambda_k - \alpha_{i,j}) \exp(-\alpha_{i,j} t)}{\lambda_k - \alpha_{i,j} + D_k k_n^2} \right\} \quad (46)
\end{aligned}$$

$$k_n \equiv \frac{n\pi}{L}, \quad L \equiv R_1 - R_0. \quad (47)$$

From these equations, the nuclide fluxes at the boundary of the buffer material and rock ($r = R_1$) are given as follows

$$4\pi R_1^2 (-\epsilon D_{f,1} \frac{\partial N_1}{\partial r}) \Big|_{r=R_1} = -4\pi R_0 R_1 \epsilon D_{f,1} \int_0^t N_{s,1}(t-\tau) e^{-\lambda_1 \tau} u'_1(R_1, \tau) d\tau \quad (48)$$

$$\begin{aligned}
4\pi R_1^2 \left(-\varepsilon D_{f,2} \frac{\partial N_2}{\partial r} \right) \Big|_{r=R_1} &= -4\pi R_0 R_1 \varepsilon D_{f,2} \left[\int_0^t N_{s,2}(t-\tau) e^{-\lambda_2 \tau} u'_2(R_1, \tau) d\tau \right. \\
&\quad \left. + \frac{\lambda_1 D_2}{D_2 - D_1} \int_0^t N_{s,1}(t-\tau) \Psi'_{2,1}(R_1, \tau) d\tau \right]
\end{aligned} \quad (49)$$

$$\begin{aligned}
4\pi R_1^2 \left(-\varepsilon D_{f,3} \frac{\partial N_3}{\partial r} \right) \Big|_{r=R_1} &= -4\pi R_0 R_1 \varepsilon D_{f,3} \left[\int_0^t N_{s,3}(t-\tau) e^{-\lambda_3 \tau} u'_3(R_1, \tau) d\tau \right. \\
&\quad + \frac{\lambda_2 D_3}{D_3 - D_2} \int_0^t N_{s,2}(t-\tau) \Psi'_{3,2}(R_1, \tau) d\tau \\
&\quad \left. + \frac{\lambda_1 \lambda_2}{D_1 D_2 \omega} \int_0^t N_{s,1}(t-\tau) \{ \Psi'_{3,1}(R_1, \tau) - \Psi'_{3,2}(R_1, \tau) - \Psi'_{2,1}(R_1, \tau) \} d\tau \right]
\end{aligned} \quad (50)$$

where

$$e^{-\lambda_i t} u'_i(r, t) \equiv -\frac{D_i}{L} \sum_{n=-\infty}^{\infty} k_n^2 e^{ik_n(r-R_0) - (D_i k_n + \lambda_i)t} \quad (51)$$

$$\begin{aligned}
\Psi'_{i,j}(r, t) \equiv & -\frac{D_i - D_j}{L} \sum_{n=-\infty}^{\infty} (-1)^n \cdot \frac{k_n^2 \cos k_n(R_1 - r)}{\lambda_i - \lambda_j + (D_i - D_j)k_n^2} \\
& \{ \exp[-(\lambda_i + D_i k_n^2)t] - \exp[-(\lambda_j + D_j k_n^2)t] \}
\end{aligned} \quad (52)$$

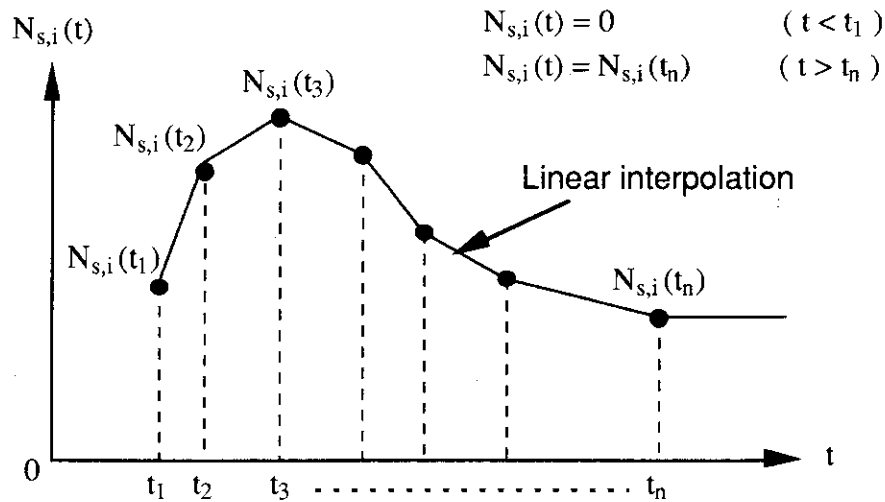


Fig. 7 Treatment of solubility-limit of radionuclide i on the surface of the spherical waste form

In this model, the solubility-limit of radionuclide i $N_{s,i}(t)$ is given as a time-dependent variable shown as Fig. 7. The curve consists of several data points, and intermediate values among two points are obtained by a linear interpolation. The leaching time of this model T is determined by assuming that the integral of the nuclide flux from zero to T with respect to time at the boundary of the buffer material and rock is equal to the total inventory of the nuclide in the waste form as shown in Fig. 8. As the nuclide flux on the surface of the waste form tends to infinity when the leaching of the nuclide begins, the nuclide flux at the buffer-rock interface was chosen for estimating the leaching time. The leaching time is little bit overestimated because it includes the travel time through the buffer material, and this estimate is a conservative one.

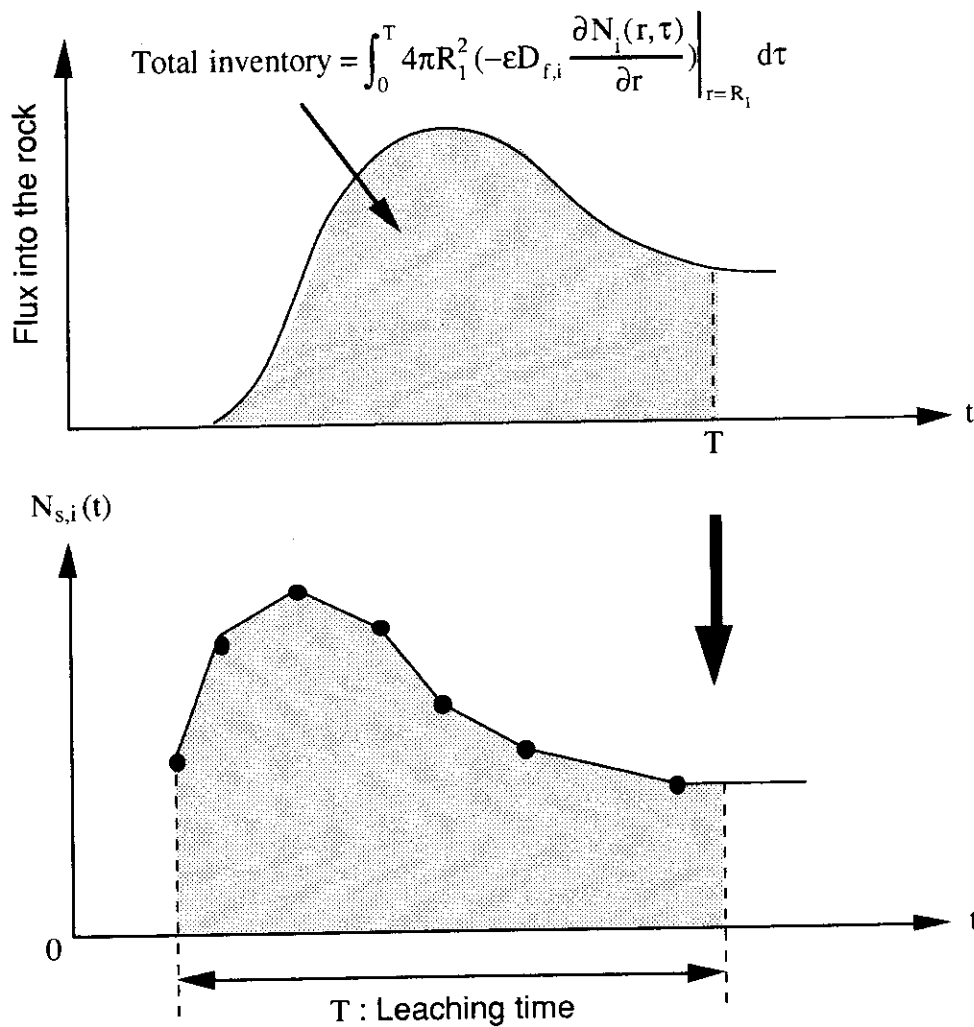


Fig. 8 Estimation of the leaching time in the model-2 simulation

3. GEOSPHERE MODEL

The radioactive wastes will be disposed of into a deep stable rock mass which has few fractured zone as shown in Fig. 9. Accordingly we can assume that the rock mass is homogeneous, and radionuclide transport in the rock mass is simulated by a one-dimensional advection and three-dimensional dispersion model. Effect of the transverse dispersion is important for a radionuclide source of finite extent. Waste packages will be emplaced in the waste repository leaving appropriate spaces between the waste packages. The waste packages in the repository can be treated as an array of point sources because the size of the waste package is sufficiently small as compared with the size of the rock mass. The strength of the point source is given by the source term model.

There are several pathways in which radionuclides migrate through the rock mass and transport to the biosphere. Each pathway is probably composed of several fractured zones, and radionuclide transport in it can be simulated by the one-dimensional advection and dispersion model.

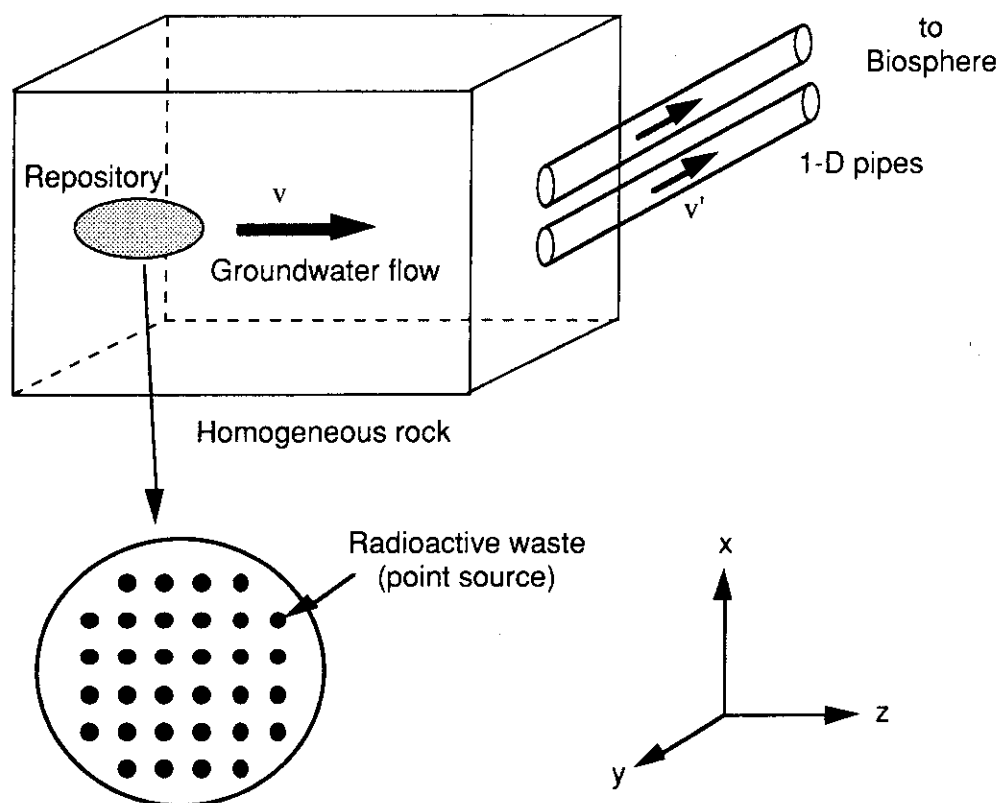


Fig. 9 Conceptual model of the geosphere

In this methodology, several pathways to the biosphere can be taken into account for a simulation of radionuclide transport.

In this way, the geosphere model in the GSRW code is divided into two parts: 1) one-dimensional advection and three-dimensional dispersion model which describes radionuclide transport around the repository (homogeneous rock mass), 2) one-dimensional advection and dispersion model which describes radionuclide transport in the far field (pathway from the rock mass to the biosphere). Both geosphere models are connected with each other by a concentration or flux boundary condition as specifying by input data.

3.1 One-dimensional advection and three-dimensional dispersion model

A uniform one-dimensional flow field is assumed in this model in order to obtain analytical solutions. We first consider the time-space-dependent concentration of a radionuclide released from a point source in an infinite porous medium, with transverse dispersion. Transport of a chain of decaying solute species is described by the following equation considering equilibrium sorption.

$$K_i \frac{\partial N_i}{\partial t} = D_x \frac{\partial^2 N_i}{\partial x^2} + D_y \frac{\partial^2 N_i}{\partial y^2} + D_z \frac{\partial^2 N_i}{\partial z^2} - v \frac{\partial N_i}{\partial z} - \lambda_i K_i N_i + \lambda_{i-1} K_{i-1} N_{i-1} + S_i \quad (53)$$

where K_i : the retardation factor of radionuclide i (-),

N_i : the concentration of radionuclide i in the groundwater (atom/m³ or Bq/m³),

D_x : the dispersion coefficient along x-direction (m²/yr),

D_y : the dispersion coefficient along y-direction (m²/yr),

D_z : the dispersion coefficient along z-direction (m²/yr),

v : the groundwater velocity (m/yr),

λ_i : the decay constant of radionuclide i (1/yr), and

S_i : the volumetric source term of radionuclide i (atom/m³yr or Bq/m³yr).

If we introduce the following transformation of coordinates

$$\bar{x} = x \sqrt{D_z/D_x} \quad (54)$$

$$\bar{y} = y \sqrt{D_z/D_y} \quad (55)$$

$$\bar{z} = z, \quad (56)$$

then the equation (53) becomes

$$\begin{aligned} K_i \frac{\partial N_i}{\partial t} = D_x \left(\frac{\partial^2 N_i}{\partial x^2} + \frac{\partial^2 N_i}{\partial y^2} + \frac{\partial^2 N_i}{\partial z^2} \right) - v \frac{\partial N_i}{\partial z} - \lambda_i K_i N_i \\ + \lambda_{i-1} K_{i-1} N_{i-1} + S_i. \end{aligned} \quad (57)$$

We introduce the following notations

$$l \equiv D_x / v \quad (58)$$

$$v_i \equiv v / K_i \quad (59)$$

where l is a characteristic length of the dispersion process, and represents the ratio of the magnitudes of dispersion and advection. Using eqs. (58) and (59), and dividing by K_i , eq. (57) becomes

$$\begin{aligned} \frac{\partial N_i}{\partial t} = l v_i \left(\frac{\partial^2 N_i}{\partial x^2} + \frac{\partial^2 N_i}{\partial y^2} + \frac{\partial^2 N_i}{\partial z^2} \right) - v_i \frac{\partial N_i}{\partial z} - \lambda_i N_i \\ + \frac{\lambda_{i-1} v_i}{v_{i-1}} N_{i-1} + \frac{S_i}{K_i}. \end{aligned} \quad (60)$$

Considering that both of the last two terms of eq. (60) are sources of the i -th radionuclide, eq. (60) can be written as

$$\frac{\partial N_i}{\partial t} = l v_i \left(\frac{\partial^2 N_i}{\partial x^2} + \frac{\partial^2 N_i}{\partial y^2} + \frac{\partial^2 N_i}{\partial z^2} \right) - v_i \frac{\partial N_i}{\partial z} - \lambda_i N_i + S'_i \quad (61)$$

where

$$S'_i \equiv \frac{\lambda_{i-1} v_i}{v_{i-1}} N_{i-1} + \frac{S_i}{K_i}. \quad (62)$$

For a discrete point source of radionuclide, the volumetric source term at (x_0, y_0, z_0) is

$$S_i = S_i^P(t) \frac{D_z}{\sqrt{D_x D_y}} \delta(\bar{x} - x_0) \delta(\bar{y} - y_0) \delta(\bar{z} - z_0) \quad (63)$$

where $S_i^P(t)$ is the source strength of radionuclide i (atom/yr or Bq/yr).

The initial and boundary conditions to be solved are

$$N_i(\bar{x}, \bar{y}, \bar{z}, 0) = 0 \quad \text{for any } \bar{x}, \bar{y}, \bar{z}, \quad (64)$$

$$N_i(\pm\infty, \bar{y}, \bar{z}, 0) = N_i(\bar{x}, \pm\infty, \bar{z}, 0) = N_i(\bar{x}, \bar{y}, \pm\infty, 0) = 0 \quad (65)$$

for an infinite medium. Then we have the following solution which is given by the sum of solutions for the point source and decaying from the parent nuclide⁹⁾.

$$\begin{aligned} N_i(\bar{x}, \bar{y}, \bar{z}, t) = & \int_0^t \frac{S_i^P(\theta)}{K_i} e^{-\lambda_i(t-\theta)} G[\bar{x} - x_0, lv_i(t-\theta)] \cdot \\ & G[\bar{y} - y_0, lv_i(t-\theta)] G[\bar{z} - z_0 - v_i(t-\theta), lv_i(t-\theta)] d\theta \\ & + \int_0^t d\theta \int \int \int_{-\infty}^{\infty} du dv dw \frac{\lambda_{i-1} v_i}{v_{i-1}} N_{i-1}(u, v, w, \theta) e^{-\lambda_i(t-\theta)} \cdot \\ & G[\bar{x} - x_0 - u, lv_i(t-\theta)] G[\bar{y} - y_0 - v, lv_i(t-\theta)] \cdot \\ & G[\bar{z} - z_0 - w - v_i(t-\theta), lv_i(t-\theta)] \end{aligned} \quad (66)$$

where

$$G[\alpha, \mu] \equiv \frac{1}{4\pi\mu} e^{-\frac{\alpha^2}{4\mu}}. \quad (67)$$

For a step release of radionuclide i , eq. (66) becomes

$$N_i^s = \frac{W_0^1}{v l \Gamma} E(0, 0, 1) \quad \text{for 1-st nuclide} \quad (68)$$

$$\begin{aligned}
N_2^s &= \frac{W_0^2}{v_l T} E(0,0,2) && \text{for 2-nd nuclide} \\
&+ \frac{W_0^1 \lambda_1}{v_l T v_1 \gamma_{001} - \gamma_{002}} \frac{4l}{\gamma_{001} - \gamma_{002}} \{E(0,0,2) - E(0,0,1) + E(1,2,1) - E(1,2,2)\} && (69)
\end{aligned}$$

$$\begin{aligned}
N_3^s &= \frac{W_0^3}{v_l T} E(0,0,3) && \text{for 3-rd nuclide} \\
&+ \frac{W_0^2 \lambda_2}{v_l T v_2 \gamma_{002} - \gamma_{003}} \frac{4l}{\gamma_{002} - \gamma_{003}} \{E(0,0,3) - E(0,0,2) + E(2,3,2) - E(2,3,3)\} \\
&+ \frac{W_0^1 \lambda_1}{v_l T v_1 \gamma_{001} - \gamma_{002}} \frac{4l}{\gamma_{001} - \gamma_{002}} \left[\frac{\lambda_2}{v_2 \gamma_{002} - \gamma_{003}} \frac{4l}{\gamma_{002} - \gamma_{003}} \{E(0,0,3) - E(0,0,2) + E(2,3,2) - E(2,3,3)\} \right. \\
&\quad - \frac{\lambda_2}{v_2 \gamma_{001} - \gamma_{003}} \frac{4l}{\gamma_{001} - \gamma_{003}} \{E(0,0,3) - E(0,0,1) + E(1,3,1) - E(1,3,3)\} \\
&\quad + \frac{\lambda_2}{v_2 \gamma_{121} - \gamma_{123}} \frac{4l}{\gamma_{121} - \gamma_{123}} \{E(1,2,3) - E(1,2,1) + E(1,3,1) - E(1,3,3)\} \\
&\quad \left. - \frac{\lambda_2}{v_2 \gamma_{122} - \gamma_{123}} \frac{4l}{\gamma_{122} - \gamma_{123}} \{E(1,2,3) - E(1,2,2) + E(2,3,2) - E(2,3,3)\} \right] && (70)
\end{aligned}$$

$$\begin{aligned}
N_4^s &= \frac{W_0^4}{v_l T} E(0,0,4) && \text{for 4-th nuclide} \\
&+ \frac{W_0^3 \lambda_3}{v_l T v_3 \gamma_{003} - \gamma_{004}} \frac{4l}{\gamma_{003} - \gamma_{004}} \{E(0,0,4) - E(0,0,3) + E(3,4,3) - E(3,4,4)\} \\
&+ \frac{W_0^2 \lambda_2}{v_l T v_2 \gamma_{002} - \gamma_{003}} \frac{4l}{\gamma_{002} - \gamma_{003}} \left[\frac{\lambda_3}{v_3 \gamma_{003} - \gamma_{004}} \frac{4l}{\gamma_{003} - \gamma_{004}} \{E(0,0,4) - E(0,0,3) + E(3,4,3) - E(3,4,4)\} \right. \\
&\quad - \frac{\lambda_3}{v_3 \gamma_{002} - \gamma_{004}} \frac{4l}{\gamma_{002} - \gamma_{004}} \{E(0,0,4) - E(0,0,2) + E(2,4,2) - E(2,4,4)\} \\
&\quad + \frac{\lambda_3}{v_3 \gamma_{232} - \gamma_{234}} \frac{4l}{\gamma_{232} - \gamma_{234}} \{E(2,3,4) - E(2,3,2) + E(2,4,2) - E(2,4,4)\} \\
&\quad \left. + \frac{\lambda_3}{v_3 \gamma_{232} - \gamma_{234}} \frac{4l}{\gamma_{232} - \gamma_{234}} \{E(2,3,4) - E(2,3,2) + E(2,4,2) - E(2,4,4)\} \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{W_0^1 \lambda_1}{v l T v_1 \gamma_{001} - \gamma_{002}} \left[\right. \\
& \frac{\lambda_2}{v_2 \gamma_{002} - \gamma_{003}} \left\{ \frac{\lambda_3}{v_3 \gamma_{003} - \gamma_{004}} \{E(0,0,4) - E(0,0,3) + E(3,4,3) - E(3,4,4)\} \right. \\
& \quad - \frac{\lambda_3}{v_3 \gamma_{002} - \gamma_{004}} \{E(0,0,4) - E(0,0,2) + E(2,4,2) - E(2,4,4)\} \\
& \quad + \frac{\lambda_3}{v_3 \gamma_{232} - \gamma_{234}} \{E(2,3,4) - E(2,3,2) + E(2,4,2) - E(2,4,4)\} \\
& \quad \left. - \frac{\lambda_3}{v_3 \gamma_{232} - \gamma_{234}} \{E(2,3,4) - E(2,3,2) + E(2,4,2) - E(2,4,4)\} \right\} \\
& - \frac{\lambda_2}{v_2 \gamma_{001} - \gamma_{003}} \left\{ \frac{\lambda_3}{v_3 \gamma_{003} - \gamma_{004}} \{E(0,0,4) - E(0,0,3) + E(3,4,3) - E(3,4,4)\} \right. \\
& \quad - \frac{\lambda_3}{v_3 \gamma_{001} - \gamma_{004}} \{E(0,0,4) - E(0,0,1) + E(1,4,1) - E(1,4,4)\} \\
& \quad + \frac{\lambda_3}{v_3 \gamma_{131} - \gamma_{134}} \{E(1,3,4) - E(1,3,1) + E(1,4,1) - E(1,4,4)\} \\
& \quad \left. - \frac{\lambda_3}{v_3 \gamma_{133} - \gamma_{134}} \{E(1,3,4) - E(1,3,3) + E(3,4,3) - E(3,4,4)\} \right\} \\
& + \frac{\lambda_2}{v_2 \gamma_{121} - \gamma_{123}} \left\{ \frac{\lambda_3}{v_3 \gamma_{123} - \gamma_{124}} \{E(1,2,4) - E(1,2,3) + E(3,4,3) - E(3,4,4)\} \right. \\
& \quad - \frac{\lambda_3}{v_3 \gamma_{121} - \gamma_{124}} \{E(1,2,4) - E(1,2,1) + E(1,4,1) - E(1,4,4)\} \\
& \quad + \frac{\lambda_3}{v_3 \gamma_{131} - \gamma_{134}} \{E(1,3,4) - E(1,3,1) + E(1,4,1) - E(1,4,4)\} \\
& \quad \left. - \frac{\lambda_3}{v_3 \gamma_{133} - \gamma_{134}} \{E(1,3,4) - E(1,3,3) + E(3,4,3) - E(3,4,4)\} \right\}
\end{aligned}$$

$$\begin{aligned}
& -\frac{\lambda_2}{v_2} \frac{4l}{\gamma_{122} - \gamma_{123}} \left\{ \frac{\lambda_3}{v_3} \frac{4l}{\gamma_{123} - \gamma_{124}} \{E(1,2,4) - E(1,2,3) + E(3,4,3) - E(3,4,4)\} \right. \\
& \quad - \frac{\lambda_3}{v_3} \frac{4l}{\gamma_{122} - \gamma_{124}} \{E(1,2,4) - E(1,2,2) + E(2,4,2) - E(2,4,4)\} \\
& \quad + \frac{\lambda_3}{v_3} \frac{4l}{\gamma_{232} - \gamma_{234}} \{E(2,3,4) - E(2,3,2) + E(2,4,2) - E(2,4,4)\} \\
& \quad \left. - \frac{\lambda_3}{v_3} \frac{4l}{\gamma_{233} - \gamma_{234}} \{E(2,3,4) - E(2,3,3) + E(3,4,3) - E(3,4,4)\} \right\} \quad (71)
\end{aligned}$$

where

$$E(i, j, k) \equiv e^{\frac{\bar{z}-z_0}{2l} - \beta_{ij}t} \cdot F(lvt, \frac{\sqrt{\gamma_{ijk}}}{2l}, \frac{\sqrt{(\bar{x}-x_0)^2 + (\bar{y}-y_0)^2 + (\bar{z}-z_0)^2}}{2}) \quad (72)$$

$$\begin{aligned}
F(u, a, b) & \equiv \int_0^u \frac{\exp(-a^2\tau - \frac{b^2}{\tau})}{(4\pi\tau)^{3/2}} d\tau \\
& = \frac{1}{16\pi b} \{e^{2ab} \operatorname{erfc}(a\sqrt{u} + \frac{b}{\sqrt{u}}) + e^{-2ab} \operatorname{erfc}(-a\sqrt{u} + \frac{b}{\sqrt{u}})\} \quad (73)
\end{aligned}$$

$$\beta_{ij} \equiv \begin{cases} \frac{v_i \lambda_j - v_j \lambda_i}{v_i - v_j} & (i, j \neq 0) \\ 0 & (i, j = 0) \end{cases} \quad (74)$$

$$\gamma_{ijk} \equiv 1 + 4l \frac{\lambda_k - \beta_{ij}}{v_k} \quad (75)$$

For a band release, the solution is obtained by

$$N_i^B = N_i^S(t) - N_i^S(t - T) \quad (76)$$

where T is the leaching time.

A generalized release pattern from a point source is obtained by dividing that into a series of band releases with different source strengths (see Fig. 10).

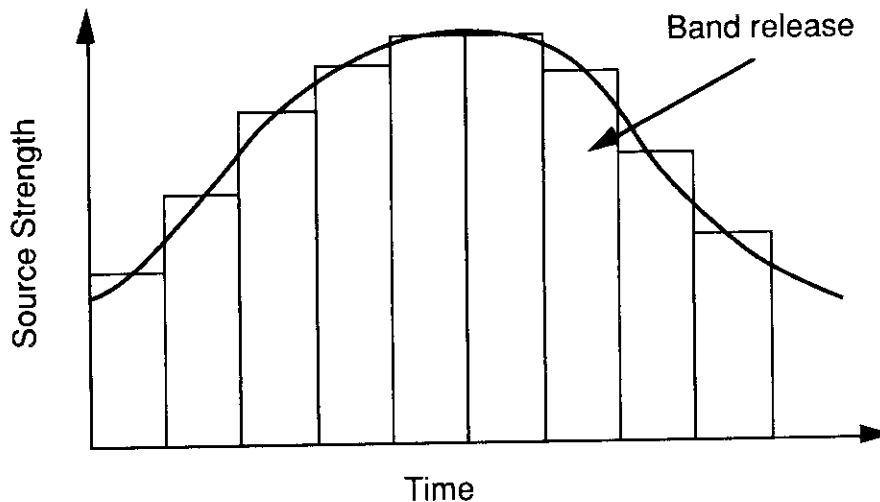


Fig. 10 Treatment of a generalized release pattern from a point source

Now consider a finite array of such point sources emplaced in the infinite medium. If we assume that the nuclide flux from an upstream point source has no effect on the release of nuclide from a downstream point source, the concentration of the array can be obtained by the superposition of eqs. (68), (69), (70) and (71). This assumption may give a conservative assessment, because such the effect causes the decrease of releasing rate of nuclide from the downstream source.

3.2 One-dimensional advection and dispersion model

This model is solved by two methods : analytical solutions assuming a homogeneous porous medium, and finite difference solutions considering multiple layers. Both methods take account of an equilibrium sorption and decay chain in addition to the advection and dispersion in the porous medium.

3.2.1 Analytical solutions

The governing equation in this case is similar to eq. (53), where the dispersion terms for x and y-directions are neglected. The analytical solutions of that are the same as those obtained by replacing the following term and function in eqs. (68), (69), (70) and (71).

$$\frac{W_0^k}{T} \rightarrow vC_0^k, \quad E(i, j, k) \rightarrow I'E'(i, j, k) \quad (77)$$

where

$$E'(i, j, k) = \frac{e^{\frac{z}{2l} - \beta_{ij}t}}{2\sqrt{\gamma_{ijk}}} \left[-e^{\frac{z\sqrt{\gamma_{ijk}}}{2l}} \operatorname{erfc}\left(\frac{z + v_k t \sqrt{\gamma_{ijk}}}{2\sqrt{l v_k t}}\right) + e^{-\frac{z\sqrt{\gamma_{ijk}}}{2l}} \operatorname{erfc}\left(\frac{z - v_k t \sqrt{\gamma_{ijk}}}{2\sqrt{l v_k t}}\right) \right] \quad (78)$$

Equation (78) is employed for the simulation using the flux boundary condition at the inlet boundary. For the simulation using the concentration boundary condition, the following equation is employed¹⁰⁾.

$$E'(i, j, k) = \frac{e^{\frac{z}{2l} - \beta_{ij}t}}{2} \left[e^{\frac{z\sqrt{\gamma_{ijk}}}{2l}} \operatorname{erfc}\left(\frac{z + v_k t \sqrt{\gamma_{ijk}}}{2\sqrt{l v_k t}}\right) + e^{-\frac{z\sqrt{\gamma_{ijk}}}{2l}} \operatorname{erfc}\left(\frac{z - v_k t \sqrt{\gamma_{ijk}}}{2\sqrt{l v_k t}}\right) \right] \quad (79)$$

3.2.2 Finite difference solution

Numerical solutions are necessary for a simulation of multiple layered system or decay chain greater than 4-members. The transport equation to be solved is given as follows

$$\frac{\partial(\phi K_i C_i)}{\partial t} = -\frac{\partial}{\partial x} (u C_i - D \frac{\partial C_i}{\partial x}) - \lambda_i \phi K_i C_i + \lambda_{i-1} \phi K_{i-1} C_{i-1} + Q_i \quad (80)$$

where ϕ : the porosity of the porous medium (-),
 u : the Darcy flow velocity (m/yr),
 D : the dispersion coefficient (m²/yr), and
 Q_i : the source term of radionuclide i (atom/m³yr or Bq/m³yr).

The initial and boundary conditions are

$$C_i(x, 0) = 0 \quad (81)$$

$$C_i = \bar{C}_i \quad \text{on } \Gamma_1 \quad (82)$$

$$q_i = -D \frac{\partial C_i}{\partial x} \quad \text{on } \Gamma_2 \quad (83)$$

$$q_i = u C_i - D \frac{\partial C_i}{\partial x} \quad \text{on } \Gamma_3. \quad (84)$$

We apply the finite difference method for the discretization of transport equation. Assuming that a one-dimensional system consists of L grids, x -coordinates of both ends of l -th grid are x_l and x_{l+1} , and the length of l -th grid is $\Delta x_l (= x_{l+1} - x_l)$, equation (80) can be rearranged as follows

$$\int_{x_l}^{x_{l+1}} \frac{\partial(\phi K_i C_i)}{\partial t} dx = -J_i|_{x_l}^{x_{l+1}} - \int_{x_l}^{x_{l+1}} (\lambda_i \phi K_i C_i - \lambda_{i-1} \phi K_{i-1} C_{i-1} - q_i) dx \quad (85)$$

where

$$J_i \equiv u C_i - D \frac{\partial C_i}{\partial x}. \quad (86)$$

The right hand first term of eq. (85) is approximated as

$$\begin{aligned} -J_i|_{x_l}^{x_{l+1}} &= -J_i(x_{l+1}, t) + J_i(x_l, t) \\ &\approx -u C_i(l, m) + D(l) \frac{C_i^+(l, m) - C_i(l, m)}{\Delta x(l)/2} \\ &\quad + u C_i(l-1, m) - D(l) \frac{C_i(l, m) - C_i^-(l, m)}{\Delta x(l)/2} \end{aligned} \quad (87)$$

where m : index of time step,

$C_i^+(l)$: the concentration at the interface l and $l+1$ -th grids,

$C_i^-(l)$: the concentration at the interface l and $l-1$ -th grids,

$C_i(l)$: the concentration at the middle point of l -th grid,

and the upward finite difference is adopted to the convective term (assuming $u > 0$). The concentrations C^+ and C^- can be expressed by the concentration C applying the continuities of nuclide flux and concentration.

$$\begin{aligned} &-u C_i(l, m) + D(l) \frac{C_i^+(l, m) - C_i(l, m)}{\Delta x(l)/2} \\ &= -u C_i(l, m) + D(l+1) \frac{C_i(l+1, m) - C_i^-(l+1, m)}{\Delta x(l+1)/2} \end{aligned} \quad (88)$$

$$C_i^-(l+1, m) \equiv C_i^+(l, m) \quad (89)$$

Therefore

$$C_i^+(l, m) - C_i(l, m) = \frac{D(l+1)/\Delta x(l+1)}{D(l)/\Delta x(l) + D(l+1)/\Delta x(l+1)} \{C_i(l+1, m) - C_i(l, m)\} \quad (90)$$

$$C_i(l, m) - C_i^-(l, m) = \frac{D(l-1)/\Delta x(l-1)}{D(l)/\Delta x(l) + D(l-1)/\Delta x(l-1)} \{C_i(l, m) - C_i(l-1, m)\}. \quad (91)$$

The right hand second term of eq. (85) is approximated as

$$\Delta x(l)\phi(l)\{-\lambda_i K_i(l)C_i(l, m) + \lambda_{i-1} K_{i-1}(l)C_{i-1}(l, m)\} + \Delta x(l)q_i(l). \quad (92)$$

The left hand term of eq. (85) is also approximated as

$$\Delta x(l)\phi(l)K_i(l)\frac{C_i(l, m) - C_i(l, m-1)}{\Delta t}. \quad (93)$$

Finally, we get the following finite difference equation

$$\begin{aligned} & \Delta x(l)\phi(l)K_i(l)\frac{C_i(l, m) - C_i(l, m-1)}{\Delta t} \\ &= -u C_i(l, m) + \frac{2D(l)D(l+1)}{D(l)\Delta x(l+1) + D(l+1)\Delta x(l)} \{C_i(l+1, m) - C_i(l, m)\} \\ &+ u C_i(l-1, m) - \frac{2D(l)D(l-1)}{D(l)\Delta x(l-1) + D(l-1)\Delta x(l)} \{C_i(l, m) - C_i(l-1, m)\} \\ &+ \Delta x(l)\phi(l)\{-\lambda_i K_i(l)C_i(l, m) + \lambda_{i-1} K_{i-1}(l)C_{i-1}(l, m)\} + \Delta x(l)q_i(l). \end{aligned} \quad (94)$$

The integration with respect to time is performed in the order of decay chain, therefore the concentration $C_{i-1}(l, m)$ in eq. (94) is known value. Equation (94) can be rearranged as the following expression, if the terms are put in order of index l specifying spatial grids.

$$e_i(l)C_i(l-1, m) + d_i(l)C_i(l, m) + f_i(l)C_i(l+1, m) = v_i(l) \quad (95)$$

where

$$e_i(l) = \frac{2D(l)D(l-1)}{D(l)\Delta x(l-1) + D(l-1)\Delta x(l)} + u(l) \quad (96)$$

$$f_i(l) = \frac{2D(l)D(l+1)}{D(l)\Delta x(l+1) + D(l+1)\Delta x(l)} \quad (97)$$

$$d_i(l) = -f_i(l) - u(l) - f_i(l-1) + d'_i(l) \quad (l \neq 1, L) \quad (98)$$

$$d'_i(l) = -\Delta x(l)\phi(l)K_i(l)(\lambda_i + 1/\Delta t) \quad (99)$$

$$v_i(l) = -\frac{\Delta x(l)\phi(l)K_i(l)}{\Delta t}C_i(l, m-1) - \Delta x(l)q_i(l) - \Delta x(l)\phi(l)K_{i-1}(l)\lambda_{i-1}C_{i-1}(l, m) \quad (l \neq 1). \quad (100)$$

The boundary conditions are taken into account in the following way.

(a) The boundary conditions at the upward side

Equations (82) and (84) are used to define the boundary conditions at the upward side of computational domain ($l = 1$). When the concentration at the boundary is prescribed by $\underline{C}_i(m)$, the terms in eq. (95) are given as follows

$$d_i(1) = -f_i(1) - u(1) - \frac{2D(1)}{\Delta x(1)} + d'_i(1) \quad (l = 1) \quad (101)$$

$$v_i(1) = -\frac{\Delta x(1)\phi(1)K_i(1)}{\Delta t}C_i(1, m-1) - \Delta x(1)q_i(1) - \Delta x(1)\phi(1)K_{i-1}(1)\lambda_{i-1}C_{i-1}(1, m) - \underline{C}_i(m)\left\{u(1) + \frac{2D(1)}{\Delta x(1)}\right\} \quad (l = 1). \quad (102)$$

When the nuclide flux at the boundary is prescribed by \underline{q}_i , the terms in eq. (95) are also given as

follows

$$d_i(1) = -f_i(1) - u(1) + d'_i(1) \quad (l = 1) \quad (103)$$

$$\begin{aligned} v_i(1) = & -\frac{\Delta x(1)\phi(1)K_i(1)}{\Delta t} C_i(1, m-1) - \Delta x(1)q_i(1) \\ & - \Delta x(1)\phi(1)K_{i-1}(1)\lambda_{i-1} C_{i-1}(1, m) - \underline{q}_i \quad (l = 1). \end{aligned} \quad (104)$$

(b) The boundary conditions at the downward side

Equations (82) and (83) are used to define the boundary conditions at the downward side of computational domain ($l = L$). When the concentration at the boundary is prescribed by $\underline{C}_i(m) = 0$, the term in eq. (95) d_i is given as follows

$$d_i(L) = -f_i(L-1) - u(L) - \frac{2D(L)}{\Delta x(L)} + d'_i(L) \quad (l = L). \quad (105)$$

When the gradient of concentration is zero at the boundary ($-D \frac{\partial C_i}{\partial x} = 0$), the term d_i is given as follows

$$d_i(L) = -f_i(L-1) - u(L) + d'_i(L) \quad (l = L). \quad (106)$$

In the previous discussion, the spatial grids are treated as common values about all nuclides. However a numerical difficulty arises when the retardation factors of nuclides remarkably vary among the nuclides in the decay chain. In such the case, the spatial grids should be chosen so that the Peclet number ($= u\Delta x/(DK_i)$) is enough small for every nuclide. The different spatial grids can be used for each nuclide in this finite difference model, in order to eliminate the numerical difficulty.

4. BIOSPHERE MODEL

The biosphere model developed here, which is based on a linear dynamic compartment model, intends to evaluate the transport behavior of radionuclides which have been released from a repository into the biosphere, and exposure doses associated with this release. The biosphere modeled here is assumed to consist mainly of the aquatic environment (surface water body: a river, a lake and marsh, and an adjacent sea near an estuary), and the terrestrial environment (the soil surface to be used as farm land). Pathways of the radionuclide transport in the biosphere are schematically shown in Fig. 11. Deep underground water contaminated with radionuclides released from the repository

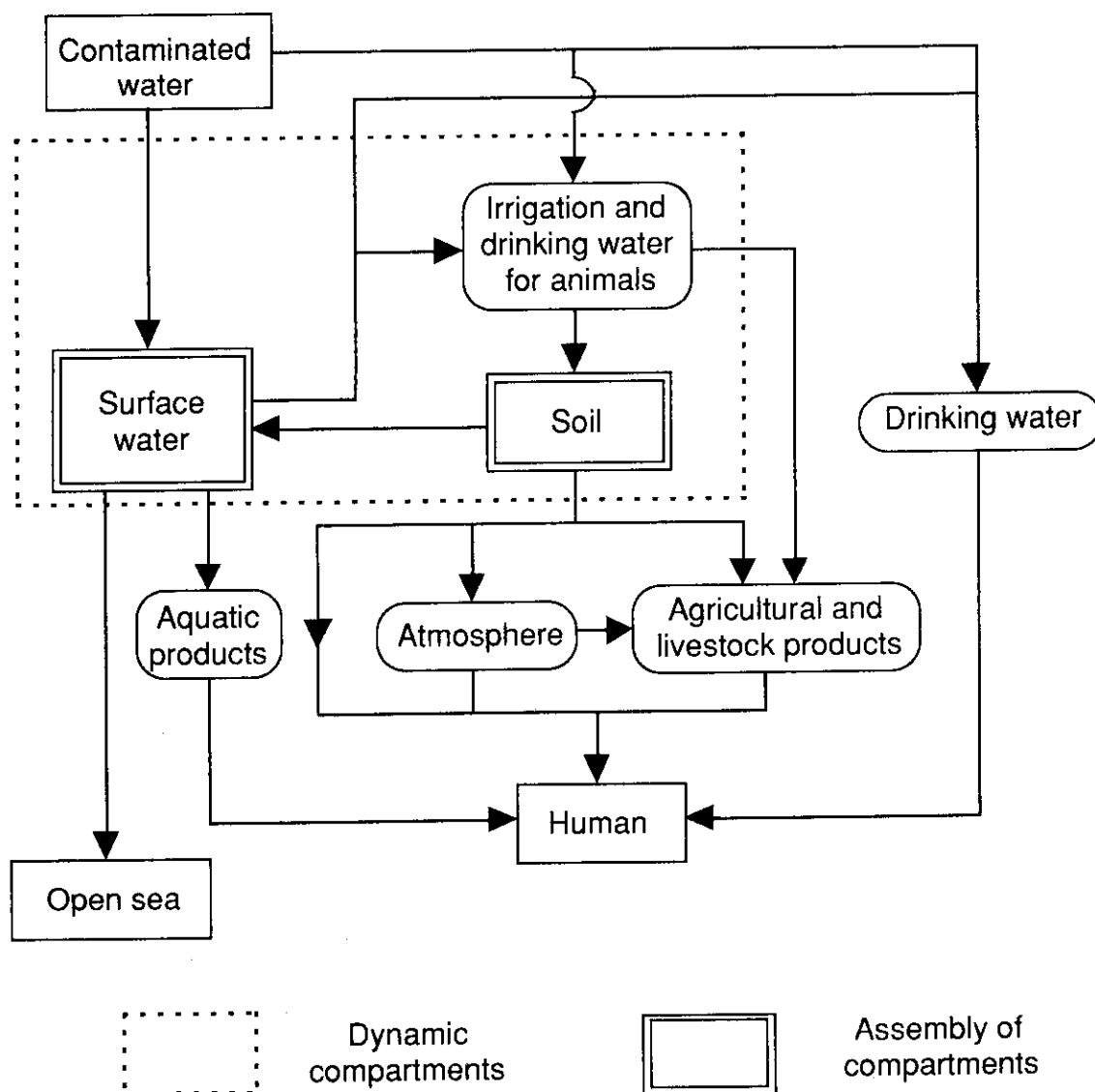


Fig. 11 Schematic pathways of radionuclide transport in the biosphere

flows through the adjacent aquifers into the surface water body. Radionuclides in water may ultimately reach the public by use of water from either a well or surface water, and by ingestion of aquatic products. Radionuclides in water used for agricultural purposes, e.g., irrigation water and animal drinking water, cause the contamination of the surface soil of farm land and then the contamination of the air above the surface by resuspension, vegetation grown on the surface and cattle fed by contaminated feeds and water. The resulting exposure pathways assumed here are summarized as follows:

- external exposure from radionuclides deposited on the surface,
- internal exposure from inhalation of radionuclides resuspended from the surface, and
- internal exposure from ingestion of food (crops, animal products and aquatic products) and drinking water.

A dosimetry submodel combined with the biosphere model evaluates the committed effective dose equivalent (internal exposures) and the effective dose equivalent (external exposures) for an individual. In addition, the submodel calculates population doses due to ingestion of contaminated food and drinking water by the public, due to external exposures to a farmer from radionuclides deposited on the surface soil of farm land, and also due to inhalation by a farmer of resuspended materials from the surface soil, provided that the population of a farmer is known for a specific site.

4.1 Surface water body

The surface water body considered here consists of the upper reaches of a river (upstream), a lake or marsh (lake), the lower reaches of a river (downstream), the adjacent sea near an estuary (adjacent sea) and the open sea. Water flow in the surface water body follows the order mentioned above as shown in Fig. 12. The user may also select to input the contaminated water flow from the aquifers directly into either component of the body except for the open sea which is assumed to be a radionuclide sink. Radionuclides in river water are assumed to do not interact with sediment, since a flow rate of a river in Japan is relatively rapid. On the other hand, the residence time of water in both a lake and the adjacent sea is, in general, longer than one year. This may necessitate, in the both cases, to consider the transport of radionuclides between water and a sediment. The resulting concentrations of radionuclides in water are the source terms for the calculation of radiological consequences to the public via specific pathways assumed here.

For releases to both lake and adjacent sea zones, the models used here evaluate the activity concentrations in both the water and the sediment. The models take into account the physical water flow, the interaction of radionuclides with suspended materials and the bottom sediment, and radioactive decay chain. Radionuclides will be transported to the bottom by the sedimentation of suspended particles which have sorbed radionuclides, and by the diffusion controlled sorption of radio-

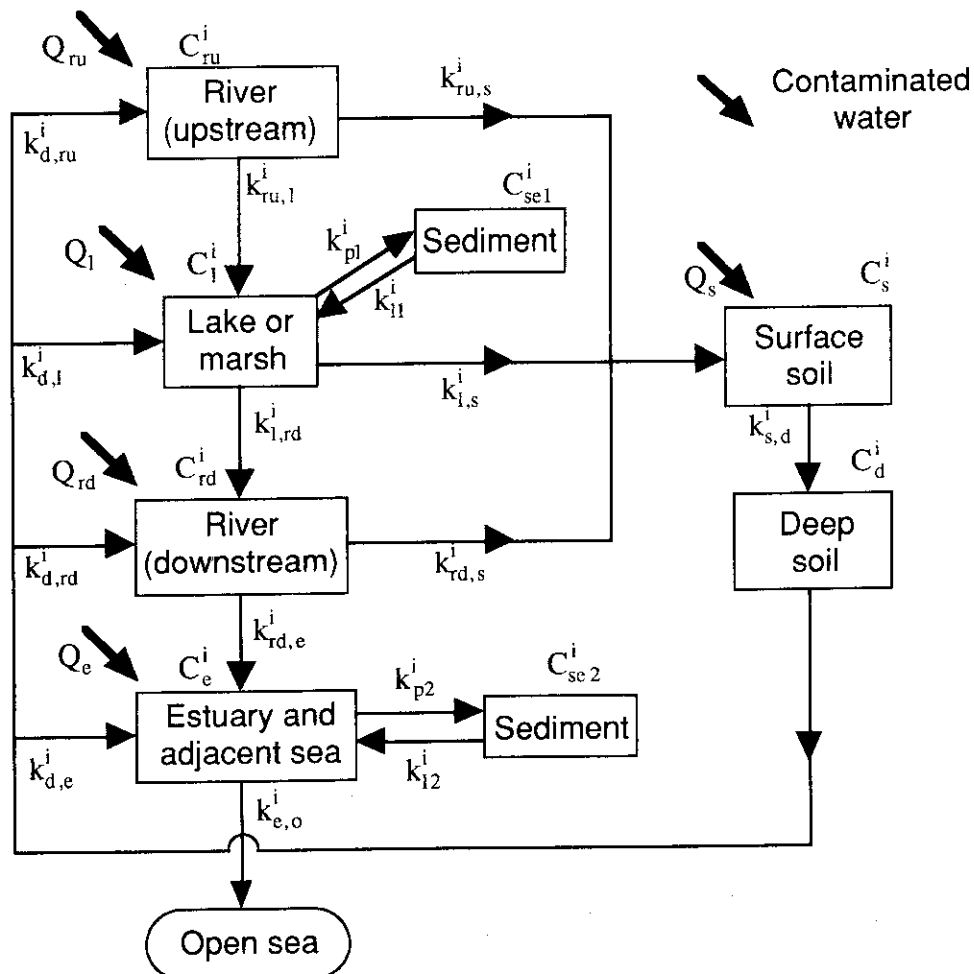
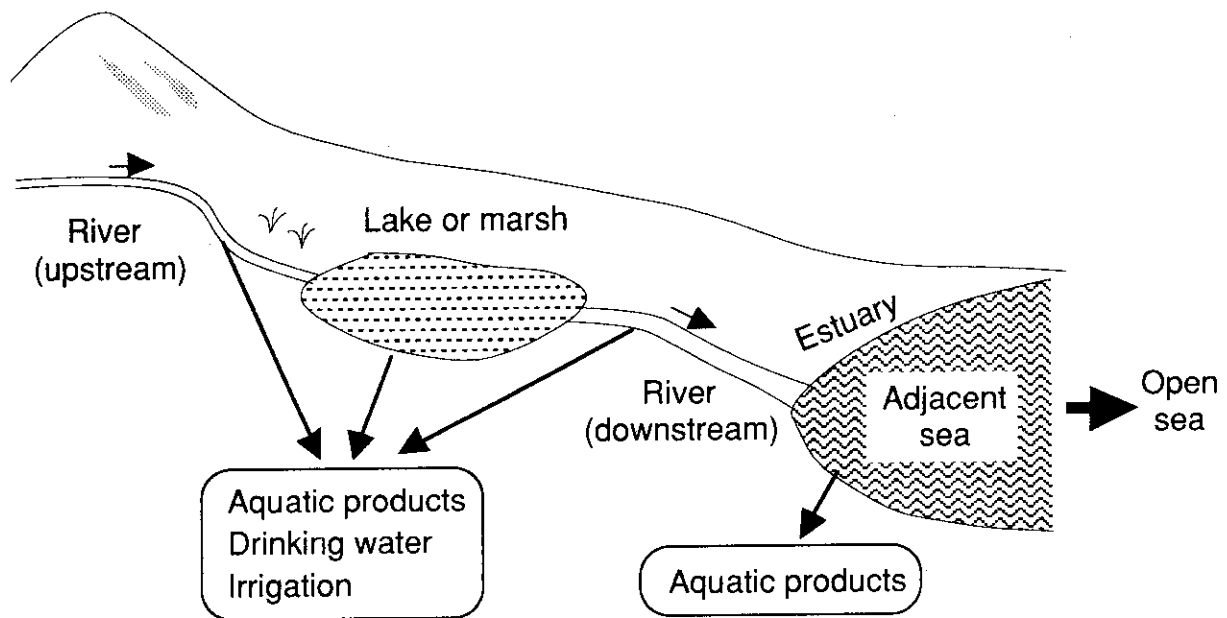


Fig. 12 Surface water body in the model

nuclides in water onto the sediment. The rate of transfer from the water into the sediment is calculated by¹¹⁾:

$$k_p^i = \frac{D}{dh} + \frac{v_s C_p^i Kd_p^i}{h} \quad (107)$$

where D : the effective diffusion coefficient in the sediment (m^2/yr),

d : the effective thickness of the sediment (m),

h : the height of water column (m),

v_s : the velocity of sedimentation (m/yr),

C_p^i : the concentration of particles in water (kg/m^3), and

Kd_p^i : the distribution coefficient in sedimentating particles (m^3/kg).

Radionuclides transferred into the sediment will be leached into water by the diffusion mechanism with a sorption equilibrium of a specific nuclide between the sediment and the water. The rate of transfer from the sediment into the water is given by:

$$k_l^i = \frac{D}{dKd_s^i \rho_s h} \quad (108)$$

where Kd_s^i : the distribution coefficient in the sediment (m^3/kg), and

ρ_s : the bulk density of the sediment (kg/m^3).

Water from fresh water compartments (rivers and lake) will transfer into the surface soil of farm land as a result of the use of it as irrigation water. The user may select the sources of irrigation water from either fresh water compartment or an appropriate combination of the compartments, taking into account the geographical conditions specific to a site to be assessed. The transfer coefficient (k_j : $k_{ru,s}$, $k_{l,s}$ and $k_{rd,s}$) is given by $k_j = I_j S / V_j$, where I_j is irrigation rate from fresh water compartment j (m/y), S is the surface area of farm land (m^2), and V_j is the water volume of fresh water compartment j (m^3).

4.2 Surface system of farm land

The surface system of farm land consists of irrigation water, the surface soil and deep soil layer, and the atmosphere above the surface. Radionuclide transport pathways in this system are schematically shown in Fig. 13. Water used for irrigation is assumed to be collected from groundwater (well water), and fresh water compartments (rivers and lakes). The concentration of radionuclides

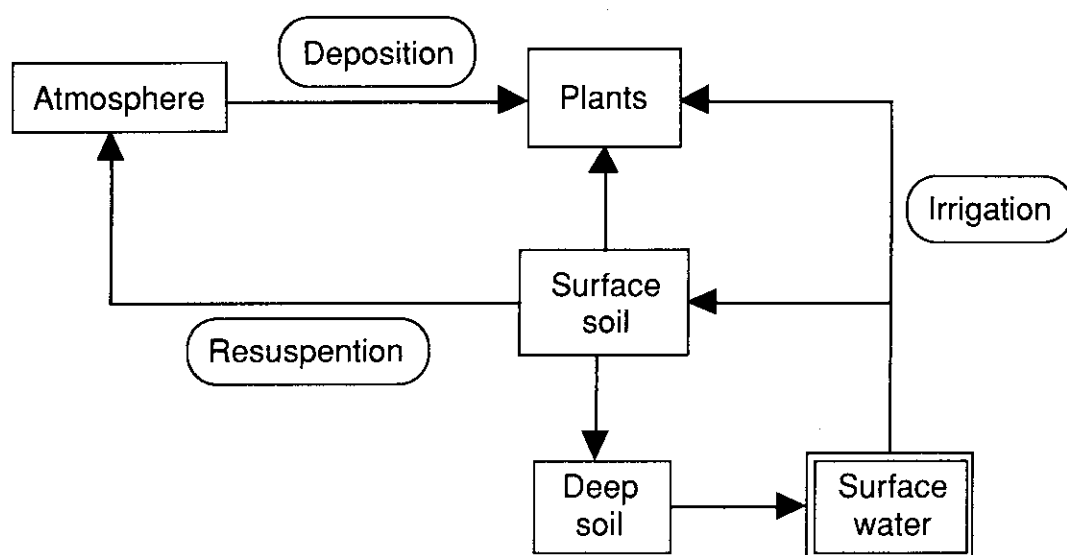


Fig. 13 Radionuclide transport pathways in the surface system of farm land

in irrigation water is an average of well and fresh water weighted by the relative amount of each that are specified by the user. The surface soil which contributes to soil-plant transfer will be contaminated only by irrigation. Radionuclides in the surface soil layer will migrate downward accompanying with the flow of precipitation and irrigation water, depending mainly on the flow rate of water in the layer and the distribution coefficient of radionuclides between water and soil¹²⁾.

$$k_{s,d}^i = \frac{P + I}{L_{pad}(1 + \rho_{so} Kd_{so}^i)} \quad (109)$$

where P : the net precipitation (m/yr),

I : irrigation rate (m/yr),

L_{pad} : the depth of the surface soil contributing to soil-plant transfer (m),

Kd_{so}^i : the distribution coefficient in soil (m³/kg), and

ρ_{so} : the bulk density of soil (kg/m³).

The radionuclides migrated into a deep soil layer, which do not contribute to soil-plant transfer, return to surface water compartments (or are removed from the compartment system).

The surface soil contaminated by radionuclides will be resuspended by man-made and wind-driven disturbances, resulting in the contamination of the air above the surface. This will be the source for the calculation of inhalation of various radionuclides, and also the contamination of leafy

vegetables via deposition onto the surface of vegetation. Resuspension caused by the man-made disturbance such as farming activities is usually localized, and is an important exposure pathway for particular individuals such as a farmer. The wind-driven resuspension is also important in a case where the surface has been widely contaminated by deposition from a passing radioactive plume released from a nuclear power plant during both normal and accidental conditions. This part particularly concerned with the assessment of radiological consequences to individuals who engaged in agricultural activities; wind-driven resuspension is not considered further. The radionuclide concentration of the air above the surface is therefore calculated by the model based on a mass-loading factor.

$$C_{\text{air}} = C_s F_{\text{ml}} \quad (110)$$

where C_{air} : the concentration of nuclide i in air (Bq/m^3),

C_s : the concentration of nuclide i in the surface soil (Bq/kg), and

F_{ml} : a mass-loading factor, dust concentration in air (kg/m^3).

4.3 Radionuclide concentration in food

4.3.1 Concentration in vegetation

The following equation estimates the concentration C_v (Bq/kg) of a specific nuclide in and on vegetation:

$$C_v = \frac{dRT_v(1 - e^{-\lambda_e t_e})}{Y_v \lambda_e} + BC_s e^{-\lambda t_h} \quad (111)$$

where C_s : the concentration of the radionuclide in dry soil (Bq/kg),

d : the input rate from deposition and irrigation ($\text{Bq/m}^2\text{day}$),

$$d = d_{\text{irr}} + d_{\text{air}} \quad (112)$$

$$d_{\text{irr}} = C_{\text{iw}} I \quad (113)$$

$$d_{\text{air}} = C_{\text{air}} V_{\text{de}} \quad (114)$$

d_{irr} : the deposition rate from irrigation ($\text{Bq/m}^2\text{day}$),

d_{air} : the deposition rate from air ($\text{Bq/m}^2\text{day}$),

C_{iw} : the concentration in irrigation water (Bq/m^3),

- I : the irrigation rate (m/day),
 C_{air} : the concentration in air (Bq/m³),
 V_{de} : the deposition velocity (m/day),
 R : the fraction of deposited radioactivity retained on the vegetation (0.25),
 T_v : The factor for translocation of externally deposited nuclides to the edible parts of the vegetation (1: leafy vegetables and grass, 0.1: all other crops),
 λ_e : the effective removal rate constant for the radionuclide from crops (1/day),

$$\lambda_e = \lambda + \lambda_w \quad (115)$$
 λ : the radioactive decay constant (1/day),
 λ_w : the removal rate constant for physical loss by weathering (1/day),
 Y_v : agricultural productivity (kg/m²),
 B : the concentration factor for uptake of the radionuclides from soil by edible portion of crops [Bq/kg(wet weight)/Bq/kg(dry soil)],
 P : effective surface density of soil [kg(dry soil)/m²],
 t_e : the time period that crops are exposed to contamination during the growing season (day), and
 t_h : the time interval between harvest and consumption of the food (day).

4.3.2 Concentration in animal products

The concentration of a specific radionuclide in animal products (meat, milk and egg) is assumed to depend directly upon the amount and radioactivity of the feed and drinking water consumed by the animal. The concentration of the radionuclides in animal products, C_m (Bq/kg or Bq/l), is estimated as

$$C_m = F_m (C_a Q_f + C_{dw} Q_w) \quad (116)$$

where F_m : the fraction of the animal's intake of the radionuclide that appears in each kg of meat and egg or each litre of milk at equilibrium (day/kg, day/l)

- C_a : the concentration of the radionuclide in the animal feed (Bq/kg),
 Q_f : the amount of dry feed consumed by the animal per day (kg/day),
 C_{dw} : the concentration of the radionuclide in the animal drinking water (Bq/kg),
 Q_w : the amount of drinking water consumed by the animal per day (kg/day),

4.3.3 Concentration of aquatic products

The concentration of a specific radionuclide in aquatic food (fish, flora and invertebrate), C_p (Bq/kg), is generally expressed by the equation,

$$C_p = C_w B_p \quad (117)$$

where C_w : the concentration of the radionuclide in water (Bq/l),

B_p : the ratio of the concentration of the radionuclides in aquatic food to its concentration in water (l/kg) known as the bioaccumulation factor.

4.4 Radionuclide concentration in compartments

The model solves a equation describing the concentration of radionuclides in compartments resulting from the releases of contaminated groundwater into them¹³⁾.

$$V \frac{dC_i}{dt} = -\lambda_i V C_i + A_i C_i + Q_i + \lambda_{i-1} C_{i-1} \quad (118)$$

where C_i : a vector of dimension n whose components are the concentration of nuclide i in the n compartments (Bq/m³),

A_i : the matrix of volumetric flow rate between the components (m³/yr), and then A_i/V is the matrix of transfer coefficient between the compartments (1/yr),

Q_i : the vector of inputs to the compartments (Bq/yr), and

V : a diagonal matrix of the compartment volumes (m³).

The model involves seven compartments: river water (upstream), lake water, lake sediment, river water (downstream), adjacent sea water, adjacent sea sediment, and surface soil. The radionuclide concentration vector for this system is given by,

$$C_i = [C_{ru}^i, C_l^i, C_{ls}^i, C_{rd}^i, C_e^i, C_{es}^i, C_s^i, C_d^i, C_{ru}^i, C_{ru}^i]^T \quad (119)$$

where T denotes transpose and the subscripts ru , l , ls , rd , e , es , s and d represent river water (upstream), lake water, lake sediment, river water (downstream), adjacent sea water, adjacent sea sediment, surface soil and deep soil, respectively. This subscription system is also used for other vector (Q) and matrix components (V and k). The differential equations to be solved are the following:

$$\frac{dC_{ru}^i}{dt} = -(k_{ru,s}^i + k_{ru,l}^i + \lambda_i)C_{ru}^i + k_{d,ru}^i \frac{V_d}{V_{ru}} C_d^i + Q_{ru} + \lambda_{i-1} C_{ru}^{i-1} \quad (120)$$

$$\begin{aligned} \frac{dC_l^i}{dt} = & -(k_{l,s}^i + k_{l,rd}^i + \lambda_i + k_{pl}^i)C_l^i + k_{ru,l}^i \frac{V_{ru}}{V_l} C_{ru}^i + k_{d,l}^i \frac{V_d}{V_l} C_d^i \\ & + k_{ll}^i \frac{V_{se1}}{V_l} C_{se1}^i + Q_l + \lambda_{i-1} C_l^{i-1} \end{aligned} \quad (121)$$

$$\frac{dC_{rd}^i}{dt} = -(k_{rd,s}^i + k_{rd,e}^i + \lambda_i)C_{rd}^i + k_{l,rd}^i \frac{V_l}{V_{rd}} C_l^i + k_{d,rd}^i \frac{V_d}{V_{rd}} C_d^i + Q_{rd} + \lambda_{i-1} C_{rd}^{i-1} \quad (122)$$

$$\begin{aligned} \frac{dC_e^i}{dt} = & -(k_{e,o}^i + \lambda_i + k_{p2}^i)C_e^i + k_{rd,e}^i \frac{V_{rd}}{V_e} C_{rd}^i + k_{d,e}^i \frac{V_d}{V_e} C_d^i \\ & + k_{l2}^i \frac{V_{se2}}{V_e} C_{se2}^i + Q_e + \lambda_{i-1} C_e^{i-1} \end{aligned} \quad (123)$$

$$\begin{aligned} \frac{dC_s^i}{dt} = & -(k_{s,d}^i + \lambda_i)C_s^i + k_{ru,s}^i \frac{V_{ru}}{V_s} C_{ru}^i + k_{l,s}^i \frac{V_l}{V_s} C_l^i + k_{rd,s}^i \frac{V_{rd}}{V_s} C_{rd}^i \\ & + Q_s + \lambda_{i-1} C_s^{i-1} \end{aligned} \quad (124)$$

$$\frac{dC_d^i}{dt} = -(k_{d,ru}^i + k_{d,l}^i + k_{d,rd}^i + k_{d,e}^i + \lambda_i)C_d^i + k_{s,d}^i \frac{V_s}{V_d} C_s^i + \lambda_{i-1} C_d^{i-1} \quad (125)$$

$$\frac{dC_{se1}^i}{dt} = -(k_{ll}^i + \lambda_i)C_{se1}^i + k_{pl}^i \frac{V_l}{V_{se1}} C_l^i + \lambda_{i-1} C_{se1}^{i-1} \quad (126)$$

$$\frac{dC_{se2}^i}{dt} = -(k_{l2}^i + \lambda_i)C_{se2}^i + k_{p2}^i \frac{V_e}{V_{se2}} C_e^i + \lambda_{i-1} C_{se2}^{i-1} \quad (127)$$

where V_n : the volume of the n compartment (m^3),
 C_n^i : the concentration of radionuclide i in the n compartment (Bq/m^3),
 Q_n : the water flux into the n compartment (m^3/yr), and
 $k_{n,m}^i$: the transfer rate of nuclide i from n to m compartment ($1/yr$).

4.5 Dosimetry

In the proceeding sections, radionuclide concentrations are given for air, surface water, sea water, groundwater and on the surface soil, and also for food products (agricultural products and aquatic products) and drinking water. These concentrations institute the bases to evaluate radiological consequences to an individual or a population to be assessed. For dose calculations, each individual is assumed to ingest all of his water from groundwater and the fresh water system, and all of his aquatic food from the fresh water system into all of which radionuclides were released from the repository. Each individual is also assumed to diet his all agricultural food which were indirectly or directly contaminated by the surface water and groundwater as irrigation water. These assumptions may give the maximum individual doses.

The dosimetry submodel evaluates the maximum individual radiological consequences from three basic exposure pathways:

- the effective dose equivalent due to gamma-irradiation from radionuclides deposited on the surface soil (Sv),
- the committed effective dose equivalent due to inhalation of resuspended materials from the surface soil of farm land (Sv), and
- the committed effective dose equivalent due to ingestion of contaminated food and drinking water.

The individual external dose to a farmer, DI_{ext} (Sv), resulting from exposure to gamma-ray from the surface soil is given by:

$$DI_{ext} = DF_{ext} C_s R_{farm} \quad (128)$$

where DF_{ext} : the external dose conversion factor (Sv/hr/Ba/kg),

C_s : the concentration of radionuclide in the surface soil (Bq/kg), and

R_{farm} : the annual residence time at farm land (hr).

All of the external dose conversion factors are calculated for the radionuclides of concern using the computer program QAD-CGGP2¹⁴⁾. The dose conversion factors listed in Table 1 are in tissue at a depth below the body surface of 1 cm (effective dose), 0.3 cm (crystalline lens dose) or 0.07 mm (skin dose), and at a height of 100 cm above the infinite surface. The calculation of the dose conversion factors for ground-surface exposure at a height of 100 cm above the surface provides a reasonable approximation to the dose conversion factors averaged over the height of an exposed individual for emitted electron energies above about 1 MeV¹⁵⁾.

The individual internal dose to a farmer, DI_{inh} (Sv), resulting from inhalation of air containing resuspended materials from the surface soil is given by:

Table 1 External dose conversion factor by gamma-ray

Nuclide	External dose conversion factor (gamma-ray, Sv.kg/Bq.hr)		
	depth = 1 cm	depth = 3 mm	depth = 0.07 mm
Sn-126	1.194E-8	1.151E-8	1.105E-8
Sb-126	6.840E-7	6.736E-7	6.610E-7
Sb-126m	3.891E-7	3.822E-7	3.744E-7
I-129	1.479E-10	1.493E-10	1.459E-10
Hg-206	2.671E-8	2.611E-8	2.525E-8
Tl-206	1.160E-11	1.150E-11	1.135E-11
Tl-206m	6.089E-7	6.007E-7	5.893E-7
Tl-207	5.236E-10	5.217E-10	5.159E-10
Tl-208	7.364E-7	7.414E-7	7.397E-7
Tl-209	4.651E-7	4.659E-7	4.642E-7
Tl-210	6.324E-7	6.320E-7	6.280E-7
Pb-210	2.287E-10	2.234E-10	2.146E-10
Pb-211	1.669E-8	1.646E-8	1.617E-8
Pb-212	3.164E-8	3.073E-8	2.983E-8
Pb-214	6.178E-8	6.028E-8	5.843E-8
Bi-211	1.213E-8	1.182E-8	1.145E-8
Bi-212	2.470E-8	2.460E-8	2.439E-8
Bi-213	2.108E-8	2.062E-8	2.010E-8
Bi-214	3.245E-7	3.249E-7	3.240E-7
Po-210	2.338E-12	2.323E-12	2.296E-12
Po-211	1.876E-9	1.857E-9	1.827E-9
Po-215	4.652E-11	4.542E-11	4.424E-11
Po-216	3.681E-12	3.657E-12	3.615E-12
At-218	5.839E-10	5.674E-10	5.400E-10
Rn-219	1.481E-8	1.442E-8	1.398E-8
Rn-220	1.547E-10	1.517E-10	1.480E-10
Rn-222	1.002E-10	9.845E-11	9.597E-11
Fr-221	6.853E-9	6.652E-9	6.467E-9
Fr-223	1.038E-8	1.010E-8	9.760E-9

Table 1 (continued)

Nuclide	Dose conversion factor (gamma-ray, Sv.kg/Bq.hr)		
	depth = 1 cm	depth = 3 mm	depth = 0.07 mm
Ra-223	2.381E-8	2.323E-8	2.241E-8
Ra-224	2.650E-9	2.573E-9	2.498E-9
Ra-225	8.223E-10	8.165E-10	7.935E-10
Ra-226	1.800E-9	1.766E-9	1.699E-9
Ra-228	2.650E-13	2.879E-13	2.875E-13
Ac-225	2.866E-9	2.787E-9	2.679E-9
Ac-227	3.104E-11	3.017E-11	2.885E-11
Ac-228	1.869E-7	1.862E-7	1.841E-7
Th-227	2.542E-8	2.473E-8	2.394E-8
Th-228	5.458E-10	5.281E-10	5.086E-10
Th-229	9.067E-9	8.838E-9	8.498E-9
Th-230	9.197E-11	8.852E-11	8.427E-11
Th-231	2.499E-9	2.411E-9	2.315E-9
Th-232	4.835E-11	4.644E-11	4.403E-11
Th-234	2.010E-9	1.938E-9	1.854E-9
Pa-231	7.327E-9	7.154E-9	6.909E-9
Pa-233	4.431E-8	4.324E-8	4.178E-8
Pa-234	3.141E-7	3.126E-7	3.090E-7
Pa-234m	2.392E-9	2.387E-9	2.367E-9
U-233	4.797E-11	4.674E-11	4.500E-11
U-234	2.402E-11	2.334E-11	2.223E-11
U-235	4.157E-8	4.073E-8	3.915E-8
U-236	1.133E-11	1.103E-11	1.054E-11
U-237	1.916E-8	1.860E-8	1.793E-8
U-238	4.941E-12	4.821E-12	4.611E-12
Np-237	3.964E-9	3.836E-9	3.688E-9
Pu-239	1.239E-11	1.206E-11	1.162E-11
Pu-240	4.506E-12	4.391E-12	4.216E-12
Pu-241	1.175E-13	1.144E-13	1.092E-13
Pu-242	4.180E-12	4.071E-12	3.907E-12
Am-241	4.322E-9	4.151E-9	3.928E-9
Cm-245	5.910E-9	5.789E-9	5.544E-9

$$DI_{inh} = DF_{inh} C_{air} VR_{farm} \quad (129)$$

where DF_{inh} : the internal dose conversion factor for inhalation (Sv/Ba),

C_{air} : the concentration of radionuclide in the air above the surface soil (Bq/m³), and

V : the rate of breathing (m³/h).

The individual internal dose to the public, DI_{ing} (Sv), resulting from ingestion of contaminated food is given by:

$$DI_{ing} = \sum_p DF_{ing} C_{food,p} U_p \quad (130)$$

where DF_{ing} : the internal dose conversion factor for ingestion (Sv/Bq),

$C_{food,p}$: the radionuclide concentration in food p (Bq/kg or Bq/l), and

U_p : the annual consumption of food p (kg or l).

The internal dose, DI_{ing} (Sv), resulting from ingestion of drinking water is given by:

$$DI_{ing} = \sum_w DF_{ing} C_{drink,w} U_w \quad (131)$$

where $C_{drink,w}$: the radionuclide concentration in drinking water taken from water source

w (Bq/m³), and

U_w : the annual consumption of drinking water from water source w (m³).

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Appendix-1 Input data for GSRW

The GSRW code is composed of three models (source term, geosphere and biosphere), and ORIGEN-II and its interface codes are used to evaluate the inventory of radionuclides in HLW. Furthermore, the source term model and geosphere model (one-dimensional dispersion model) use two different solution techniques, analytical and finite difference methods. Therefore, input data are composed of five types of data:

- 1) input data for the ORIGEN-II interface code,
- 2) input data for the source term model,
- 3) input data for the three-dimensional and one-dimensional dispersion model,
- 4) input data for the finite difference model (source term and one-dimensional dispersion geosphere model), and
- 5) input data for the biosphere model.

A series of computational jobs may be possible in the calculations using the ORIGEN-II interface code, source term and geosphere models (see Fig. A-1). A computation using the biosphere model is separately performed based on the results of geosphere model. These consecutive jobs are controlled by ISYS data. ISYS data are the following values:

$$\text{ISYS} = \text{I1} \times 1000 + \text{I2} \times 100 + \text{I3} \times 10 + \text{I4}$$

- where
- I1 : job flag of ORIGEN-II interface code (=0: without calculation, =1: calculation),
 - I2 : job flag of source term model (=0: without calculation, =1: use analytical solutions, =2: use finite difference solutions),
 - I3 : job flag of 3D-dispersion geosphere model (=0: without calculation, =1: calculation),
and
 - I4 : job flag of 1D-dispersion geosphere model (=0: without calculation, =1: use analytical solutions, =2: use finite difference solutions).

Data files necessary for GSRW code are shown in Table A-1.

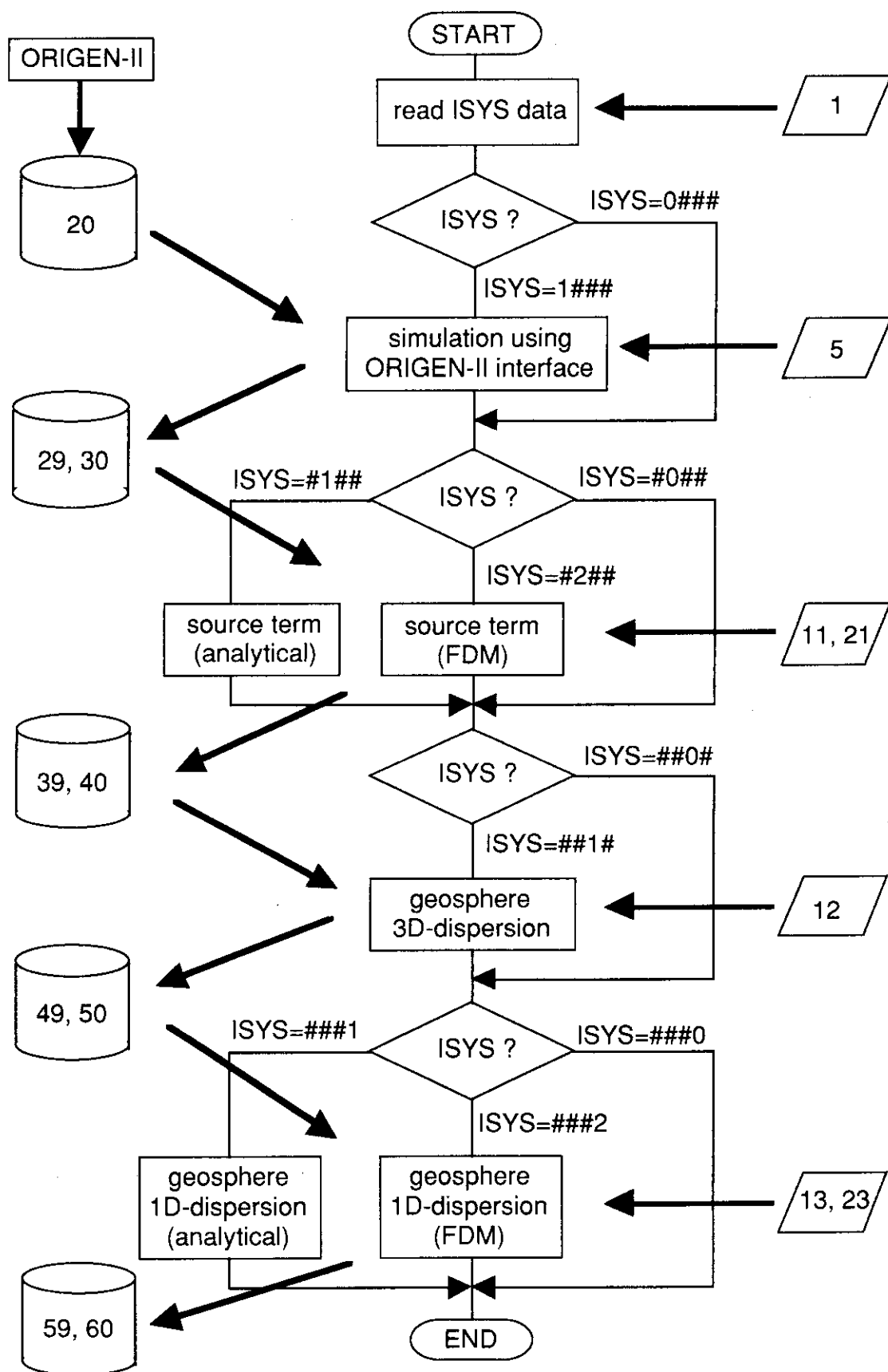


Fig. A-1 Flow chart of GSRW code (ORIGEN-II I/F code ~ geosphere model)

Table A-1 Data files necessary for GSRW code

File No.	contents
ORIGEN-II I/Fcode, source term model, geosphere model	
1	input data file for ISYS data
5	input data file for ORIGEN-II I/F code
11	input data file for source term model
12	input data file for geosphere model (3D-dispersion)
13	input data file for geosphere model (1D-dispersion)
20	binary file for ORIGEN-II I/F code (result file of ORIGEN-II code)
21	input data file for source term model (FDM case only)
23	input data file for geosphere model (1D-dispersion, FDM case only)
29	result file (text) of ORIGEN-II I/F code
30	result file (binary) of ORIGEN-II I/F code (input file for source term model)
39	result file (text) of source term model
40	result file (binary) of source term model (input file for 3-D dispersion geosphere model)
49	result file (text) of 3D-dispersion geosphere model
50	result file (binary) of 3D-dispersion geosphere model (input file for 1D-dispersion geosphere model)
59	result file (text) of 1D-dispersion geosphere model
60	result file (binary) of 1D-dispersion geosphere model (input file for biosphere model)
Biosphere	
1	input file (result file of 1D-dispersion geosphere model)
2	result file
5	input data file

A-1.1 Input data for ORIGEN-II interface code

Card	entry	contents
1	TITLE	title name of job
2	IPRINT	flag for printing, = 0 : without printing, > 0:printing of control data and results, < 0: printing of control data
	IFILF	flag for output of text file, =0: without output, >0:output
	IFILB	flag for output of binary file, =0: without output, >0:output
	ICHN	number of decay chains to be calculated
	ROU0	conversion factor, result = (calculated value)*ROU0
Cards 3 to 10 (a set of cards) must be repeated ICHN times		
3	ICFG	identification of type of decay chain, =0:straight chain, else: branch chain
	INFL	flag for input data, =0:card input, else:file input (output file from ORIGEN-II code)
	NUCL	number of nuclides
	ITIM	number of time data for output
4	TIM(I) I=1,ITIM	time changing time step
5	IDL(I) I=1,ITIM	number of time step between TIM(I-1) and TIM(I)
6	H0	step size for EPISODE package
	EPS	local error tolerance parameter (for EPISODE)
	IERROR	indicator for error control (for EPISODE), =1:absolute, =2:relative, =3:semi-relative
	MF	method flag (for EPISODE), MF=10xMETH+MITER, METH=1:implicit Adams method, =2:BDF method, MITER=0:functional iteration, =1:chord method with user-supplied Jacobian from PEDERV, =2:chord method with Jacobian generated internally, =3:chord method with diagonal approximation to Jacobian

Card	entry	contents
7	this card must be repeated NUCL times	
	I	identification number of nuclide (I=1,NUCL)
	NUCN(I)	name of nuclide (A5, use single quote '#####')
	NNZ(I)	atomic number
	NNA(I)	mass number
	NNI(I)	indicator for nuclear isomer, =0:ground state, =1:excited state
	HLF(I)	half-life (yr)
	NP(I)	number of parent nuclides (when ICFG .NE. 0)
8	this card must be repeated NP(I) times	
	IP	identification number of parent nuclide
	BRN	transfer rate from parent (IP) to daughter (I) nuclide
9	this card must be repeated NUCL times	
	RCYL(I)	recovery rate of nuclide (-), (I=1,NUCL)
	DISP(I)	volatilization rate of nuclide (-)
10	this card is necessary when INFL=0	
	Y0(I) I=1,NUCL	initial inventories of nuclides (atom)

A-1.2 Input data for source term model

Card	entry	contents
1	TITLE	title name of job
2	MODEL	flag for model selection, =1: model-1, =2:model-2
	NUCL	number of nuclides
	IUNIT	flag of units (IUNIT=I3x100+I2x10+I1) I1:unit of output, (0:atom/yr, 1:Bq/yr, 2:Ci/yr, 3:g/yr, 4:mol/yr) I2:unit of waste form (model-1) or solubility (model-2), (1:Bq/kg, 2:Ci/kg, 3:g/kg, 4:mol/kg, for model-1 0:atom/kg) (1:Bq/kl, 2:Ci/kl, 3:g/kl, 4:mol/kl, for model-2 0:atom/kl) I3:unit of waste form (model-2) (1:Bq, 2:Ci, 3:g, 4:mol, 0:atom)
	ITIM	number of time data for output
	IPRINT	same as ORIGEN-II interface code
	IFILF	same as ORIGEN-II interface code
	IFILB	same as ORIGEN-II interface code
	IIPT	input flag, =0:file (output file of ORIGEN-II interface code), =1:card input
3	TIM(I) I=1,ITIM	time changing time step
4	IDL(I) I=1,ITIM	number of time steps between TIM(I-1) and TIM(I)
5	THICK	thickness of buffer material (m)
Cards 6 to 7 are only used for model-1 simulations		
6	RHO	density of waste form (kg/kl)
	DIFSIL	diffusion coefficient of Silica
	SLICA	solubility of Silica
	ISHP	shape of waste form, =1:sphere, =2:cylinder, =3:prolate spheroid
7	RADIUS	initial radius (ISHP=1, 2), initial semi-major axis (ISHP=3)
	RADB	none (ISHP=1), height (ISHP=2), semi-minor axis (ISHP=3)
Cards 8 to 13 are only used for model-2 simulations		
8	PROSTY	porosity of buffer material
	RADIUS	radius of sphere (m)
9	NTBLT(I) I=1,NUCL	number of time data for solubility

Card	entry	contents
10		these cards (set of 2 cards) must be repeated NUCL times (I=1,NUCL)
10-a	BTIM(J,I)	time changing solubility of nuclide no.I (J=1,NTBLT(I))
10-b	BLT(J,I)	solubility of chemical form of nuclide no. I (J=1,NTBLT(I))
11	NDATI	number of time data for the estimation of leaching time
	ICHI(I) I=1,NUCL	flag of method, =0:estimated from correspond nuclide, =1:estimated from correspond nuclide and its daughter nuclides
12	TIMI(I) I=1,NDATI	time changing time step
13	IDLI(I) I=1,NDATI	number of time steps between TIMI(I-1) and TIMI(I)
Cards 14 to 16 are only used for simulation based on in-core process or file input		
14	INUC	nuclide no. of parent nuclide in a decay chain (output of ORIGIN I/F code). If several decay chains are simulated in I/F code, last decay chain is used for simulation of in-core process, and first decay chain is used for file input. INUC=0:new decay chain will be setup.
15	CTIME	life-time of container (yr)
16		this card must be repeated NUCL times (only INUC>0)
	II	nuclide no.
	DIFF(I)	diffusion coefficient of nuclide II in the buffer material
	RET(I)	retardation factor of nuclide II in the buffer material
17		this card must be repeated NUCL times (only INUC=0)
	NCLIDE	nuclide no.
	HLIFE	half-life of nuclide (yr)
	DIF	diffusion coefficient of nuclide in the buffer material
	RET	retardation factor of nuclide in the buffer material
Cards 18 to 19 are only used for simulation based on card input		
18	NCLIDE	name of nuclide (A5)
	NNA	mass number
	HLIFE	half-life of nuclide
	DIF	diffusion coefficient of nuclide in the buffer material
	RET	retardation factor of nuclide in the buffer material
19	QIN(I) I=1,NUCL	nuclide concentration (model-1) or nuclide inventory (model-2) in the waste form

A-1.3 Input data for 3D-dispersion and 1D-dispersion geosphere models (user must make 2 files)

Card	entry	contents
1	TITLE	title name of job
2	NUCLI	number of nuclides
	IUNIT	flag of units (IUNIT=I2x10+I1) I1:unit of output, (0:atom/kl, 1:Bq/kl, 2:Ci/kl, 3:g/kl, 4:mol/kl) I2:unit of boundary condition (card input) (1:Bq/kl or Bq/yr, 2:Ci/kl or Ci/yr, 3:g/kl or g/yr, 4:mol/kl or mol/yr, 0 or blank:atom/kl or atom/yr)
	ITIM	number of time data for output
	IPRINT	same as ORIGEN-II interface code
	IFILF	same as ORIGEN-II interface code
	IFILB	same as ORIGEN-II interface code
	IIPT	input flag, =0:file (output file of source term code), =1:card input
3	TIM(I) I=1,ITIM	time changing time step
4	IDL(I) I=1,ITIM	number of time steps between TIM(I-1) and TIM(I)
Cards 5 to 9 are only used for 3D-dispersion model		
5	NSOU	number of point sources
	NPIP	number of 1D-pipes
6	this card must be repeated NSOU times (I=1,NSOU)	
	X0(I)	x-coordinate of point source
	Y0(I)	y-coordinate of point source
	Z0(I)	z-coordinate of point source
7	this card must be repeated NPIP times (I=1,NPIP)	
	X1(I)	x-coordinate of place combining 3D and 1D model
	Y1(I)	y-coordinate of place combining 3D and 1D model
8	RR	size of homogeneous rock (z-direction)
	VV	groundwater velocity in the homogeneous rock
	DX	dispersion coefficient in the x-direction
	DY	dispersion coefficient in the y-direction
	DZ	dispersion coefficient in the z-direction
9	RETA(I) I=1,NUCL	retardation factor of nuclide

Card	entry	contents
Cards 10 to 12 are only used for 1D dispersion model, and this set of cards must be repeated NPIP times (I=1,NPIP)		
10	IBC(I)	flag of inlet boundary condition for 1D model, =0:concentration boundary, =1:flux boundary
11	RR(I)	length of 1D-pipe
	VV(I)	groundwater velocity in the 1D-pipe
	DZ(I)	dispersion coefficient in the 1D-pipe
12	RETA(J,I) J=1,NUCL	retardation factor of nuclide
13	INUC(I)	nuclide no. of parent nuclide in a decay chain; nuclide no. was defined by previous step (output of source term or 3D model)
Cards 14 to 16 are only used for simulation based on card input		
14	this card must be repeated NUCL I	
	NUCN	name of nuclide
	NNA	mass number
	HLIFE	half-life of nuclide
15	ITSS	number of sets of boundary condition
16	this card must be repeated ITSS times	
	TSOU(I) I=1,ITSS	time changing nuclide flux or nuclide concentration
	CSOU(I,J) J=1,NUCL I=1,ITSS	nuclide flux or nuclide concentration corresponds to TSOU(I)

A-1.4 Input data for finite difference method calculations (source term and geosphere models)

Card	entry	contents
1	NREG	number of regions
	INTER	method flag of interpolation with respect to inlet B.C. =0:linear interpolation, =1:step (use previous value), =2:step (use later value)
	IBR	flag for outlet B.C. =0:concentration=0, =1:gradient of concentration=0
2	DDD	flag for time step, <0:EPST= DDD (automatic set up), $\frac{u^2 \Delta t}{2\phi K_i D} = \text{EPST}$ =0:EPST=0.5 (automatic set up), >0:time step (yr)
	BETA	flag for treatment of radioactive equilibrium, <0:use approximate solution (set BETA=1), $C_i \approx \frac{\lambda_{i-1} K_{i-1}}{\lambda_i K_i} C_{i-1}$ =0:do not use approximate solution, >0:use approximate solution
	LDMOD	flag for modification of decay constant (this treatment is used for a case that half-life of nuclide is nearly equal to the time step), =0:without modification, $(e^{\lambda \Delta t} - 1) / \Delta t \rightarrow \lambda'$ =1:modify
3	this card must be repeated NREG times (I=1,NREG)	
	RRR(I)	flag for region size, <0:(region size)=(pass length)x RRR , =0:(region size)=(pass length), >0:enter region size (pass length is set by the other input data)
	IFRG(I)	flag for spatial mesh size of region I, <0:automatic set up of mesh (use EPSX parameter), =0:number of mesh is defined, >0:mesh size is defined
	AMS(J,I) J=1,NUCL	parameters corresponding to IFRG, IFRG<0 and AMS>0:EPSX=AMS, $\frac{u \Delta x}{2D} = \text{EPSX}$ IFRG<0 and AMS<=0:EPSX=0.5, IFRG=0:AMS=number of mesh, IFRG>0:AMS=mesh size
Cards 4 to 6 are only necessary when NREG>1, (sets of cards 5 and 6 must be repeated NREG-1 times)		
4	PHI(I) I=1,NREG	porosity of region I (-)
5	DIF(J,I) J=1,NUCL	dispersion or diffusion coefficient of nuclide J in the region I
6	RET(J,I) J=1, NUCL	retardation factor of nuclide J in the region I

A-1.5 Input data for biosphere model

Card	entry	contents
1	JPLOT	job flag, =0:calculation only, >0:calculation and plotting, <0:plotting only
	INCOME	source term for biosphere model, =0:output of geosphere model (use card 10), else:user input (use cards 4~9)
	NUCL	number of nuclides for simulation, INCOME<0 and NUCL<0:number of nuclides is same as that of geosphere model
	ITMAX	number of time data for simulation
2	this card must be repeated ITMAX times (I=1, ITMAX)	
	DSTEP(I)	time step between TSTEP(I-1) and TSTEP(I)
	TSTEP(I)	time changing time step
	LPSTEP(I)	output interval for line-printer = every DSTEP(I)*LPSTEP(I)
	IFSTEP(I)	output interval for file-output = every DSTEP(I)*IFSTEP(I)
3	LPCMP	flag for printing of the inventory or concentration of nuclides in the compartments, LPCMP.NE.0: print out
	IFCMP	flag for file-output of the inventory or concentration of nuclides in the compartments, IFCMP.NE.0: file-output
	LPDI	flag for printing of individual dose from each pathway and anual dose, LPDI.NE.0: print out
	IFDI	flag for file-output of individual dose from each pathway and anual dose, LPDI.NE.0: file-output
	LPDC	flag for printing of collective dose from each pathway and anual dose, LPDI.NE.0: print out
	IFDC	flag for file-output of collective dose from each pathway and anual dose, LPDI.NE.0: file-output
Cards 4~9 are necessary when INCOME .NE. 0		
4	this card must be repeated NUCL times (I=1,NUCL)	
	NCLIDE(I)	name of nuclide (A5, use single quote '#####')
5	TRELI1	initial time of release
	TENDI1	final time of release
	CONCI1(I) I=1,NUCL	flux (Bq/yr) or concentration (Bq/kl) of nuclide flow into the groundwater
	FLUXI1(I) I=1,NUCL	flux of contaminated water flow into the groundwater, FLUXI1(I) <0:CONCI1(I) is nuclide flux

Card	entry	contents
6	TRELI2	initial time of release
	TENDI2	final time of release
	CONCI2(I) I=1,NUCL	flux (Bq/yr) or concentration (Bq/kl) of nuclide flow into the upstream of river
	FLUXI2(I) I=1,NUCL	flux of contaminated water flow into the upstream of river, FLUXI1(I) < 0: CONCI1(I) is nuclide flux
7	TRELI3	initial time of release
	TENDI3	final time of release
	CONCI3(I) I=1,NUCL	flux (Bq/yr) or concentration (Bq/kl) of nuclide flow into the lake or marsh
	FLUXI3(I) I=1,NUCL	flux of contaminated water flow into the lake or marsh, FLUXI1(I) < 0: CONCI1(I) is nuclide flux
8	TRELI4	initial time of release
	TENDI4	final time of release
	CONCI4(I) I=1,NUCL	flux (Bq/yr) or concentration (Bq/kl) of nuclide flow into the downstream of river
	FLUXI4(I) I=1,NUCL	flux of contaminated water flow into the downstream of river, FLUXI1(I) < 0: CONCI1(I) is nuclide flux
9	TRELI5	initial time of release
	TENDI5	final time of release
	CONCI5(I) I=1,NUCL	flux (Bq/yr) or concentration (Bq/kl) of nuclide flow into the estuary and adjacent sea
	FLUXI5(I) I=1,NUCL	flux of contaminated water flow into the estuary and adjacent sea, FLUXI1(I) < 0: CONCI1(I) is nuclide flux
10	this card is necessary when INCOME=0	
	NPIPI1	number of pipes of geosphere model flow into aquifer
	NPIPI2	number of pipes of geosphere model flow into upstream of river
	NPIPI3	number of pipes of geosphere model flow into lake or marsh
	NPIPI4	number of pipes of geosphere model flow into downstream of river
	NPIPI5	number of pipes of geosphere model flow into estuary and adjacent sea

Card	entry	contents
11	PPI1IW	intake rate from contaminated groundwater for irrigation (kl/yr)
	PPR1IW	intake rate from upstream of river for irrigation (kl/yr)
	PPR2IW	intake rate from downstream of river for irrigation (kl/yr)
	PPLKIW	intake rate from lake or marsh for irrigation (kl/yr)
12	PPI1DW	intake rate from contaminated groundwater for drinking water (kl/yr)
	PPR1DW	intake rate from upstream of river for drinking water (kl/yr)
	PPR2DW	intake rate from downstream of river for drinking water (kl/yr)
	PPLKDW	intake rate from lake or marsh for drinking water (kl/yr)
13	WFI2R1	inflow rate of contaminated groundwater into upstream of river (kl/yr) (this variable will be neglected when inflow of nuclide is flux)
	WFFWR1	inflow rate of uncontaminated water into upstream of river (kl/yr)
	WFR1LK	outflow rate of water from upstream of river into lake or marsh (kl/yr)
14	WFI3LK	inflow rate of contaminated groundwater into lake or marsh (kl/yr) (this variable will be neglected when inflow of nuclide is flux)
	WFFWLK	inflow rate of uncontaminated water into lake or marsh (kl/yr)
	WFLKR2	outflow rate of water from lake or marsh into downstream of river (kl/yr)
15	ARLK	area of lake or marsh (m**2)
	DHLK	average depth of lake or marsh (m)
	DPSED1	effective thickness of sediment (m)
	RHOLK	density of sediment (kg/kl) (POROLK<0:bulk density, POROLK>0:real density)
	POROLK	porosity of sediment (-) (<0:this value will be ignored)
16	ALKSS	concentration of particles in lake or marsh (kg/kl)
	RTLKSS	velocity of sedimentation (kg/yr/m**2)

Card	entry	contents
17	this card must be repeated NUCL times (I=1,NUCL)	
	AKDLK(I)	distribution coefficient of nuclide I in sedimenting particles (ml/g) (lake or marsh)
	AKDSD1(I)	distribution coefficient of nuclide I in sediment (ml/g)
	DFLK(I)	diffusion coefficient of nuclide I in water (cm**2/s)
	DFSED1(I)	diffusion coefficient of nuclide I in sediment (cm**2/s)
18	WFI4R2	inflow rate of contaminated groundwater into downstream of river (kl/yr) (this variable will be neglected when inflow of nuclide is flux)
	WFFWR2	inflow rate of uncontaminated water into downstream of river (kl/yr)
	WFLKS1	outflow rate of water from downstream of river into estuary and adjacent sea (kl/yr)
19	WFI5S1	inflow rate of contaminated groundwater into estuary and adjacent sea (kl/yr) (this variable will be neglected when inflow of nuclide is flux)
	WFFWS1	inflow rate of uncontaminated water into estuary and adjacent sea (kl/yr)
	WFS1S2	outflow rate of water from estuary and adjacent sea into open sea (kl/yr)
20	ARS1	area of estuary and adjacent sea (m**2)
	DHS1	average depth of estuary and adjacent sea (m)
	DPSED2	effective thickness of sediment (m)
	RHOS1	density of sediment (kg/kl) (POROS1< 0:bulk density, POROS1> 0:real density)
	POROS1	porosity of sediment (-) (< 0:this value will be ignored)
21	AS1SS	concentration of particles in estuary and adjacent sea (kg/kl)
	RTS1SS	velocity of sedimentation (kg/yr/m**2)
22	this card must be repeated NUCL times (I=1,NUCL)	
	AKDS1(I)	distribution coefficient of nuclide I in sedimenting particles (ml/g) (estuary and adjacent sea)
	AKDSD2(I)	distribution coefficient of nuclide I in sediment (ml/g)
	DFS1(I)	diffusion coefficient of nuclide I in water (cm**2/s)
	DFSED2(I)	diffusion coefficient of nuclide I in sediment (cm**2/s)

Card	entry	contents
23	this card must be repeated 3 times (I=1,3) I=1:paddy field, I=2:farm, I=3:grassland	
	RHOAS(I)	density of soil in arable land I (kg/kl) (POROAS < 0:bulk density, POROAS > 0:real density)
	POROAS(I)	porosity of soil in arable land I (-)
	DEPAS(I)	depth of cultivation in arable land I (m)
	AREAS(I)	area of arable land I (m**2)
24	this card must be repeated NUCL times (I=1,NUCL)	
	AKAS1(I)	distribution coefficient of nuclide I in soil of paddy field (ml/g)
	AKAS2(I)	distribution coefficient of nuclide I in soil of farm (ml/g)
	AKAS3(I)	distribution coefficient of nuclide I in soil of grassland (ml/g)
25	PRAIN	rainfall rate in arable land (mm/yr)
	PEVAP	evaporation rate in arable land (mm/yr)
	PPRUN	run-off factor in arable land (-)
26	RHODS	density of deep soil (kg/kl) (PORODS< 0:bulk density, PORODS> 0:real density)
	PORODS	porosity of deep soil (-) (< 0:this value will be ignored)
	DEPDS	effective thickness of deep soil (m)
27	PD(I) I=1,NUCL	half-life of radionuclide I (yr)

Card	entry	contents
28	this card must be repeated NUCL times (I=1,NUCL)	
	VDEP(I)	deposition velocity of nuclide I (m/day)
	WEATH(I)	removal rate of nuclide I for physical loss by weathering (1/day)
29	PDPT	agricultural productivity of grass (kg/m**2)
	PDCR	agricultural productivity of crops (kg/m**2)
	PDVT	agricultural productivity of vegetables (kg/m**2)
30	PAPT	areal ratio of grassland to arable land (-)
	PACR	areal ratio of crops field to arable land (-)
	PAVT	areal ratio of vegetables field to arable land (-)
31	PIPT	irrigation rate to grassland (m/yr)
	PICR	irrigation rate to crops field (m/yr)
	PIVT	irrigation rate to vegetables field (m/yr)
32	this card must be repeated NUCL times (I=1,NUCL)	
	PPPT(I)	fraction of deposited radioactivity retained on the vegetation from irrigation water (-) (grass)
	PPCR(I)	fraction of deposited radioactivity retained on the vegetation from irrigation water (-) (crops)
	PPVT(I)	fraction of deposited radioactivity retained on the vegetation from irrigation water (-) (vegetables)
33	this card must be repeated NUCL times (I=1,NUCL)	
	TRNSL(I,1)	translocation factor of externally deposited nuclides to the edible parts of vegetation (-) (crops)
	TRNSL(I,2)	translocation factor of externally deposited nuclides to the edible parts of vegetation (-) (vegetables)
	TRNSL(I,3)	translocation factor of externally deposited nuclides to the edible parts of vegetation (-) (grass)
34	this card must be repeated NUCL times (I=1,NUCL)	
	CFPT(I)	concentration factor for uptake of radionuclides from soil by edible portion of grass (-)
	CFCR(I)	concentration factor for uptake of radionuclides from soil by edible portion of crops (-)
	CFVT(I)	concentration factor for uptake of radionuclides from soil by edible portion of vegetables (-)
35	this card must be repeated 3 times (I=1,3) (1:crops, 2:vegetables, 3:grass)	
	GRWTH(I)	time period that vegetation I is exposed to contamination during growing season (day)
	CNSUM(I)	time interval between harvest and consumption of vegetation I (day)

Card	entry	contents
36	WFIWCD	intake rate of drinking water for animals from irrigation water (kl/yr)
	WFTWCD	intake rate of drinking water for animals from drinking water (kl/yr)
37	this card must be repeated NUCL times (I=1,NUCL)	
	FFMT(I)	fraction of animal's intake of radionuclide that appears in each kg of meat at equilibrium (day/kg)
	FFEG(I)	fraction of animal's intake of radionuclide that appears in each kg of egg at equilibrium (day/kg)
	FFMK(I)	fraction of animal's intake of radionuclide that appears in each litre of milk at equilibrium (day/l)
38	RFMT	amount of feed consumed by meat animals per year (kg/yr)
	RFEG	amount of feed consumed by chicken per year (kg/yr)
	RFMK	amount of feed consumed by milch cow per year (kg/yr)
39	PIPT	amount of water consumed by meat animals per year (kl/yr)
	PICR	amount of water consumed by chicken per year (kl/yr)
	PIVT	amount of water consumed by milch cow per year (kl/yr)
40	RDMT	production rate of meat per unit feed (-)
	RDEG	production rate of egg per unit feed (-)
	RDMK	production rate of milk per unit feed (-)
41	this card must be repeated NUCL times (I=1,NUCL)	
	TFFW(I,1)	bioaccumulation factor of nuclide I to fresh-water fish (l/kg)
	TFFW(I,2)	bioaccumulation factor of nuclide I to fresh-water invertebrate (l/kg)
	TFSW(I,1)	bioaccumulation factor of nuclide I to sea-water fish (l/kg)
	TFSW(I,2)	bioaccumulation factor of nuclide I to sea-water invertebrate (l/kg)
	TFSW(I,3)	bioaccumulation factor of nuclide I to seaweeds (l/kg)
42	PDF1	haul of aquatic food from upstream of river (kg/yr)
	PDF2	haul of aquatic food from downstream of river (kg/yr)
	PDFL	haul of aquatic food from lake or marsh (kg/yr)
	PDFS	haul of aquatic food from estuary and adjacent sea (kg/yr)

Card	entry	contents
43	RMTW(I) I=1,NUCL	removal rate of nuclide I in filtration plant of drinking water (-)
44	JHTW	annual consumption of drinking water (kl/yr)
	JHFP	annual consumption of fresh-water food (kg/yr)
	JHFS	annual consumption of sea-water food (kg/yr)
	JHCR	annual consumption of crops (kg/yr)
	JHVT	annual consumption of vegetables (kg/yr)
	JHMT	annual consumption of meat (kg/yr)
	JHEG	annual consumption of egg (kg/yr)
	JHMK	annual consumption of milk (kl/yr)
45	PWTW	amount of contaminated water release to biosphere per year (kl/yr)
46	RTF1	ratio of fresh-water products from upstream of river to total fresh-water products (-)
	RTF2	ratio of fresh-water products from downstream of river to total fresh-water products (-)
	RTFL	ratio of fresh-water products from lake or marsh to total fresh-water products (-)
47	FMSLD(1)	mass-loading factor in grass lands (g/kl)
	FMSLD(2)	mass-loading factor in paddy fields (g/kl)
	FMSLD(3)	mass-loading factor in farms (g/kl)
48	VENT	breathing rate of man (kl/hr)
	WORKH(1)	annual working hours in grass lands (hr/yr)
	WORKH(2)	annual working hours in paddy fields (hr/yr)
	WORKH(3)	annual working hours in farms (hr/yr)
49	this card must be repeated NUCL times (I=1,NUCL)	
	DFIG(I)	dose conversion factor for ingestion (Sv/Bq)
	DFIH(I)	dose conversion factor for inhalation (Sv/Bq)
	DFAS(I)	external dose conversion factor (Sv Kg/Bq/hr)

Appendix-2 Concentration factors for uptake of radionuclides from soil by edible portion of crops

Element	Soil to plant (unit:kg·wet/kg)	Element	Soil to plant (unit:kg·wet/kg)
C	1.0E-3	Tl	0.25
Se	1	Pb	1E-2
Sr	0.3	Bi	0.1
Zr	5E-3	Po	2E-4
Nb	1E-2	Ra	4E-2
Tc	5	Ac	1E-3
Ru	8E-3	Th	5E-4
Pd	5	Pa	4E-2
Sn	2.5E-3	U	2E-3
Sb	1E-2	Np	4E-2
I	2E-2	Pu	5E-4
Cs	3E-2	Am	1E-3
Pr	2.5E-3	Cm	1E-3
Tb	2.6E-3	Cf	2.5E-3
Hg	0.38		

Appendix-3 Fractions of animal's intake of radionuclides those appear in each kg of meat and egg or each litre of milk at equilibrium

Element	Soil to grass (kg (dry)/kg)	Feed to egg (day/l)	Feed to milk (day/kg)	Feed to beef (day/kg)	Feed to pork (day/kg)	Feed to chicken (day/kg)
C	1.0E-3	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2
Se	1.3	9.3	4.0E-3	1.0	3.2E-1	8.5
Zr	2.0E-2	1.2E-3	3.0E-5	2.0E-2	1.0E-3	1.0E-4
Tc	2.0E-1	1.9	1.0E-2	1.0E-2	9.9E-4	6.3E-2
Pd	5.0	4.0E-3	5.0E-3	1.0E-3	5.0E-3	3.0E-4
Sn	2.5E-3	9.9E-4	1.2E-3	9.9E-4	9.9E-4	9.9E-4
I	9.0E-1	2.8	1.0E-2	1.0E-2	3.3E-3	4.0E-3
Cs	1.0E-1	4.9E-1	8.0E-3	2.0E-2	2.5E-1	4.4
Hg	3.8E-1	9.9E-4	1.9E-2	1.0E-1	3.1	2.7E-2
Tl	2.5E-1					
Pb	9.0E-2	9.9E-4	3.0E-4	8.0E-4	9.9E-4	9.9E-4
Bi	5.0E-1	9.0E-4	5.0E-4	2.0E-2	9.9E-4	9.9E-4
Po	4.0E-3	9.9E-4	1.0E-4	3.0E-3	9.9E-4	9.9E-4
Ra	2.0E-1	2.0E-5	6.0E-4	5.0E-4	9.9E-4	9.9E-4
Ac	4.0E-3	2.0E-3	2.0E-5	2.0E-5	1.0E-2	4.0E-3
Th	1.0E-3	2.0E-3	5.0E-6	1.0E-4	1.0E-2	4.0E-3
Pa	1.0E-1	2.0E-3	5.0E-6	1.0E-3	1.0E-2	4.0E-3
U	1.0E-2	9.9E-1	6.0E-4	3.0E-2	4.0E-2	1.2
Np	1.0E-1	2.0E-3	5.0E-6	1.0E-3	1.0E-2	4.0E-3
Pu	1.0E-3	7.6E-3	1.0E-7	1.0E-5	1.0E-2	1.6E-4
Am	4.0E-3	8.5E-3	4.0E-7	2.0E-5	1.0E-2	1.8E-4
Cm	4.0E-3	2.0E-3	2.0E-5	2.0E-5	1.0E-2	4.0E-3
Cf	2.5E-3	2.0E-3	7.5E-7	5.0E-3	1.0E-2	4.0E-3

Appendix-4 Bioaccumulation factors of nuclides in aquatic products

Element	Marine			Freshwater		
	flora	invertertebrate	fish	flora	invertertebrate	fish
C	1790	1430	1790	4550	9100	4600
Se	1000	1000	4000	1000	167	157
Zr	2000	20	200	1000	667	3.33
Tc	4000	50	10 0	40	5.0	20 0
Pd	2000	2000	10 0	200	3.00	10 0
Sn	100	1000	3000	100	1000	3000
I	4000	50	10	40	400	40 0
Cs	20	20	30 0	80	1000	2000
Hg	1000	33300	1670	1000	100000	1000
Tl	-	15000	10000	-	15000	10000
Pb	1000	1000	300	200	100	300
Bi	-	-	15	-	-	15
Po	2000	20000	2000	2000	20000	50
At	4000	50	10	40	5	15
Rn	1	1	1	1000	1	57.1
Fr	20	20	30	80	100	400
Ra	100	100	50	2500	250	500
Ac	5000	1000	25	5000	1000	255
Th	3000	2000	10000	1500	500	300
Pa	6	10	10	1130	113	11.3
U	68.7	10	10	1000	100	100
Np	6	10	10	1000	4.00	100
Pu	350	100	3.5	350	1.00	4
Am	5000	1000	25	5000	1000	30
Cm	5000	1000	25	5000	1000	25
Bk	5000	1000	25	5000	1000	25
Cf	5000	1000	25	5000	1000	25
Es	60	10	10	1000	100	10
Fm	60	10	10	1000	100	10

Appendix-5 Internal dose conversion factors of radionuclides

Nuclide	Internal dose conversion factor (Sv/Bq)	
	oral	inhalation
Se-79	2.31E-09	2.43E-09
Pd-107	3.74E-11	3.40E-09
Sn-126	4.73E-09	2.32E-08
Cs-135	1.90E-09	1.22E-09
Pb-210	1.36E-06	3.40E-06
Pb-209	5.50E-11	2.40E-11
Pb-211	1.18E-10	2.10E-09
Pb-212	1.09E-08	4.19E-08
Pb-214	1.56E-10	1.80E-09
Bi-210	2.07E-08	4.30E-07
Bi-212	2.68E-10	5.70E-09
Bi-213	1.85E-10	4.50E-09
Bi-214	6.60E-11	1.76E-09
Fr-223	2.34E-09	1.67E-09
Ac-225	2.80E-06	2.13E-06
Ac-227	3.78E-06	1.81E-03
Ac-228	5.81E-10	8.00E-08
Pa-231	2.89E-06	3.44E-04
Pa-233	8.94E-10	2.29E-09
Pa-234	5.58E-10	2.02E-10
Ra-223	1.50E-07	2.00E-06
Ra-224	8.83E-08	7.90E-07
Ra-225	8.14E-08	2.00E-06
Ra-226	3.05E-07	2.13E-06
Ra-228	3.30E-07	1.16E-06

(continued)

Nuclide	Internal dose conversion factor (Sv/Bq)	
	oral	inhalation
Th-227	9.78E-09	4.30E-06
Th-228	1.02E-07	8.30E-05
Th-229	9.40E-07	5.70E-04
Th-230	1.45E-07	8.60E-05
Th-231	3.47E-10	2.21E-10
Th-232	7.40E-07	4.40E-04
Th-234	3.48E-09	8.90E-09
U-233	7.18E-08	3.60E-05
U-234	7.07E-08	3.60E-05
U-235	6.84E-08	3.30E-05
U-236	6.72E-08	3.40E-05
U-237	7.30E-10	8.90E-10
U-238	6.32E-08	3.20E-05
U-240	1.11E-09	5.82E-10
Np-237	3.01E-06	1.29E-04
Np-240	4.60E-11	1.30E-11
Pu-239	9.56E-07	1.14E-04
Pu-240	9.56E-07	1.14E-04
Pu-241	1.80E-08	2.26E-06
Pu-242	9.03E-07	1.09E-04
Pu-244	8.92E-07	1.07E-04
Am-241	9.68E-07	1.17E-04
Cm-245	1.01E-06	1.20E-04
Cm-248	3.62E-06	4.35E-04
Cf-252	2.70E-07	4.01E-05