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THE SAVANNAH RIVER LABORATORY

DOSTOMAN CODE: A COMPARTMENTAL PATHWAYS COMPUTER MODEL OF CONTAMINANT TRANSPORT

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SUMMARY

The Savannah River Laboratory DOSTOMAN code has been used since 1978 for environmental pathway analysis of potential migration of radionuclides and hazardous chemicals. The DOSTOMAN work will be reviewed including a summary of historical use of compartmental models, the mathematical basis for the DOSTOMAN code, examples of exact analytical solutions for simple matrices, methods for numerical solution of complex matrices, and mathematical validation/calibration of the SRL code. The review includes the methodology for application to nuclear and hazardous chemical waste disposal, examples of use of the model in contaminant transport and pathway analysis, a user's guide for computer implementation, peer review of the code, and use of DOSTOMAN at other Department of Energy sites.

1.0 INTRODUCTION

Assessing the impact of radioactive and hazardous chemical waste disposal on man is an important problem in environmental science and engineering. An essential part of impact assessment is prediction of the long term transport of material in the environment. However, environmental transport is difficult to predict with precision, especially for time periods extending far into the future. This is because of the complex nature of the environment and environmental transport. Environmental systems are highly heterogeneous and subject to change and environmental transport is governed by a variety of physical, chemical, and biological processes that are difficult to quantify. In spite of these difficulties and uncertainties, transport estimates must be made in order to assess the hazard associated with existing disposal sites or to evaluate the suitability of new ones. For example, federal regulations[1-2] governing the licensing of radioactive waste disposal sites require estimates of long term transport. For low-level waste, predictions are required to 500 years; for high-level waste they are required to 10,000 years. It is reasonable to expect analogous requirements to be established eventually for hazardous chemical waste sites.

One method of predicting transport through complex environmental systems is by compartmental modeling. Developed and used extensively in biological tracer applications,[3-6] the compartmental method has only recently been applied to environmental transport problems.[7-9]

Although not very elegant, compartmental modeling is an extremely practical method for making transport predictions. It is a semi-empirical technique in which complex environmental transport pathways are approximated as a series of discrete, interconnected, homogeneous compartments. An environmental compartment is conceptually analogous to the continuous-flow, stirred-tank reactor (CFSTR) used in chemical engineering reactor modeling. Material accumulation in a CFSTR is dependent on influent flow concentration and various gains and losses within the reactor vessel. An environmental compartment is essentially a CFSTR in which material inputs, material outputs, and reactions are approximated as first-order processes and thus are quantified by first-order rate constants. The rate constants are given the name transfer coefficients and are based either on field data, laboratory data, or theory.

The time rate of change of material inventory in a given compartment is given by a first-order differential equation. A complete compartmental model consists of a series of simultaneous, linear, first-order differential equations. Solution of the set of equations yields compartment inventories as a function of time. Generally, closed-form analytical solutions are possible only for simple systems. For example, systems consisting of compartments in series with unidirectional transport are described by a set of equations identical to those for a radioactive decay chain. Solution of the set of equations yields the Bateman equations.[10]

Systems with only a few compartments and bidirectional transfer, such as those encountered in many biological applications, can be solved analytically using Laplace transforms.[11] A four-compartment system which includes the transport of radioactive daughters of a transuranic nuclide was solved by the eigenvalue technique.[8] For systems containing more than three compartments with either multiple inputs to any given compartment or bidirectional transport, the analytical techniques mentioned above are generally not practical and numerical methods are usually required.[12] One such large system is a 70 compartment model used to estimate long term dose to man due to shallow land burial of radioactive wastes at the Savannah River Plant.[7]

This report will illustrate the mathematical evolution of the compartmental model from small to large systems and provide examples of the use of the compartmental approach in analysis of transport of radionuclide and chemical contaminants.

2.0 THE COMPARTMENTAL MODEL

2.1 Historical Review

Compartmental modeling began in the field of mathematical biology. In the 1930's, isotopic tracers were used to identify metabolic pathways in mammalian systems. As the use of tracers proliferated in the 1940's, experiments were designed to be more quantitative in analyzing biological processes. This led to the use of simple compartmental models in analyzing experimental data. Terminology was also established during this time period and the term "compartment" was first used by Sheppard.[14] A compartment was defined as having "homogeneous contents that are separated by real boundaries or," for radiotracer purposes, "can be generalized so that a substance such as a chemical element can be considered to be in a different state of chemical combination." In the radiotracer literature there is some confusion in the distinction between compartments and metabolic pools. They are treated as the same in some references;[4-6] however, pools can be distinguished as a mixture of compounds that are lumped together due to their kinetic equivalence in the synthesis of biological macromolecules. An example is the lumping together of amino acids for protein synthesis. This distinction, however, only represents a more precise biological terminology and does not have any consequence on the theoretical derivation of compartmental modeling.

The use of compartmental models has extended beyond the realm of the biological radiotracer applications. Of specific interest here are applications involving metabolic and environmental transport of radionuclides. The International Commission on Radiological Protection (ICRP) uses compartmental models to quantify the transport of radionuclides to various body organs due to inhalation (lung model) or ingestion (gastrointestinal model).[15] The ICRP combines transport predictions with radiation dose calculations to establish limits for intakes of radionuclides by nuclear workers. Environmental transport applications include migration and distribution of radionuclides in lakes;[16] the movement of radionuclides in agricultural systems;[18] the transport of radioactive iodine, strontium, and cesium in the forage-cow-milk pathway;[17] and the global cycling of long-lived radionuclides such as ^{3}H, ^{14}C, ^{85}Kr, and ^{131}I.[16] The 70 compartment model used at the Savannah River Plant is based on the forage-cow-milk model developed at Oak Ridge National Laboratory. It is unique, however, due to its incorporation of both environmental and metabolic compartments in a single model and its resulting large size. The model is used to estimate radiation dose to man due to low-level burial operations at the site.

2.2 Theoretical Basis

Environmental compartmental models in use today are based largely on intuition and empiricism. However, a theoretrical foundation for the method can be established from the general mass transport equation.[18] For an incompresible fluid, the equation can be written in the following form:

$$\frac{\partial C(\bar{r},t)}{\partial t} = \Delta.\bar{k}\Delta C(\bar{r},t) - \bar{v}(\bar{r},t).\Delta C(\bar{r},t) + g(\bar{r},t) - l(\bar{r},t), \qquad (2.1)$$

where

$C(\bar{r},t)$ = material concentration,

$\bar{K}$ = material dispersion coefficient including molecular and turbulent diffusion,

g = material generation rate per unit volume,

l = material loss rate per unit volume.

Integrating over the volume of a compartment yields

$$\int_V \frac{\partial C(\bar{r},t)}{\partial t}\,dV = \int_V \nabla.\bar{K}\nabla C(\bar{r},t)dV - \int_V \nabla.\bar{v}C(\bar{r},t)dV + \int_V g(\bar{r},t)dV - \int_V l(r,t)dV \quad . \qquad (2.2)$$

Applying the divergence theorem to the second term on the right hand side gives:

$$-\int_V \nabla.\bar{v}C(\bar{r},t)dV = -\oint_A C(\bar{r},t)\bar{v}.d\bar{A} \quad . \qquad (2.3)$$

A compartment, by definition, is homogeneous and is defined such that flows in and out are discrete. Thus, Equation 2.3 can be written as:

$$-\oint_A C(\bar{r},t)\bar{v}.d\bar{A} = \sum_j C(t)_j F_j - \sum_i C(t)F_i \quad , \qquad (2.4)$$

where

C_j = inlet flow concentration,

C = the compartment concentration,

F_i and F_j = volumetric flow rates into and out of the compartment.

The remaining terms can be simplified by noting that $C(\bar{r},t) = 0$ and by defining the following:

$$g(t) = \int_V g(\bar{r},t)dV \quad , \tag{2.5}$$

$$l(t) = \int_V l(\bar{r},t)dV \quad . \tag{2.6}$$

The compartmental transport equation (Equation 2.2) thus takes the form,

$$V\frac{dC(t)}{dt} = \sum_j C_j(t)F_j - \sum_i C(t)F_i + g(t)V - l(t)V. \tag{2.7}$$

For radionuclides, it is convenient to let $Q = CV$ be the total activity in a compartment, $g = 0$, and $l = \lambda Q$. Thus Equation 2.7 can be written as

$$\frac{dQ}{dt} = \sum_j Q_j F_j/V_j - \sum_i QF_i/V - \lambda Q \quad , \tag{2.8}$$

where λ is the radionuclide decay constant.

Data on the flow rate associated with material transport, F, is generally not available. However, by noting that F/V can be interpreted physically as the fraction of material transferred per unit time, Equation 2.8 can be written as

$$\frac{dQ}{dt} = \sum_j \gamma_j Q_j - \sum_i \gamma_i Q - \lambda Q \quad , \tag{2.9}$$

where γ_j is a first-order rate constant for the transport of material from compartment j to compartment i. The first-order rate constants (also referred to as transfer coefficients) quantify the kinetics of material transfer from one compartment to another.

Equation 2.9 can be generalized for N compartments as follows:

$$\frac{dQ_n}{dt} = \sum_{m=1}^{N} \gamma_{n,m} Q_m - \sum_{m=1}^{N} \gamma_{m,n} Q_n - \lambda Q_n \quad , \tag{2.10}$$

where Q_n represents the amount of material in compartment n and Q_m represents the amount of material in compartment m. The transfer coefficient for movement of material to compartment n from compartment m is $\gamma_{n,m}$ and, similarly, the tranfer coefficient for movement to compartment m from compartment n is $\gamma_{m,n}$. The units for the transfer coefficients are inverse time.

At this point the model has become empirical since it is often not possible to obtain field or laboratory data on material transfer in terms of volumetric flows and compartmental volumes. In addition, some transfer processes, such as adsorption, may not be associated with fluid flow. It is obvious that the validity of a compartmental transport model depends largely upon the transfer coefficients and their ability to approximate material transport. Presented in Appendix A are some specific examples of equations for calculating transfer coefficients in the SRP model.

2.3 Examples of Compartmental Models

Before beginning the somewhat abstract topic of solution methods for compartmental models, it is worthwhile to illustrate the modeling approach with some actual examples. The two examples presented below are for transport of radionuclides from low-level waste burial sites at the Savannah River Plant.[19]

The compartmental model illustrated in Figure 2.1 is used to predict dose to man through possible drinking water pathways. In this model, buried waste material comprises the original compartment for radionuclides. When radionuclides leak or are leached out

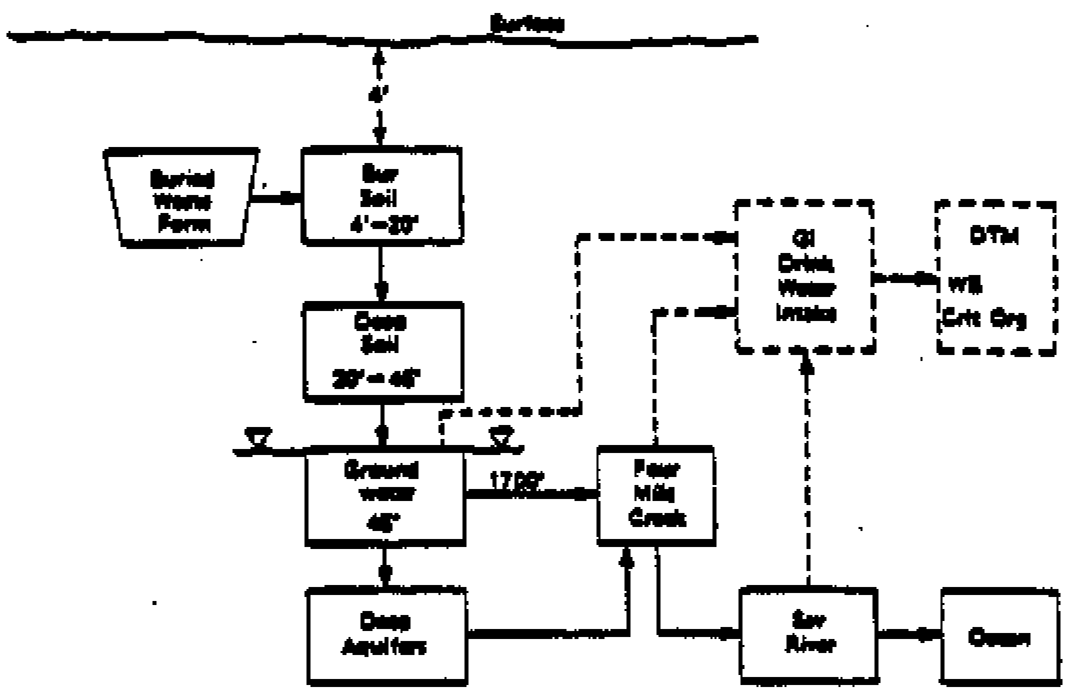


Figure 2.1. Compartmental Model for Transport of Material from a Burial Site (19)

of the buried material, they enter the buried soil compartment. This compartment is defined as the soil zone extending from a depth of 4 feet to 20 feet. Next is the deep soil compartment, defined as the soil zone extending from a depth of 20 feet to 45 feet, which is the groundwater depth. Both of these soil zones can be further compartmentalized to provide a model with greater spatial resolution. From the deep soil compartment, radionuclides enter the groundwater compartment. There are three possible routes for transfer out of the groundwater compartment: uptake by man as drinking water, outcropping into Four Mile Creek, or transfer to a deep aquifer. From the deep aquifer compartment, transfer is to the Four Mile Creek compartment, from which there is transfer either to man or to the Savannah River. From the Savannah River, transfer is either to man or to the ocean. This model is used to predict transport over the near term, i.e., for time periods, on the order of 10-50 years. For this time frame, the hydrologic pathways are the most significant.

For time periods on the order of 100-500 years, atmospheric and terrestrial foodchain pathways can be important. For example, vegetation can be included in either of two compartments, one for deep rooted plants and one for shallow rooted plants. Transport to these compartments results from direct root uptake or airborne and irrigation deposition. In turn, a herbivore consumes a quantity of this vegetation or drinks from a contaminated stream. Therefore, various internal organs of the herbivore are represented as compartments which eventually may be consumed by man. It is obvious that this particular environmental system can become rather complex. Presented in Figure 2.2 is the 70 compartment model used to estimate the long term dose to man following decommissioning of the SRP burial grounds. This model represents a specific scenario in which a limited population occupies land currently used for burial of low level radioactive waste materials.

This document presents the details of the evolution of the 70 compartment model and its use in analysis and management of nuclear and chemical waste.

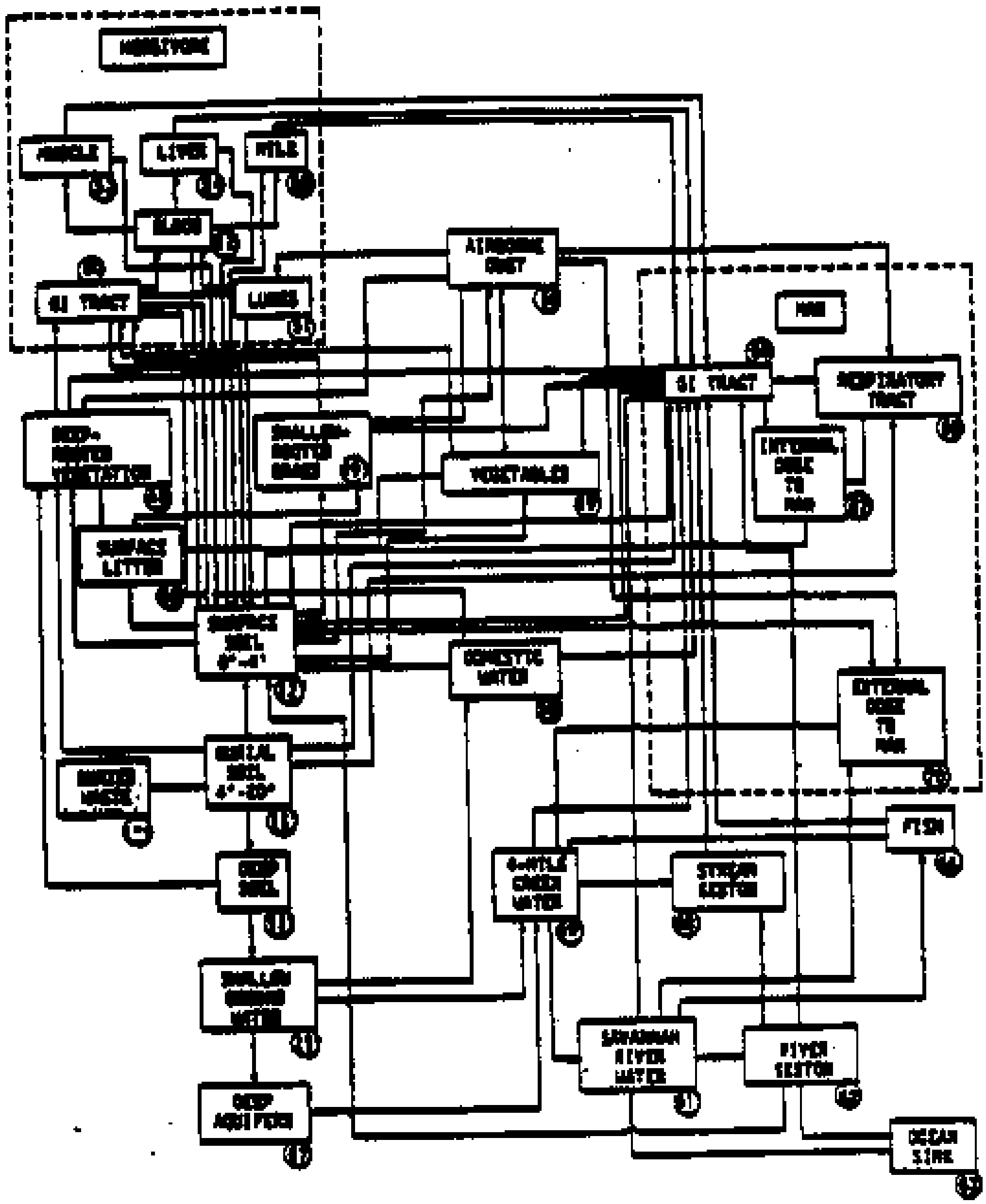


Figure 2.2. Schematic of a Complex Environmental Transport System (19)

3.0 SOLUTION TECHNIQUES

Simple compartmental models consisting of less than four compartments or involving unidirectional transport between compartments can generally be solved by standard analytical techniques such as substitution or Laplace transforms. However, these straightforward approaches are either not applicable or impractical for large, complex systems; and numerical methods, such as finite difference, or alternate analytical methods, such as the matrix analytical technique, are necessary. Presented first in this chapter are closed-form analytical solutions for three simple systems. These solutions are used to verify the mathematical accuracy of the finite difference and matrix analytical solutions. Presented next is the finite difference technique as applied to compartmental models. Finally, the matrix analytical technique is detailed.

3.1 Solutions for Simple Systems

Closed-form analytical solutions are given for three simple compartmental models. The first consists of five compartments with unidirectional transport, the second contains four compartments with branching, and the third has three compartments with bidirectional transport.

A five compartment model with unidirectional transport is illustrated in Figure 3.1. This system is analogous to the successive decay of the members of a radioactive series. The solution to the set of differential equations which describe

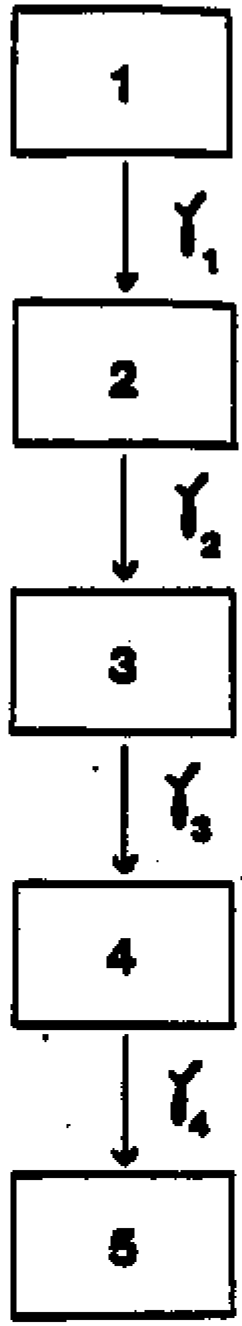


Figure 3.1. Five Compartment Model with Unidirectional Transport

differential equations which describe successive decay is the general Bateman equation (10). The solution is obtained in a straightforward manner by successive substitution. This involves solving the first differential equation, substituting the result into the second equation, solving the second equation and continuing the process. When applied to compartmental transport, the Bateman equation for calculating the inventory for the nth compartment at time t is

$$Q_n = Q_{10}[h_1 e^{-\gamma_1 t} + h_2 e^{-\gamma_2 t} + \ldots + h_{n-1} e^{-\gamma_{n-1} t} + h_n e^{-\gamma_n t}] \quad (3.1)$$

where

$$h_1 = \frac{\gamma_1}{\gamma_n - \gamma_1} \; \frac{\gamma_2}{\gamma_2 - \gamma_1} \; \frac{\gamma_3}{\gamma_3 - \gamma_1} \cdots \frac{\gamma_{n-1}}{\gamma_{n-1} - \gamma_1} \; ,$$

$$h_2 = \frac{\gamma_1}{\gamma_1 - \gamma_2} \; \frac{\gamma_2}{\gamma_n - \gamma_2} \; \frac{\gamma_3}{\gamma_3 - \gamma_2} \cdots \frac{\gamma_{n-1}}{\gamma_{n-1} - \gamma_2} \; , \qquad \vdots$$

$$h_{n-1} = \frac{\gamma_1}{\gamma_1 - \gamma_{n-1}} \; \frac{\gamma_2}{\gamma_2 - \gamma_{n-1}} \; \frac{\gamma_3}{\gamma_3 - \gamma_{n-1}} \cdots \frac{\gamma_{n-1}}{\gamma_n - \gamma_{n-1}} \; ,$$

$$h_n = \frac{\gamma_1}{\gamma_1 - \gamma_n} \; \frac{\gamma_2}{\gamma_2 - \gamma_n} \; \frac{\gamma_3}{\gamma_3 - \gamma_n} \cdots \frac{\gamma_{n-1}}{\gamma_{n-1} - \gamma_n} \; .$$

Using this equation, the equations for the inventories in compartments one through five are

$$Q_1 = Q_{10} e^{-\gamma_1 t} \; , \quad (3.2)$$

$$Q_2 = Q_{10} \frac{\gamma_1}{\gamma_2 - \gamma_1} (e^{-\gamma_1 t} - e^{-\gamma_2 t}) \quad (3.3)$$

$$Q_3 = Q_{10}\Big(\frac{\gamma_1}{\gamma_1 - \gamma_3} \; \frac{\gamma_2}{\gamma_2 - \gamma_3} e^{-\gamma_3 t} + \frac{\gamma_1}{\gamma_1 - \gamma_2} \; \frac{\gamma_2}{\gamma_3 - \gamma_2} e^{-\gamma_2 t}$$

$$+ \frac{\gamma_1}{\gamma_3 - \gamma_1} \; \frac{\gamma_2}{\gamma_2 - \gamma_1} e^{-\gamma_1 t}\Big) \; . \quad (3.4)$$

$$Q_4 = Q_{10}\Big(\frac{\gamma_1}{\gamma_4 - \gamma_1}\ \frac{\gamma_2}{\gamma_2 - \gamma_1}\ \frac{\gamma_3}{\gamma_3 - \gamma_1}\, e^{-\gamma_1 t}$$

$$+ \frac{\gamma_1}{\gamma_1 - \gamma_2}\ \frac{\gamma_2}{\gamma_4 - \gamma_2}\ \frac{\gamma_3}{\gamma_3 - \gamma_2}\, e^{-\gamma_2 t}$$

$$+ \frac{\gamma_1}{\gamma_1 - \gamma_3}\ \frac{\gamma_2}{\gamma_2 - \gamma_3}\ \frac{\gamma_3}{\gamma_4 - \gamma_3}\, e^{-\gamma_3 t}$$

$$+ \frac{\gamma_1}{\gamma_1 - \gamma_4}\ \frac{\gamma_2}{\gamma_2 - \gamma_4}\ \frac{\gamma_3}{\gamma_3 - \gamma_4}\, e^{-\gamma_4 t}\Big) \ , \tag{3.5}$$

$$Q_5 = Q_{10}\Big(-\frac{\gamma_2}{\gamma_2 - \gamma_1}\ \frac{\gamma_3}{\gamma_3 - \gamma_1}\ \frac{\gamma_4}{\gamma_4 - \gamma_1}\, e^{-\gamma_1 t}$$

$$- \frac{\gamma_1}{\gamma_1 - \gamma_2}\ \frac{\gamma_3}{\gamma_3 - \gamma_2}\ \frac{\gamma_4}{\gamma_4 - \gamma_2}\, e^{-\gamma_2 t}$$

$$- \frac{\gamma_1}{\gamma_1 - \gamma_3}\ \frac{\gamma_2}{\gamma_2 - \gamma_3}\ \frac{\gamma_4}{\gamma_4 - \gamma_3}\, e^{-\gamma_3 t}$$

$$- \frac{\gamma_1}{\gamma_1 - \gamma_4}\ \frac{\gamma_2}{\gamma_2 - \gamma_4}\ \frac{\gamma_3}{\gamma_3 - \gamma_4}\, e^{-\gamma_4 t} + 1\Big) \ . \tag{3.6}$$

A branched four compartment model with unidirectional transfer is presented in Figure 3.2 The set of differential equations describing this system is as follows:

$$\frac{dQ_1}{dt} = -\gamma_1 Q_1 - \gamma_2 Q_1 \ , \tag{3.7}$$

$$\frac{dQ_2}{dt} = \gamma_1 Q_1 - \gamma_3 Q_2 \ , \tag{3.8}$$

$$\frac{dQ_3}{dt} = \gamma_2 Q_1 + \gamma_3 Q_2 - \gamma_4 Q_3 \ , \tag{3.9}$$

$$\frac{dQ_4}{dt} = \gamma_4 Q_3 \ . \tag{3.10}$$

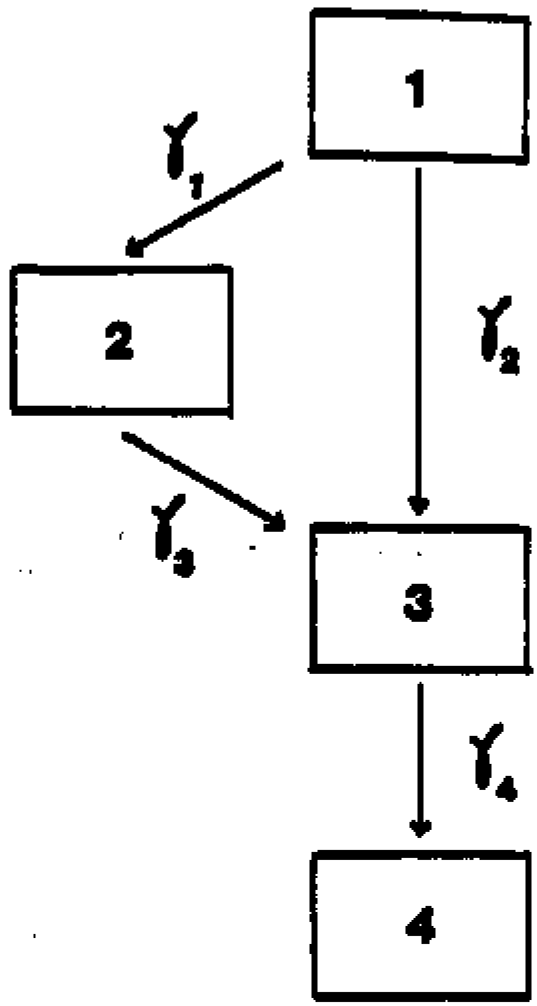


Figure 3.2. Branched, Four Compartment Model with Unidirectional Transport

Solutions to these equations can be obtained by successive substitution. These solutions are

$$Q_1 = Q_{10}e^{-(\gamma_1 - \gamma_2)t} \tag{3.11}$$

$$Q_2 = \frac{\gamma_1}{\gamma_2 - (\gamma_1 + \gamma_2)} Q_{10}(e^{-(\gamma_1 + \gamma_2)t} - e^{-\gamma_3 t}) \quad , \tag{3.12}$$

$$Q_3 = Q_{10}\ [\frac{\gamma_2}{a} e^{-(\gamma_1 + \gamma_2)t} + \frac{\gamma_1}{ab} e^{-(\gamma_1 + \gamma_2)t} - \frac{\gamma_1}{b(\gamma_4 - \gamma_3)} e^{-\gamma_3 t}$$

$$- (\frac{\gamma_2}{a} + \frac{1}{b}(\frac{1}{a} - \frac{1}{(\gamma_4 - \gamma_3)}))e^{-\gamma_4 t}] \quad , \tag{3.13}$$

$$Q_4 = Q_{10}[- \frac{\gamma_2}{a(\gamma_1 + \gamma_2)} e^{-(\gamma_1 + \gamma_2)t} - \frac{\gamma_1}{ab(\gamma_1 + \gamma_2)} e^{-(\gamma_1 + \gamma_2)t}$$

$$+ \frac{\gamma_1}{bc\gamma_3} e^{-\gamma_3 t} + (\frac{\gamma_2}{a} + \frac{\gamma_1}{b}(\frac{1}{a} - \frac{1}{c}))(e^{-\gamma_4 t})/\gamma_4 + \frac{\gamma_2}{a(\gamma_1 + \gamma_2)}$$

$$+ \frac{\gamma_1}{ab(\gamma_1 + \gamma_2)} - \frac{\gamma_1}{bc\gamma_3} - (\frac{\gamma_1}{a} + \frac{\gamma_2}{b}(\frac{1}{a} - \frac{1}{c}))]/\gamma_4 \quad , \tag{3.14}$$

where

$$a = (\gamma_4 - \gamma_2 - \gamma_1),$$

$$b = [1 - \frac{\gamma_1 + \gamma_2}{\gamma_3}],$$

$$c = (\gamma_4 - \gamma_3).$$

The third model consists of three compartments with bidirectional transport between each compartment as illustrated in Figure 3.3. Due to bidirectional transport, solution to this model cannot be obtained by the successive substitution method used for the first two. However, a closed-form solution can be obtained using Laplace transforms (11). The

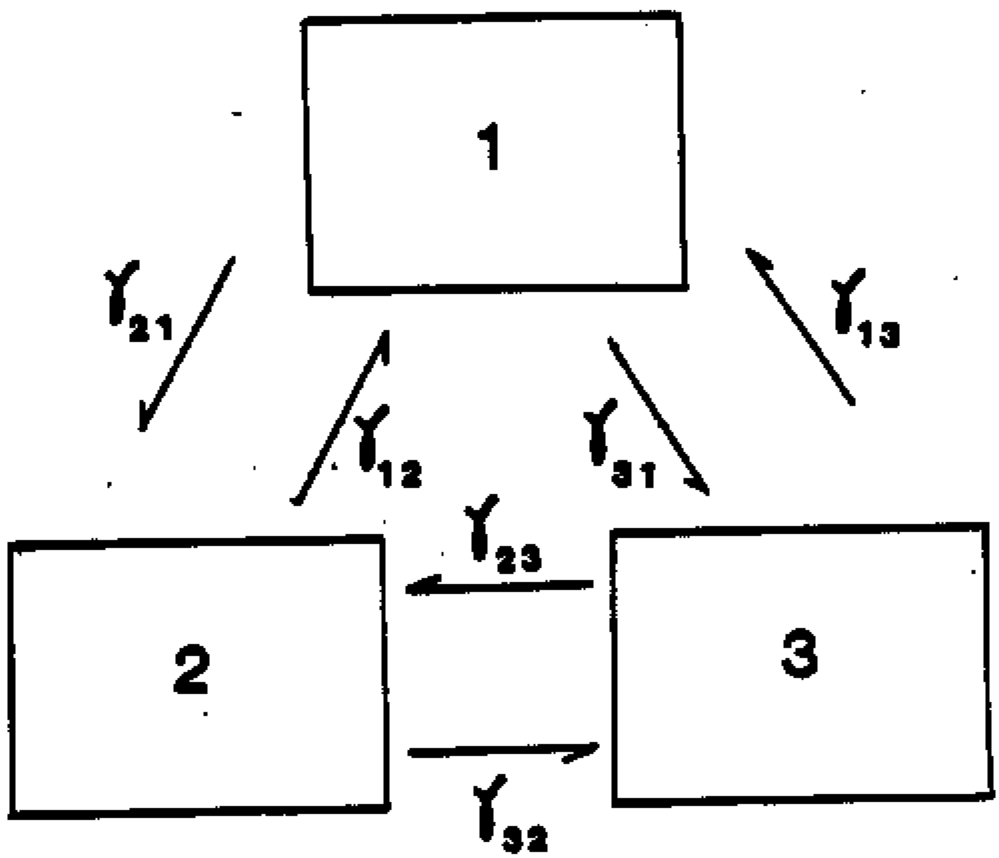


Figure 3.3. Three Compartment Model with Bidirectional Transport

procedure involves taking Laplace transforms of the differential equations, solving the resulting set of algebraic equations by Cramer's Rule, and taking inverse Laplace transforms of the results. The solutions are

$$Q_1 = Q_{10}\left[\frac{f}{xy} + \frac{(x^2 - dx + f)}{x(x - y)}e^{-xt} + \frac{(y^2 - dy + f)}{y(y - x)}e^{-yt}\right] , \qquad (3.15)$$

$$Q_2 = Q_{10}\gamma_{21}\left[\frac{g}{xy} + \frac{(g - x)}{x(x - y)}e^{-xt} + \frac{(g - y)}{y(y - x)}e^{-yt}\right] , \qquad (3.16)$$

$$Q_3 = Q_{10}\gamma_{31}\left[\frac{h}{xy} + \frac{(h - x)}{x(x - y)}e^{-xt} + \frac{(h - y)}{y(y - x)}e^{-yt}\right] , \qquad (3.17)$$

where

$$x = \frac{b - (b^2 - 4c)^{1/2}}{2}$$

$$y = [b + (b^2 - 4c)^{1/2}]/2,$$

$$b = \gamma_{12} + \gamma_{21} + \gamma_{13} + \gamma_{31} + \gamma_{23} + \gamma_{32},$$

$$c = (\gamma_{21} + \gamma_{31})(\gamma_{12} + \gamma_{32}) + (\gamma_{12} + \gamma_{32})(\gamma_{13} + \gamma_{23})$$
$$+ (\gamma_{21} + \gamma_{31})(\gamma_{13} + \gamma_{23}) - \gamma_{13}\gamma_{31} - \gamma_{12}\gamma_{21} - \gamma_{23}\gamma_{32},$$

$$d = \gamma_{12} + \gamma_{32} + \gamma_{13} + \gamma_{23},$$

$$f = (\gamma_{12} + \gamma_{32})(\gamma_{13} + \gamma_{23}) - \gamma_{23}\gamma_{32},$$

$$g = \gamma_{23} + \gamma_{13} + \gamma_{23}\gamma_{31}/\gamma_{21},$$

$$h = \gamma_{12} + \gamma_{32} + \gamma_{21}\gamma_{32}/\gamma_{31}.$$

It is worth noting that the algebra required to obtain the above solution is tedious and complex. Extension of the Laplace transform technique to systems composed of more than three compartments is probably not practical.

The Finite Difference Solution

The generalized differential equation for the time rate of change of material inventory in a compartment (Equation 2.10) can be simplified to an algebraic equation by expressing it in the following finite difference form:

$$\sum_{m=1}^{N} \gamma_{n,m} Q_m - \sum_{m=1}^{N} \gamma_{m,n} Q_n - \lambda Q_n = \frac{Q_n - Q_n^o}{\Delta t} , \qquad (3.18)$$

where

Δt = a specified finite time interval,

Q_n^o = radionuclide inventory in compartment n at the end of a time step,

Q_n = radionuclide inventory in compartment n at the beginning of a time step.

Equation 3.18 can be partially expanded for compartment n = 1 as follows:

$$\gamma_{1,1} Q_1 + \gamma_{1,2} Q_2 + \ldots + \gamma_{1,N} Q_N - Q_1 \sum_{m=1}^{N} \gamma_{m,1} - \lambda Q_N = \frac{Q_1 - Q_1^o}{\Delta t} . \qquad (3.19)$$

Isolating terms containing Q_1 gives

$$[\gamma_{1,1} - \sum_{m=1}^{N} \gamma_{m,1} - \frac{1}{\Delta t} - \lambda] Q_1 + \gamma_{1,2} Q_2 + \ldots + \gamma_{1,N} Q_N = \frac{Q_1^o}{\Delta t} . \qquad (3.20)$$

The expanded equation can be generalized for compartment n as

$$\gamma_{n,1} Q_1 + \ldots + \gamma_{n,n-1} Q_{n-1} + [\gamma_{n,n} - \sum_{m=1}^{N} \gamma_{m,n} - \frac{1}{\Delta t} - \lambda] Q_n$$

$$+ \gamma_{n,n+1} Q_{n+1} + \ldots + \gamma_{n,N} Q_N = \frac{Q_1^o}{\Delta t} , \qquad (3.21)$$

where n = 1, 2, ..., N.

The expansion above yields a set of simultaneous, linear, algebraic equations for material inventory in compartment n as a function of time. In these equations, material inventory at the end of a time step is expressed in terms transfer coefficients (γ) and initial compartment inventories (Q^o). The set of algebraic equations can be written in matrix terms as $M \cdot Q + N$ where

$$M = \begin{bmatrix} [\gamma_{1,1} - \sum_{m=1}^{N} \gamma_{m,1} - \frac{1}{\Delta t} - \lambda] & \gamma_{1,2} \cdots & \gamma_{1,N} \\ \gamma_{2,1} & [\gamma_{2,2} - \sum_{m=1}^{N} \gamma_{m,2} - \frac{1}{\Delta t} - \lambda] \cdots & \gamma_{2,N} \\ \vdots & \vdots & \vdots \\ \gamma_{N,1} & \gamma_{N,2} \cdots [\gamma_{N,N} - \sum_{m=1}^{N} \gamma_{m,N} - \frac{1}{\Delta t} - \lambda] \end{bmatrix},$$

$$Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_N \end{bmatrix}$$

$$N = \begin{bmatrix} -Q_1^o/\Delta t \\ -Q_2^o/\Delta t \\ \vdots \\ -Q_N^o/\Delta t \end{bmatrix}.$$

Solving this matrix equation for Q yields $Q = M \cdot N$. The result is an estimate of material inventory (Q) for each compartment n, n = 1, 2, ..., N.

4.0 CALIBRATION/VALIDATION OF THE COMPARTMENTAL PATHWAYS CODE: MATHEMATICAL AND EMPIRICAL

Environmental transport modeling of low-level radioactive waste disposal sites is a significant ongoing effort within the Department of Energy complex. Generally, the purpose of such mathematical exercises is to project the environmental impact to future generations of current operations in which low-activity radioactive materials are introduced to the environment by land disposal. To lend credence to such calculations, computer codes used to simulate environmental transport should be mathematically and empirically validated against suitable, site-specific radionuclide data bases. For the DOSTOMAN Code, an exact analytical solution of a set of linear differential equations which simulate radionuclide transport from buried waste, through the unsaturated zone, to the groundwater table, was derived and used to demonstrate that the set of equations simulating transport are mathematically valid, with the error introduced by numerical solution techniques at <0.2%. In addition, an experimental data base on tritium in the groundwater below the Savannah River Plant burial ground is available from monitoring wells. The DOSTOMAN transport equations were used to simulate the observed tritium plume as a function of time, and compared with field data. Results illustrate that the transport code is capable of replicating the tritium empirical data base within experimental error. The ability to replicate experimental data bases lends additional credence to future projections of radionuclide environmental transport.

For a simplified description of mass transport of radionuclides into the environment, an exact analytical solution can be derived, as shown in Figure 4.1. Even in this form, the exact solution is rather complex. The exact solution is analogous to the Bateman equations for successive radioactive decay of a nuclide. The exact solution can now be compared with the numerical solution techniques - used for solution of the more complex problem - based upon Gauss-Jordan elimination/finite element/matrix inversion methods. Results are illustrated in Figure 4.2. Several environmental compartments are shown since the mass transfer coefficients (λ_n's) will vary considerably as a function of environmental compartment and radionuclide environmental properties. The results well illustrate that the numerical approximation methods employed introduce minor error (<0.2%) into the environmental impact analysis. The numerical approximation methods are mathematically valid.

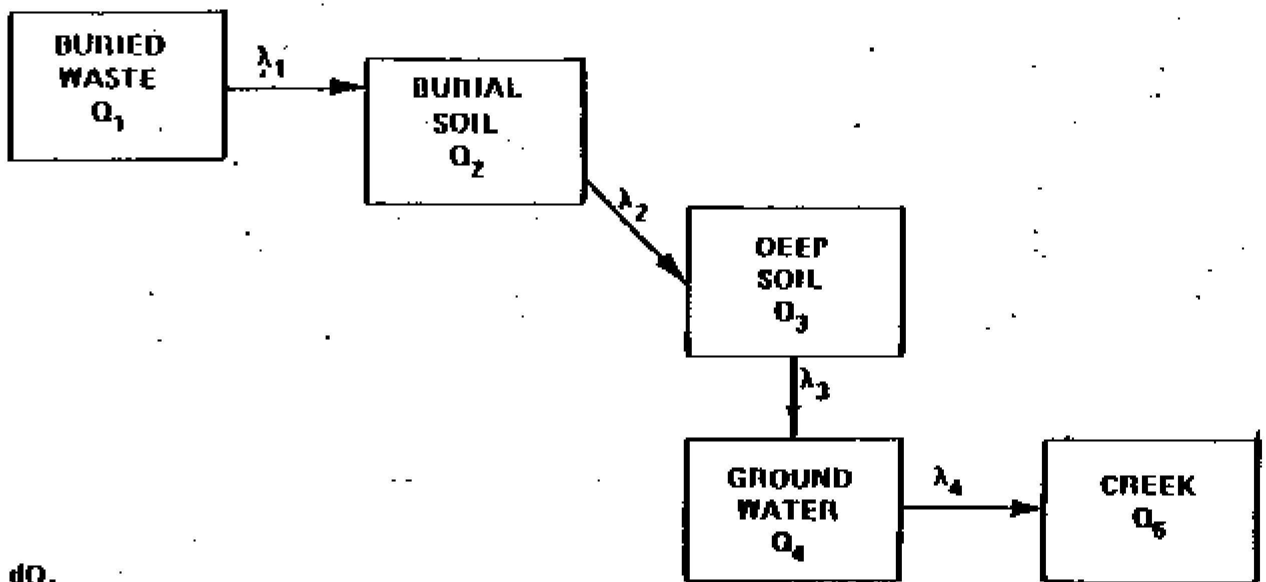
The next step in the model validaton exercise is to use the transport equations to replicate actual field data. The best experimental data base for pursuing this exercise is based upon tritium monitoring at the Savannah River Plant. Low levels of tritium waste have been managed at the Savannah River Plant by shallow land burial since 1955. Extensive grid well monitoring programs have been used for many years to characterize tritium movement into the environment. Tritium leached from buried waste is known to move freely with the groundwater. Slow movement of the groundwater through long flowpaths permits much of the tritium to decay before outcropping into a nearby stream. About 25,000 Ci of tritium are estimated to be in the groundwater. The containment factor of the burial ground for tritium is about 10^2. The presence of tritium has been valuable for defining the groundwater flowpath from the burial ground to a nearby creek. Analyses for tritium of soil cores from the drainage areas have provided a detailed picture of the flowpath. The flowpath data, coupled with detailed information on tritium release rates, inventory in buried waste, and soil adhension properties have permitted a calculation of the effect of year-after-year earthen trench disposal of tritium. The transport equations have therefore been used to project the curie magnitude of the tritium plume as a function of time for direct comparison with the experimental data base.

The results of this analysis are illustrated in Figure 4.3 with the magnitude of the SRP tritium plume plotted as a function of number of years of operation of the land disposal facility. Transport calculations (solid curve) and experimental observations since 1974 (plotted points) are illustrated. Approximately five years after initial land disposal, tritium had begun to move to the water table, and is projected to reach a maximum level in the late 1980's. The plume is projected to decrease as radioactive decay becomes the controlling factor since tritium disposal in this portion of the burial ground ceased in 1973.

Although there is wide variation in the experimental observations in this nine year period, these results illustrate the ability of the mass transport equations of the DOSTOMAN code to project the plume within experimental error.

The transport code is quite useful for replicating real-time experimental data bases which lends additional credence on projections of future environmental transport and environmental impact.

FIGURE 4.1



$$\frac{dQ_1}{dt} = -\lambda_1 Q_1$$

$$\frac{dQ_2}{dt} = \lambda_1 Q_1 - \lambda_2 Q_2$$

$$\frac{dQ_3}{dt} = \lambda_2 Q_2 - \lambda_3 Q_3$$

$$\frac{dQ_4}{dt} = \lambda_3 Q_3 - \lambda_4 Q_4$$

INITIAL CONDITIONS: $Q_1(O) = Q_1(O)$
$Q_2(O) = Q_3(O) = Q_4(O) = 0$

SOLUTIONS

$$Q_1(t) = Q_1(0)e^{-(\lambda_1)t}$$

$$Q_2(t) = \frac{Q_1(0)\lambda_1}{(\lambda_2 - \lambda_1)}\left(e^{-(\lambda_1)t} - e^{-(\lambda_2)t}\right)$$

$$Q_3(t) = \frac{Q_1(0)\lambda_1\lambda_2 e^{-(\lambda_1)t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} - \frac{Q_1(0)\lambda_1\lambda_2 e^{-(\lambda_2)t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)} + \frac{Q_1(0)\lambda_1\lambda_2 e^{-(\lambda_3)t}}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)}$$

$$Q_4(t) = \frac{Q_1(0)\lambda_1\lambda_2\lambda_3 e^{-(\lambda_1)t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)} - \frac{Q_1(0)\lambda_1\lambda_2\lambda_3 e^{-(\lambda_2)t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)}$$
$$+ \frac{Q_1(0)\lambda_1\lambda_2\lambda_3 e^{-(\lambda_3)t}}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_3)} + \frac{Q_1(0)\lambda_1\lambda_2\lambda_3 e^{-(\lambda_4)t}}{(\lambda_4 - \lambda_1)(\lambda_4 - \lambda_2)(\lambda_4 - \lambda_3)}$$

FIGURE 4.1

FIGURE 4.2 DOSTOMAN Model Validation
Analytic Soln vs Matrix Inver

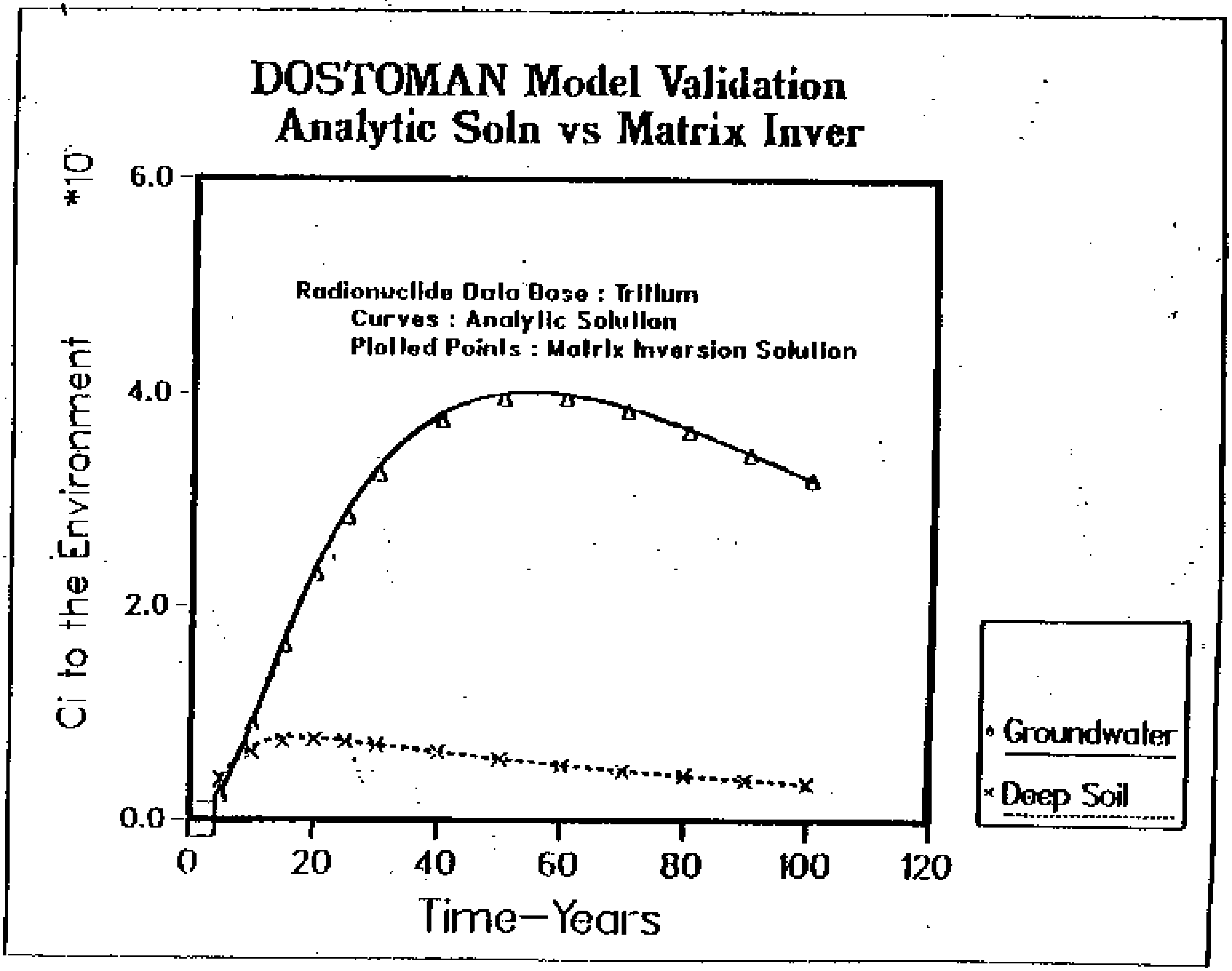
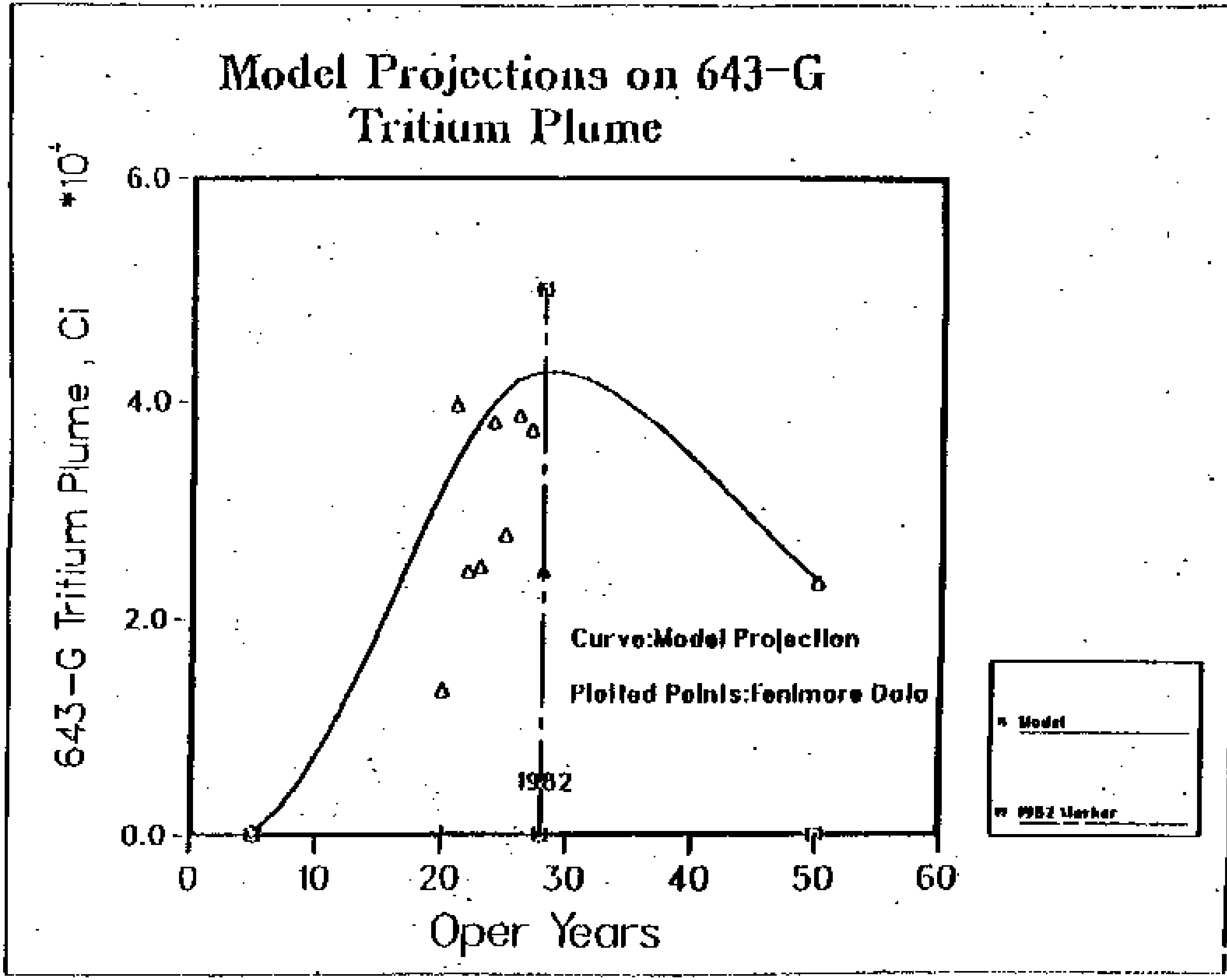

DOSTOMAN Model Validation
Analytic Soln vs Matrix Inver
Radionuclide Data Base : Tritium
Curves : Analytic Solution
Plotted Points : Matrix Inversion Solution
Ci to the Environment *10
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
Time—Years
Groundwater
Deep Soil

FIGURE 4.2

FIGURE 4.3 Model Projections on 643-G
Tritium Plume



Model Projections on 643-G
Tritium Plume
643-G Tritium Plume , Ci
*10⁴
6.0
4.0
2.0
0.0
0
10
20
30
40
50
60
Oper Years
Curve:Model Projection
Plotted Points:Fenimore Data
1982
Model
1982 Marker

FIGURE #4.3

5.0 METHODOLOGY FOR APPLICATION TO NUCLEAR WASTE DISPOSAL

5.1 Basic Design Features

A mathematical model has been developed to provide estimates of long-term dose to man from buried low-level radioactive waste. The model consists of compartments which represent different portions of the environment including vegetation, herbivores, the atmosphere, groundwater, surface water, and man. Movement of radionuclides between compartments is controlled by transfer coefficients, which specify the fraction of radionuclide entering or leaving a compartment during a specified time period. Time controls account for the time lag in movement induced by such factors as the delayed presence of man. Sources and sinks independent of the natural radionuclide movement are provided.

The general form of the equation was derived by personnel at the Oak Ridge National Laboratory for a study to predict the uptake of selected radioactive species by cows.[1/] Later refinements were made by personnel at the Savannah River Laboratory.

The approach used in the Savannah River Laboratory DOSTOMAN model for projecting radiation doses to man employs a single equation that considers only the mass transport of radionuclides through the system. Such factors as water and wind velocity are accounted for in the transfer coefficients.

5.2 Model Organization

Module DOSTOMAN is divided into two basic sections:
1) calculation of radionuclide inventories in compartments assuming transfer coefficients are continuous exponential or Gaussian functions with time or discontinuous step functions and
2) calculation of inventories assuming that some component of a transfer coefficient changes either additively or geometrically during the period being simulated.

Subroutine INPUT reads in the initial data from seven records, including: radioactive decay constant, number of compartments, number with sources or sinks, time step, values and locations of sources or sinks, initial compartment radionuclide inventory, transfer coefficient components, time functions to control the application of the transfer coefficients, and factors to perturb components of transfer coefficients, if applicable. Other input records give plotting and editing specifications. The only calculations performed in this subroutine involve the transfer coefficients, which are of the form A V^X. The individual components A, V, and X are read at this time and the transfer coefficients are calculated. If requested, all input data is printed by subroutine PRINTIN.

In the main program, all transfer coefficients, sources, and sinks are corrected for time dependence, if any, and the coefficient matrix is set up. Subroutine LAM is then called to calculate the terms on the main diagonal in the A matrix. This involves summing the λ's from m=1 to m=N and subtracting $1/\Delta t$ and λ_R. After this calculation, coefficients of the A matrix are ready for the solution of the simultaneous equation.

Subroutine RHS is then called to set up the right-hand side of the simultaneous equations. This involves making each term (B_n) in the B matrix equal to $-Q_n^o/\Delta t$ where n=1,2,N. If compartment n contains a source or sink, the time dependence of the source or sink is accounted for and the B_n are adjusted accordingly.

Upon returning to the main program, the matrices A, X, and B are ready for solution by matrix inversion. The solution is accomplished by calling subroutine MINVS, which calculates the determinant and the inverse of the A matrix (the λ values) for the matrix problem AX=B and finds the solution vector X. Upon return from MINVS, matrix A contains the inverse matrix; therefore, the original matrix A is destroyed. Matrix B then contains the solution vector X (in this case, the Q_n). The solution is accomplished by the standard Gauss-Jordan elimination method. The Q_n values are then printed and any requested plots are made.

At this point in the program, time is incremented by either a specified or a calculated time step and the model is rerun to calculate Q_n values for a new time. This is done until the specified simulation time is achieved or the number of time steps is consumed.

The second part of module DOSTOMAN calculates radionuclide inventories if any component of a transfer coefficient is to be changed, or perturbed, during the run. Specifications for such perturbations, if any, are read in subroutine INPUT. If a perturbation of a transfer coefficient is to occur, the original transfer coefficient values are read in and the perturbation is calulated. The perturbation may be geometric or additive in nature and the Q_n values resulting from the perturbation are calculated only for steady-state conditions. The same calculation method for Q_n is used here as was used for the first part of module DOSTOMAN. Q_n values are then printed out.

5.3 Model Operating Characteristics

As discussed in Section 5.2, the DOSTOMAN model calculates the radionuclide inventory in each compartment at the end of every time step specified. The model uses a finite difference technique to solve the simultaneous equations; therefore, there is some possibility of error accumulating during a simulation run. This error can be minimized by controlling the specification of the time steps. If radionuclide movement is occurring quickly, due, for example, to rapid groundwater transport, small time steps (on the order of one year) should be used. Later in the simulation run, larger time steps can be used. In the case of slowly moving radionuclides, such as those highly susceptible to retention in the soil by ion exchange, larger time steps can be used throughout.

The time required to run a simulation with the model will depend greatly on the characteristics of the computer facilities available to the user. On the IBM 360/195 at the Savannah River Laboratory, a simulation involving 200 time steps, 200 transfer coefficients, and 70 separate compartments requires about six minutes of central processing unit time. About 500 K bytes of core are required for such a simulation. Only one radionuclide can be considered in each run: the radioactive decay constant and many of the compartment inventories and transfer coefficients will be specific to that radionuclide.

Two means of evaluating the numerical stability of the code are included in the program. Subroutine RESID determines the difference (residual) between the calculated values for the right- and left-hand sides of the set of simultaneous equations solved by matrix inversion in subroutine MINVS. The subroutine RHS uses the values calculated at a particular time; therefore, the difference between the two sides of each equation is a measure of how accurate the solution is. Ideally, the residual should be zero; some small residual can be accounted for by round-off and truncation errors in the calculations and is usually insignificant.

An initial inventory is provided to the system by the Q_n values. If no sources or sinks add to or remove from the system during the run, this initial amount of radionuclide must be maintained throughout the run, adjusted, of course, for radioactive decay. Subroutine MASBAL calculates the state of mass balance by

FIGURE 5.1 Flow Diagram for the DOSTOMAN Computer Program

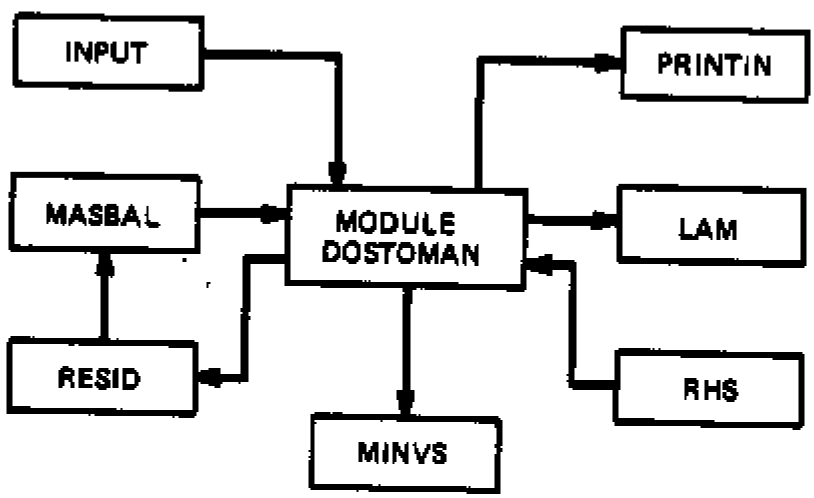


FIGURE 5.1 Flow Diagram for the DOSTOMAN Computer Program

summing all of the Q_n values at a particular time and comparing the total to the sum of initial Q_n values. Ideally, the deviation from mass balance should be zero; again, round-off and truncation errors may contribute to a small deviation.

5.4 Flow Diagram

The computer program consists of a main program (module DOSTOMAN) and seven subroutines (Figure 5.1).

Module DOSTOMAN performs the main control function by coordinating the input and output of data and the calculations of compartment radionuclide inventories. The entire module is run for each time step specified and subroutines are actuated in clockwise sequence as shown in Figure 5.1, beginning with subroutine INPUT.

5.5 Applicability

The DOSTOMAN model as developed and coded is a compartmentalized simulation of environmental transport. As such it may be applied to any location - only the initial radionuclide inventories and the transfer coefficients input make it site-specific. However, the model was intended for application to humid locations - those with relatively high rates of precipitation and shallow water table. The Savannah River Plant can be classified as such a site. Therefore, the following discussion deals with conditions and practices only at SRP, with references to other sites where appropriate.

Disposal Alternatives

One objective of the program to determine dose to man is to develop criteria for preparing the burial grounds for minimal post-operational control. In the short-term this involves evaluating expected dose to man based on established burial and site maintenance procedures. The effects of modifications to these procedures can be evaluated and recommendations can be made. In the long-term, the modeling will guide management decisions on decommissioning alternatives, which may include abandonment or other course, and on establishing the length of institutional control.

Waste Characteristics

Solid low-level waste at SRL includes contaminated equipment, reactor and reactor fuel hardware, spent lithium-aluminum targets, incidental waste from laboratory and production operations, and occasional shipments from offsite. Accurate records are kept of the contents, radiation level, and storage location of each load of waste. Trench burial is used for alpha waste only if it contains less than 10 nanocuries per gram alpha contamination and no measurable beta-gamma activity, and for beta-gamma waste containing less than 10 nanocuries per gram alpha contamination. An exception to this is for large bulky waste which is too contaminated with gamma emitters to feasibly monitor the alpha content; such waste is buried directly in soil on top of a 6-ft backfill to keep the equipment above water that might accumulate in the trench bottom.

Hydrogeological Environments

The solid waste burial grounds at SRP are underlain by several hundred feet of unconsolidated and semi-consolidated sandy clay and clayey sand sediments which rest on granitic and gneissic crystalline bedrock. The sediments are saturated to within 40 to 60 feet of the ground surface. Clay lenses and layers are scattered irregularly through the subsurface and retard downward water flow to varying degrees. Groundwater beneath the burial grounds generally flows laterally toward neighboring surface streams, with some flow downward which ultimately discharges to these same streams. Groundwater velocities are on the order of 40 feet per year horizontally in the saturated zone and seven feet per year vertically in the unsaturated zone. Approximately 1.3 feet of precipitation reaches the water table annually.

The DOSTOMAN model was designed for simulating environments where the water table is very shallow. Flow through the unsaturated zone is treated very simplistically (constant soil moisture content is assumed) and therefore does not realistically handle hydrogeological environments in which significant transport occurs in the unsaturated zone.

Climate

The climate in the Savannah River area is relatively temperate, with long summers and mild winters. The average winter temperature is 9°C, and the average summer temperature is 27°C. Average annual precipitation (mostly in the form of rainfall) is

47 inches and occurs mainly in the late winter and from spring to late summer. Approximately one-third of this precipitation goes to each of surface runoff, evapotranspiration, and groundwater recharge. Average wind velocity is 6 miles per hour and generally comes from the west or southwest. There is some possibility of hurricanes and tornadoes affecting the site.

Similar conditions occur at moist humid eastern sites, with some local variations. Arid regions, on the other hand, would have very little precipitation and therefore little groundwater recharge and vegetation.

Initiating Incidents

Initiating incidents for radionuclide movement at SRP are primarily a consequence of the humid environment of the site. Water percolating down from the surface mobilizes radionuclides from buried waste and transports them through the soil to ground water and ultimately to surface water or to man's immediate environment. Much of this movement, however, is so slow as to allow radioactive decay to reduce concentrations of many radionuclides to relatively low levels. Ion exchange acting in clayey sediments assists in retarding radionuclide transport.

Another consequence of the relatively humid environment is the growth of vegetation, both deep-rooted and shallow-rooted varieties, that may pick up some contamination. Other means of initiating radionuclide movement are intrusion by man and animals, and by exposure of the waste by surface erosion.

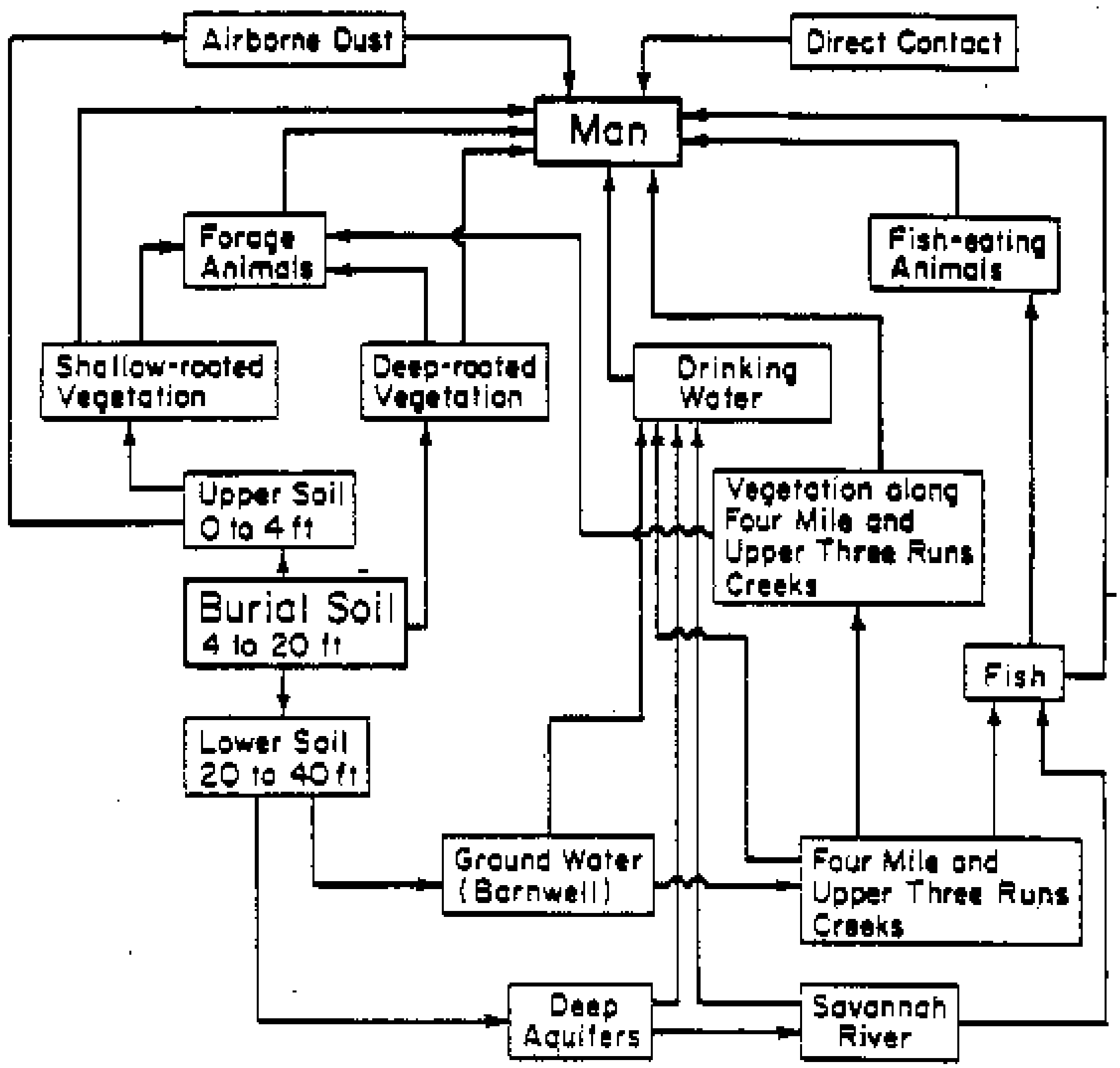
Pathways

The pathways for radionuclide movement in the environment consist of all processes and transport mediums which will move either dissolved ions or particulates. Figure 5.2 shows a generalized pathways conceptual model for SRP. It was developed to simulate a specific land-use scenario involving four persons living on a home farm occupying the entire 200 acres of the burial ground All food (meat, milk, and vegetables) are grown on the site and all water is obtained from a well drilled into the ground water underlying the site. The people occasionally intrude into the buried waste and contaminated soil and routinely breathe the air above the site. Also, the people occasionally swim in surface water which may be receiving contaminants from the burial grounds.

Although this conceptual pathways model was developed for a specific land-use scenario, its application is much broader. Other proposed land-use scenarios may add to or delete from the compartments and transfers shown, or modify their relative significance. The same is true for the use of the DOSTOMAN model at other geographic locations and under other climatic influences.

In most situations not all of the pathways shown in Figure 5.2 are significant contributors to the transport of radionuclides to man. These "critical" pathways will depend very much on the characteristics of the land-use scenario being simulated and on the particular radiodnuclide. In the home farm scenario for SRP described earlier, two critical pathways stand out:

Figure 5.2 Radionuclide Transport Model



5.2
Figure 4. Radionuclide Transport Model

1) The penetration of deep-rooted vegetation into the waste and contaminated soil brings radionuclides to the surface where they may be ingested directly by man or may enter livestock. This pathway can be critical for both short- and long-lived nuclides.

2) Radionuclides are carried down through the soil into the saturated zone and can be ingested directly by man in his water supply. Soil generally retards movement by this pathway so this may be critical only for long-lived radionuclides. An exception to this is for tritium which is not significantly retarded by the soil. However, the projected length of institutional, post-operational control over the burial ground (on the order of 100 years) will allow for the radioactive decay of tritium.

Receptors

Man is the ultimate receptor of concern of the dose from radionuclides moving through the environment. The model can be set up to account for the effects on all critical body organs. Internal and external dose can be considered. Both individual and population dose can be determined, depending on the proposed land use. Additional receptors can be livestock and other animal foods which may be affected adversely by radiation. The main concern with respect to animals is, however, where they fit into the pathways for contributing dose to man.

Biological Uptake/Transfer

In the home farm scenario, biological uptake and transfer occurs through vegetative pathways (deep-rooted vegetation, shallow-rooted grass, and vegetable crops) and through herbivore (cow and deer) and fish pathways. Other animal vectors such as birds and wild animals other than deer can be considered also.

Vegetative uptake occurs both through the roots by their contact with buried waste and contaminated soil and through the leaves due to fallout. Concentration factors control the distribution of radionuclides between plant and soil and are specific for the type of plant, type of radionuclide, and geochemical parameters such as the ratio of radionuclide to other nuclides in the soil. Transfer occurs as ions move up through the vegetation at the rate of plant internal processes. Determining transfer coefficients for vegetative uptake and transfer depends on knowing:

1) Soil-to-plant concentration factors
2) Plant root and surface vegetation growth rates
3) Root distributions
4) Root death rates

The effects of fallout require knowing:

1) Total vegetation surface area liable to catch fallout
2) Depositional velocity of particles carrying radionuclides

Animal uptake occurs when they consume contaminated food and water, breathe contaminated air, and ingest contaminated soil. Transfer will then occur from the gastrointestinal and respiratory tracts to critical body organs and to body parts consumed by man (especially muscle). Calculating animal uptake requires knowing:

1) Ingestion rates of soil, water, and vegetation

2) Inhalation rates

3) Animal mass

Internal transfer to critical body organs and to consumable body parts has been measured for many animal species. For uptake of radionuclides by fish, the following are needed:

1) Water-to-fish concentration factors

2) Fish mass

The transfer of accumulated radionuclides from vegetation and animals to man depends on his ingestion rate of these species as foodstuffs. Therefore, the following are required:

1) Consumption rate of animals and plants and their products (e.g., milk)

2) Animal and plant mass

5.6 Data Input Requirements

The data required to run the model include all those factors which influence the rate of movement of radionuclides in the environment. Such hydrologic, geochemical, and lithologic information as water table disposition, ion distribution coefficents, bulk density, and porosity must be known. The radionuclide inventory must be defined as an initial condition for a simulation. Data must also be available on plant and animal concentration factors. Site-specific data are desirable; however, considerable information may be obtained from the literature.

Specifically, these items must be provided:

1) Initial radionuclide inventory of each compartment. If the run is a continuation of a previous simulation, the initial inventories will be the inventories existing in the compartments at the end of the previous run. For first runs, the inventories should be best-estimates of the quantity of radionuclide in the compartment, based on records or measurements. Only one radionuclide can be considered in each simulation run.

2) Transfer coefficients between compartments. Transfer coefficients must be read into the model in the form $A \cdot V^X$.

This allows the numerator and denominator of a calculated transfer coefficient to be kept separate. For example, if

$\lambda_{a,b}$ = (growth rate)/(total mass)

then the transfer coefficient is read in as

$\lambda_{a,b}$ = (growth rate) x (total mass)$^{-1}$

Transfer coefficients may consist of several components, which can vary in sign. Therefore, factors influencing the movement of radionuclides between two compartments in either direction can be combined into one transfer coefficient, assuming that all factors are operating over the same time period.

The nature or makeup of the transfer coefficients will depend greatly on the particular interaction considered. Coefficients accounting for radionuclide movement in groundwater will depend upon the flow velocity, radionuclide distribution coefficient, soil bulk density, and soil porosity. Coefficients simulating vegetative uptake require data on soil-to-plant concentration factors, mass growth rate, and root distribution. Some coefficients may be relatively simple in specification, such as a leach rate.

The list of specific data required by the model is given in Table 5.1. Additions to or deletions from this list may be required depending on the land-use scenario under consideration.

Table 5.1 DOSTOMAN Input Requirements

General Data Required

Length of institutional control period
Area of the land of interest

Geologic Data Required

Radionuclide distribution coefficient
Groundwater flow rates (saturated and unsaturated)
Soil bulk density
Soil porosity
Saturated aquifer thickness
Depth to mean water table
Surface erosion rates
Particle transport rate
Fraction of soil in respirable range
Rate of sediment deposition
Surface water body volumes and flow rates
Stream sediment loads

Waste Data Required

Leach rates
Radionuclide inventory
Depth of burial
Particle transport rate

Atmospheric Data Required

Airborne concentration of dust
Rate of surface soil loss due to erosion
Atmospheric mixing depth

Human Factor Data Required

Man's inhalation rate
Duration of intrusion into waste or contaminated soil
Soil ingestion rate during intrusion
Number of persons involved
Meat, milk, and vegetable consumption rates
Particle depositional velocities
Duration of exposure to contaminated surface water
Fraction of radionuclides absorbed by gastrointestinal and respiratory tracts
Water consumption rate
Probability of intrusion into waste or contaminated soil

Animal Factor Data Required

Inhalation rates
Soil ingestion rates
Number of animals involved
Food ingestion rates
Milk production rate
Mass of each animal type
Water consumption rates
Concentration factors
Fraction of radionuclides absorbed by different parts of each animal
Death rates

Vegetative Factor Data Required

Leaf surface areas
Area of land applied to each type of vegetation
Number of plants involved

Rate of decay of surface litter
Concentration factors beween plant and soil
Plant growth rates
Root distributions with depth
Mass of each vegetation type
Death rates

The availability of data for transfer coefficient calculations occurs widely in the literature. For site-specific data, however, laboratory and field tests may be necessary.

3) Compartment interactions. In order for the DOSTOMAN model to set up the transfer coefficient matrix, compartmental interaction must be specified. For each compartment, it must therefore be specified which compartments receive radionuclides and send radionuclides to contiguous compartments. Therefore, each possible interaction is listed as part of the input.

4) Radioactive decay constant. Simulation runs with the DOSTOMAN model can handle only one radionuclide at a time; therefore, one decay constant needs to be specified prior to the run. It should be in units consistent with those of the transfer coefficients (e.g., 1/time).

5) Time step size. Specification of the time step should be consistent with the expected rate of movement of the radionuclide and the anticipated length of time to be simulated. As discussed in Section 5.3 periods of time in which radionuclide inventories in compartments are rapidly changing should be simulated with small time steps (on the order of one year). However, if long periods of time are to be simulated, it is

advisable to increase the time step size later in the simulation. Time step size increases should be made at a rate of no greater than 1.5X for each increase (i.e., t_{i+1} is equal to or less than $1.5 \times t_i$) in order to reduce computational errors.

6) Time functions. In certain situtations, a transfer coefficient may not be applicable for a certain period of time. For example, if deep-rooted vegetation is excluded from a waste disposal site for a period of years after operations have ceased, transfer of radionuclides from buried waste or contaminated soil to the surface via this pathway will not begin immediately. For this situation, a time lag should be specified for use of this transfer coefficient. If a time lag is not specified, the transfer is assumed to be occurring from the beginning of the simulation run.

7) Sources or sinks. In certain situations, other sources or sinks for radionuclides may develop in parts of the modeled system other than the original location (e.g., a buried waste site). For example, radionuclides may be introduced as fallout to surface soil, or exhumation of buried waste may occur after radionuclide movement in the environment has begun. Such sources or sinks (with their locations, strengths, and times of application) should be specified.

The DOSTOMAN model may be used on any modern computer facility. Core requirements will vary with the number of compartments and time steps being simulated, but average requirements will be on the order of 500 K bytes for 69 compartments, 200 transfer coefficients, and 200 time steps. At the Savannah River Laboratory, the IBM 360/195 and the IBM 370/158 provide more than adequate capabilities. Hardware for plotting is desirable. The model is written in the FORTRAN computer language.

6.0 USER'S GUIDE FOR THE DOSTOMAN COMPARTMENTAL PATHWAYS MODEL

A User's Guide which documents the development and computer implementation of the Savannah River Laboratory compartmental pathways computer code used to simulate radionuclide transport was published in 1981. The User's Guide provides all the necessary information for the prospective user to input the required data, execute the computer program, and display results. The User's Guide is reproduced in its entirety in Appendix B.

7.0 EXAMPLES OF USE OF THE MODEL IN TRANSPORT AND PATHWAY ANALYSES

The DOSTOMAN code developed by SRL solves a mass balance equation based on a set of simultaneous linear differential equations that simulate radionuclide transport. The code extends the calculations to a number of pathways by scenario analysis. Realistic scenarios such as hydrologic transport and hypothetical scenarios such as future land occupation are used to estimate environmental impacts, usually stated as dose commitments. These in turn are used to evaluate site performance, radionuclide disposal limits, improved concepts for land disposal of waste, and decommissioning alternatives. The code relies on site-specific input data such as radionuclide inventory, chemical form, release rate, K_d's and geohydrologic parameters.

Recent modeling studies with the DOSTOMAN code have included identification of factors for reduction of dose commitments, evaluations of disposal limits for transuranic (TRU) waste, and analysis of the projected behavior of the mobile radionuclides, tritium, Tc-99, and I-129.

Factors for Reduction of Exposure

Model analyses for a variety of radionuclides have shown that the two most significant pathways for potential exposure from radioactive waste burial grounds are:

- hydrologic transport of radionuclides such as tritium, Tc-99, and I-129 that have low soil adherence biotic transport via plant uptake of radionuclides such as Sr-90, Cs-137, Pu-238, and Pu-239 that have high soil adherence

Several factors that will minimize these routes have been identified by sensitivity analyses with the model. The factors are: radionuclide inventory control; moisture infiltration barriers, such as low permeability matrices or site caps; site vegetation control or overburden; and deeper burial, which requires a deeper water table. The model can determine a decremental environmental impact effect on each factor. These factors have been incorporated into new concepts for improved shallow land burial operations and for greater confinement disposal.

TRU Waste Disposal Limits

The effect of a 100 nCi/g demarcation value for land disposal of TRU radionuclides was evaluated using site-specific transport modeling and pathway analysis. Since 1968, the demarcation value has been 10 nCi/g. However, prior to 1968 all TRU waste at SRP (including that >100 nCi/g) was routinely buried. The consequences of this practice have been carefully monitored, and the monitoring data supply input to the transport model for evaluating potential TRU disposal limits. The incremental environmental impact of the higher demarcation value (100 nCi/g) depends on the scenario chosen, but in all cases studied was insignificant.

Transportable Radionuclides

Tritium behavior in the closed 31-hectare burial ground at SRP has been modeled. The calculations predict that tritium in groundwater will increase about 10% in coming years and then decrease mostly by radioactive decay. The rate of outcrop to surface streams is calculated to be less than 500 Ci/yr, which has a negligible effect at the site boundary. Scenario calculations based on 100-year institutional control followed by land occupation of the site predict that the hydrologic pathway will continue to dominate. However, because of decay of the buried tritium and long migration paths, the environmental effect will be minimal.

Tc-99, primarily present as the pertechnetate anion, has been shown to have low soil adherence. Model projections on movement of Tc-99 to the water table are in good agreement with experimental observations. Concentrations of Tc-99 in the groundwater at the SRP burial ground are predicted to remain small and well below standards for surface streams. Scenario calculations predict that the water pathway will contribute 70% and vegetative uptake 30% to the environmental effect. The vegetative pathway is significant because plant uptake factors for Tc-99 are reported to be large.

I-129 migration was modeled using data on, the estimated inventory of I-129 as silver iodide, and near-zero soil adherence. Under these conditions, the flux of I-129 to the water table is calculated to be about 10^{-} %/yr, with a calculated groundwater concentration of about 10^{-} pCi/L, well below environmental standards for I-129. The calculation also was performed as a function of soil permeability to demonstrate the effect of a clay cap that reduces rainwater infiltration. In this case, the flux is about 10^{-} %/yr, and the groundwater concentration is about

10^{-5} pCi/L. Finite soil adherence of I-129, as found in laboratory tests, would be expected to decrease calculated I-129 fluxes and concentrations by at least an order of magnitude.

Biotic Transport Calculations

Vegetative uptake of Sr-90 is the primary pathway leading to exposure because the calculation assumes that roots will penetrate the buried waste. The code predicts that vegetative uptake of Sr-90 can be controlled by increasing the distance from the surface to the waste. This could be accomplished by adding 3-5 m of overburden above the waste, which is a decommissioning alternative, or by deeper burial, which is an option for new disposals.

Exposures from Tc-99 are predicted to be minor, in part because of the small inventory of Tc-99 in the buried waste. Technetium, in the form of pertechnetate anion, is a case where the mobile species has little or no soil adherence. The calculated value of Tc-99 concentration in groundwater is in good agreement with field measurements at the burial ground.

Cs-137 transport and exposures are calculated to be less significant than those of Sr-90 because vegetative uptake is less for cesium.

A sensitivity analysis of the model projections was compelted, using the Sr-90 data base. Key input parameters, the dosimetry data base, the scenarios, and various burial ground management options all were varied to determine the most sensitive features of the calculation. This exercise demonstrated the importance of vegetative uptake of Sr-90 and showed that this pathway could be eliminated by increased depth from surface to waste.

The model sensitivity analyses and the derivation of the TRU demarcation value are given in Appendix D. A complete list of SRL publications and technical reports on use of the compartmental pathways model in analysis of radionuclide transport is given in Appendix E.

8.0 PEER REVIEW AND IMPLEMENTATION OF THE MODEL AT DEPARTMENT OF ENERGY SITES

In 1982, personnel from EG&G Idaho and the National Low Level Waste Management Program conducted a peer review of available codes for pathway analysis and environmental impact for evaluation of radionuclide land disposal operations. Pathway analysis codes from DOE sites were specifically studied. Included were codes from:

SRL (DOSTOMAN)

Battelle PNL (ARRRG, FOOD, KRONIC, SUBDOSA, DACRIN, PABLM, MAXI)

Los Alamos National Lab (BIOTRAN, CREAMS)

Idaho National Engineering Lab (BURYIT)

Nuclear Regulatory Commission (GRWATER, INTRUDE)

Environmental Protection Agency (PRESTO, AMRAW).

The DOSTOMAN Code was evaluated to be flexible, straight forward, easily understood, and sufficiently documented to be used at other sites. In addition, its dynamic or time-dependent nature was considered advantageous as opposed to many assessment models which presume equilibrium or no net flow of contaminants.

In 1983, the DOSTOMAN computer code and available details on methodology, user's guide, matrix inversion, and transfer coefficient calculations were transmitted to EG&G/Idaho. Similar information has also been transmitted to the Argonne National Laboratory and the Environmental Protection Agency.

In 1984, the SRL code was applied to the development of Threshold Guidance Limits for the potential management of waste below regulatory concern (so called "de minimis" waste) by EG&G/-Idaho personnel (DOE/LLW-40T, "Development of Threshold Guidance", January 1985).

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APPENDIX A

TRANSFER COEFFICIENT CALCULATIONS

Appendix A

Transfer Coefficient Calculations

There are numerous physical parameters that influence the transfer coefficients (29). The examples of the transfer coefficient calculations presented here are representative of the theoretical and empirical considerations necessary for the formulation of the dose-to-man compartmental model.

The transfer coefficient for transfer from burial soil to deep soil is determined by

$$\gamma = V_r/D + P_w/D \quad ,$$

where V_r is radionuclide velocity through the burial soil, P_w is the particle transport weight and D is the soil depth. The particle transport component is due to movement of small waste/soil particles through the bulk soil matrix by infiltrating groundwater. Radionuclide velocity is calculated from the equation

$$V_r = V_w/(1 + K_d R)$$

where

V_w = velocity of the water,

K = the distribution coefficient,

R = the ratio of soil mineral weight to water volume per unit volume of soil column.

The distribution coefficient is a measure of the ion exchange capacity of the soil and is dependent on a variety of factors such as soil properties, pH of percolating water and presence of coexisting ions in underground water, to name a few. Distribution coefficients are usually determined empirically from laboratory experiments.

n_i = the number of individuals of species i under consideration.

Another example would be transfer from a herbivore's blood to muscle. The transfer coefficient is represented by

$$\gamma = F_m \quad ,$$

where F_m is the fraction of activity transferred from blood to muscle per unit time.

There are also transfer coefficients associated with airborne dust. The transfer coefficient for transfer from the airborne dust compartment to the herbivore compartment is given by

$$\gamma = \sum_i \frac{I_i H_i F_{Di}}{V_a} \quad ,$$

where

I_i = the inhalation rate of species i,

H_i = the number of herbivores of species i,

FD_i = the fraction of inhaled particles deposited in the lung of species i,

V_a = the volume of air in the airborne dust compartment.

Transfer coefficients for airborne deposition of dust to vegetation are calculated from

$$\gamma = \frac{DA_v}{V_a}$$

where

D = the deposition velocity of dust onto plant surfaces,

A_v = the area of the exposed foliage,

V_a = the total volume of the airborne dust compartment.

Airborne deposition to surface soil is calculated in the same manner.

The transfer coefficient for burial soil to deep rooted vegetation is calculated from

$$Y = CF\, M_v F_m / M_s \quad ,$$

where

CF = the concentration factor or fraction of material absorbed for deep roots,

M_v = growth rate of the deep-rooted vegetation growing over the burial ground,

M_s = weight of soil in the burial ground compartment,

F_m = fraction of root mass in the burial ground compartment.

These parameters are determined empirically from field measurements and laboratory experiments.

There has been extensive research to determine concentration factors on a variety of plants and fish for a number of radionuclides, and transfer coefficients for the distribution of radionuclides in animals (30). There are a number of equations to calculate transfer coefficients for vegetation to meat, vegetation to man, and meat to man pathways using NRC methodology (31). These equations are based on consumption rates, concentration factors, and internal transfer coefficients. An example would be the transfer of radionuclides from shallow-rooted grass to a herbivore's gastrointestinal tract. The transfer coefficient is calculated from the equation

$$Y = \sum_i V_i g_i n_i \div \text{Biomass} \quad ,$$

where

v_i = the ingestion rate for species i,

g_i = the fraction of total grazing activity that an individual of species i spends over the burial ground, River and stream pathways to fish and man can be a significant part of the environmental transport compartmental model. The coefficient for transfer from the water compartment to the fish compartment is given by

$$\gamma = \frac{CF\,M\,F}{V_r}$$

where

CF = the concentration factor for fish,

M = the average weight of individual fish,

F = the number of fish,

V_r = the flow rate of the creek or river.

The creek or river water to man transfer coefficient is calculated from the following equation

$$\gamma = \frac{S V_s}{V_c}$$

where

S = the number of swims per year,

V_s = the volume of water ingested per swim,

V_c = the volume of the stream or river compartment.

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June 13, 1978

M E M O R A N D U M

TO: S. L. ALBENESIUS

FROM: E. L. WILHITE *E.L. Wilhite*

PATHWAYS FOR DOSE TO MAN FROM BURIED SOLID WASTE

SUMMARY

A conceptual model has been developed to estimate the rate and extent of nuclide transport from buried solid waste through the environment to man and subsequent dose to man. This memorandum describes in detail the pathways of the model. The general form for the transfer coefficient for each pathway is also described.

INTRODUCTION

Solid waste contaminated with alpha-emitting transuranium (TRU) nuclides, with beta/gamma-emitting activation and fission products, and with tritium, has been buried at the SRP burial ground since 1953. To aid planning for the eventual decommissioning of the burial ground, the long term dose to man from each type of waste must be estimated. The dose projections will provide guidance in choosing alternatives for a burial ground decommissioning plan. Such alternatives may include limiting the total curie quantity of a particular nuclide or group of nuclides in the burial ground; exhumation of a portion of the buried wastes (such as the unencapsulated TRU waste); or, establishing a minimum period of custodial control of the burial ground to allow for decay of certain nuclides. Dose to man estimations will be made by means of a mathematical model as described below.

MODEL DESCRIPTION

The conceptual nuclide transport model is diagrammed in Figure 1. Each block in the diagram represents an environmental compartment that may contain nuclides from buried waste. The arrows indicate the direction of nuclide movement between compartments. In formulating the conceptual model, all credible pathways were included. Some of the pathways may prove to be unrealistic and, if so, will be dropped from further consideration.

The rate of nuclide movement between compartments is represented by the transfer coefficient (λ). For movement between two compartments (designated n and m), the transfer coefficient ($\lambda_{n,m}$) represents the fraction of nuclide initially in compartment m that is transferred to compartment n per year. The rate of change of the quantity of nuclide in compartment n is represented by:

$$\frac{dQ_n}{dt} = \Sigma \lambda_{n,m} Q_m - \Sigma \lambda_{m,n} Q_n - \lambda^R Q_n$$

where: Q_n represents the quantity of nuclide in compartment n, and Q_m is the quantity of nuclide in compartment m.

$\lambda_{n,m}$ is the transfer coefficient for transport of nuclide from compartment m to compartment n. $\lambda_{m,n}$ is the transfer coefficient for transport from compartment n to compartment m.

λ^R represents loss by radioactive decay.

Units for transfer coefficients are $(\text{years})^{-1}$.

Thus, the first term in the equation is the sum of all inputs to compartment n, the second term is the sum of all loss rates from compartment n and the third term is the loss due to radioactive decay. A similar equation can be written for each compartment of the model, yielding a set of simultaneous, linear, differential equations. A computer program (Joshua module DOSTOMAN) has been prepared by Computer Applications Division to solve the equations.

The key input parameter of the model is the transfer coefficient between each pair of compartments. Transfer coefficients will depend on the model formulation, the process involved and on the nuclide. Initial estimates of transfer coefficients can be obtained from literature data. To provide better estimates of transfer coefficients, several studies are underway or planned. These studies include test exhumations of buried equipment, a number of lysimeter and laboratory leaching tests, monitoring of wells in and around the burial ground, and analyses of soil and waste samples from alpha waste trenches.

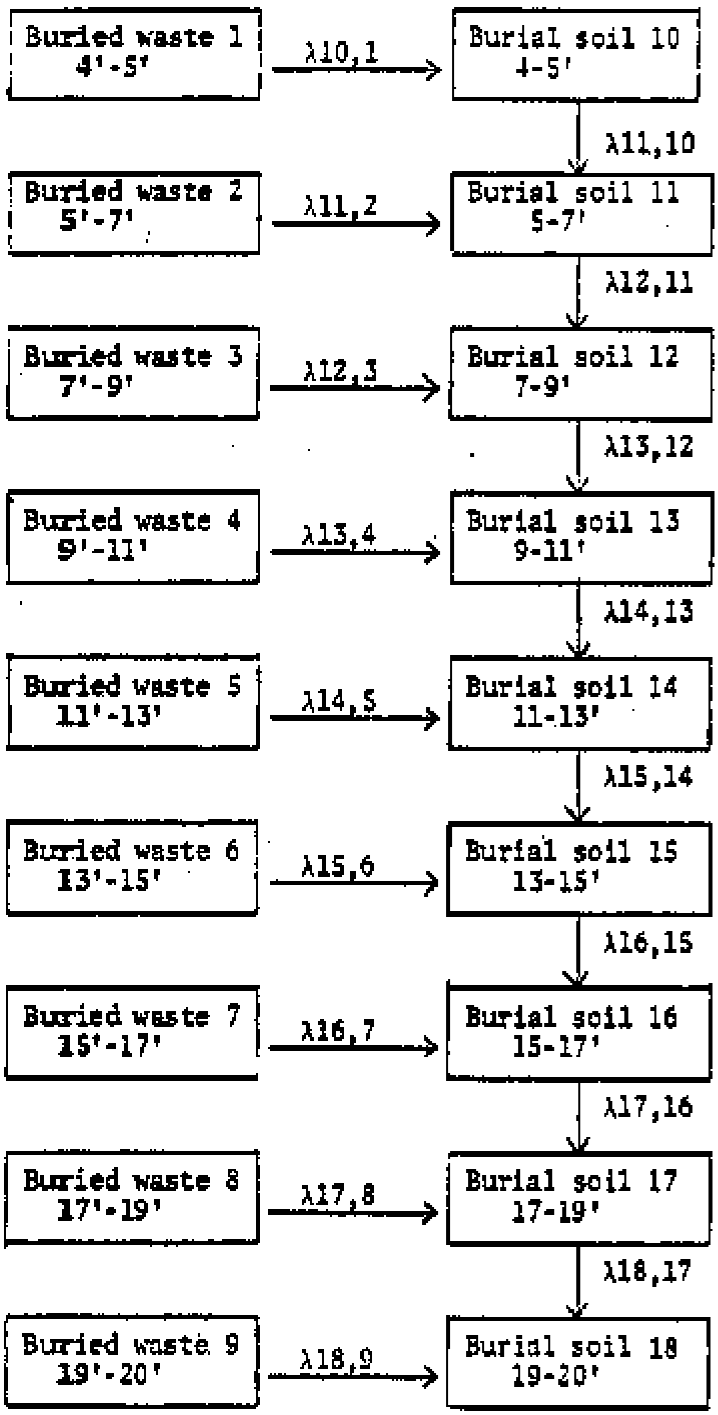
The general radionuclide transport model will be applied to several possible future uses of the burial ground. One scenario to be tested is the establishment of a farm on the burial ground. Another scenario is the covering of the site by a climax forest. These and other scenarios will be tested to determine the most critical pathways for dose to man. Knowledge of the critical pathways will provide guidance in developing a decommissioning plan.

PATHWAYS DESCRIPTION

The individual pathways of the conceptual model (Figure 1) are described in detail. The physical and biological processes operative in each pathway are described. The general mathematical form of the transfer coefficient for each pathway is also described. The transfer coefficient described for each pathway, $\lambda_{n,m}$, implies transfer of a radionuclide from compartment m to compartment n. In certain cases, where there are competing processes represented in the transfer coefficient, the actual direction of transport will depend on the values chosen for the parameters that are included in the transfer coefficient.

1. Buried waste to burial soil:

The trench volume (4'-20' deep) is subdivided vertically into 9 subsections.



For each of these λ's ($\lambda_{10,1}$ - $\lambda_{18,9}$) there are two components:

- leaching: Percolating rainwater will dissolve nuclides from the waste.
- mechanical: Percolating rainwater will slough small particles from the waste. The nuclides from these particles may not be dissolved by the soil water.

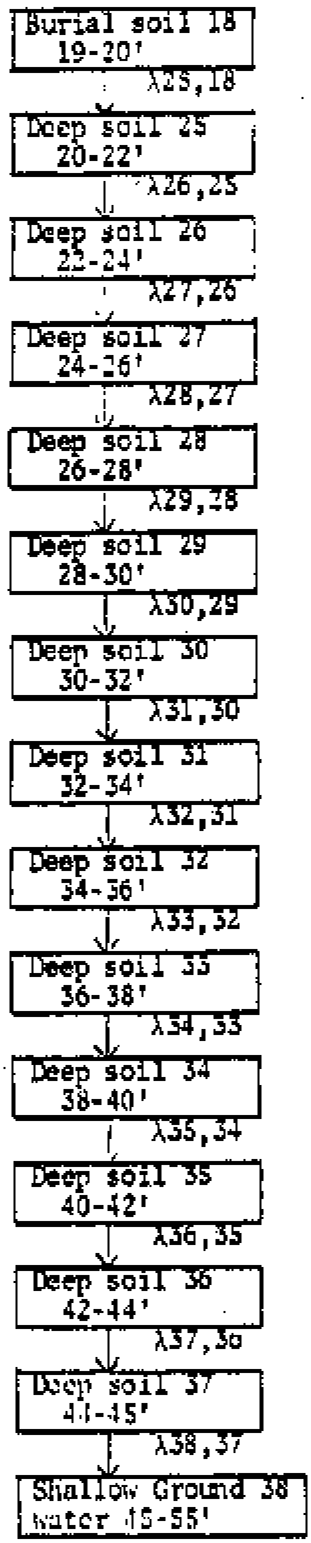
λ = leach rate + particle loss rate

Assume that waste is emplaced uniformly in the buried waste compartments. Therefore, 6.25% of the waste will be emplaced in compartments 1 and 9 and 12.5% each in compartments 2 through 8.

[For λ's between burial soil compartments ($\lambda_{11,10}$ - $\lambda_{18,17}$) see section 3.]

2. Burial soil to deep soil:

The deep soil (20' to 45') is subdivided vertically into 13 compartments:



Hydrologic transport:

Infiltrating ground water will transport nuclides through the soil according to the following equation:

$$V_{nuclide} = \frac{V_{water}}{1 + K_d R}$$

where: $V_{nuclide}$ and V_{water} are the velocities of the nuclide and water, respectively. $V_w \cong 7$ ft/yr in the burial ground.

K_d is the distribution coefficient.

R is the ratio of soil mineral weight to water volume per unit volume of soil column. $R \cong 6.4$ for unsaturated burial ground soils.

$$V_{nuclide} = \frac{7 \text{ ft/yr}}{1+(6.4)\ (K_d)}$$

To arrive at λ, divide $V_{nuclide}$ by the spacing between compartments.

For example: $\lambda_{26,25} = \frac{7 \text{ ft/yr}}{1+(6.4)(K_d)} \div 2$ ft

Particle transport:

Infiltrating ground water will also move small waste/soil particles through the bulk soil matrix. This component of the transfer coefficient is, for example:

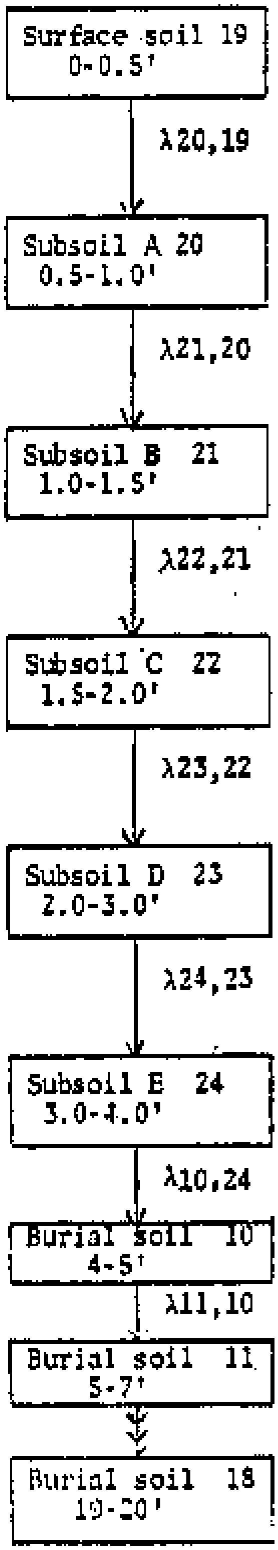
$\lambda_{26,25}$ = (particle transport rate, ft/yr) ÷ 2 ft.

These transfer coefficients ($\lambda_{26,25}$ - $\lambda_{38,37}$) will have two components. For example:

$$\lambda_{26,25} = \left(\frac{7 \text{ ft/yr}}{1+(6.4)(K_d)} \div 2 \text{ ft}\right) + ((\text{particle transport r} \ldots \text{ ft/yr}) \div 2 \text{ ft})$$

3. Burial soil to surface soil:

The surface soil (0' to 4') is subdivided vertically into 6 compartments:



These transfer coefficients have 4 components: erosion, plant uptake, hydrologic transport and particle transport in soil moisture.

Erosion: Erosion of the surface soil will act indirectly to transport nuclides nearer the surface.

$$\lambda_{n,m(\text{erosion})} = \frac{\text{Erosion Rate, ft/yr}}{(\text{Compartment spacing, ft})}$$

Plant uptake: Roots of deep-rooted plants will assimilate nuclides and translocate them upward through the root structure. However, the root may die, leaving the nuclide at a more shallow depth.

$$\lambda_{n,m(\text{plant uptake})} = \frac{(CF)(M_r)(F_n)}{(M_s)}$$

where: CF is the concentration factor for deep roots

M_r is the growth rate of deep roots

F is the fraction of the root mass in compartment n that dies each year

M_s is the soil mass in compartment m

Hydrologic transport: See item #2

Particle transport: See item #2

for $\lambda_{20,19} - \lambda_{18,17}$: $\lambda_{n,m} = \lambda_{n,m(\text{hydrologic transport})} + \lambda_{n,m(\text{particle transport})} - \lambda_{n,m(\text{erosion})} - \lambda_{n,m(\text{plant uptake})}$

4. Surface litter to surface soil:

$\lambda_{19,68}$: This represents decay of plant litter and subsequent incorporation into surface soil

$$\lambda_{19,68} = \text{decay rate of litter (fraction per year)}$$

5. Burial soil to deep-rooted vegetation:

$\lambda_{48,m}$: $m = 10\text{-}18$ Vegetation, such as trees, with roots penetrating deeper than 4 feet will assimilate nuclides into their roots. This transfer coefficient will vary depending on the projected land usage. If long-term control of the burial site is projected, there may be no deep-rooted vegetation. If the site is farmed or put in pasture, there may be a minimum of deep-rooted species. However, if the site is not controlled, natural succession will occur and deep-rooted species may predominate.

$$\lambda_{48,m} = \frac{(CF)(M_V) \times F_m}{M_s}$$

where: CF is the concentration factor for deep roots (pCi/g of plant/pCi/g of soil)

M_V is the growth rate of the deep-rooted vegetation growing over the burial ground

M_s is the weight of soil in compartment m

F_m is the fraction of root mass in compartment m

6. Burial soil to man's respiratory tract:

$\lambda_{66,m}$: $m = 10,18$ This pathway will occur only if man excavates into the burial site. The transfer coefficient ($\lambda_{66,m}$) is dependent on the assumed frequency of intrusion and on the assumed extent of man's activity during the intrusion.

$$\lambda_{66,m} = \frac{(P_I)(C_A)(I)(T)(F_{\text{nuclide respirable}})}{(\text{Mass of soil in Compartment m}) * F_{\text{soil respirable}}}$$

where: P_I = probability of intrusion (events per year)

C_A = postulated airborne concentration of dust during intrusion

I = inhalation rate

T = postulated duration of intrusion

$F_{\text{soil respirable}}$ = fraction of soil in respirable range (<2μ)

$F_{\text{nuclide respirable}}$ = fraction of nuclide in <2μ soil

7. Burial soil to man's gastro-intestinal tract:

$\lambda_{65,m}$: This pathway is similar to the above.

m = 10,18 $$\lambda_{65,m} = \frac{(P_I)\ (M_I)}{\text{(Mass of soil in compartment m)}}$$

where: P_I = probability of intrusion (events per year)

M_I = postulated mass of soil ingested during intrusion

8. Surface soil to airborne dust:

$\lambda_{56,19}$: Transfer of surface soil to airborne dust occurs as wind erosion. If the extent of wind erosion, E, can be assessed, then

$$\lambda_{56,19} = \frac{\text{E (mass of soil eroded per acre per year)} \times \text{(B.G. area, acres)} \times 0.1^{(5)}}{\text{(Mass of soil in compartment 19)}}$$

The United States Department of Agriculture has developed a method to estimate soil loss from wind erosion.[4] Their equation is:

$E = f(I', K', C', L', V')$ = tons per acre per year

where: I' = soil erodibility index

K' = soil ridge roughness factor

C' = climatic factor

L' = field length along prevailing wind erosion direction

V = equivalent quantity of vegetative cover

The USDA handbook provides tables and charts to estimate the above parameters.

9. Surface soil to man's gastro-intestinal tract:

$\lambda_{65,19}$: Direct ingestion of surface soil would result from ingestion of soil on a person's hands, vegetables, etc.

$$\lambda_{65,19} = \frac{S \times P \times 365.25}{M_{19}}$$

where: S = the soil ingestion rate g/day per person

P = number of people

365.25 = the number of days per year

M_{19} = the total mass of soil in the surface soil compartment, g

10. Surface soil to herbivore's G.I. tract:

$\lambda_{50,19}$: Direct ingestion of soil would result from ingestion of soil while grazing, licking, etc. The amount would depend on the type of herbivore (cow or wild animal, i.e., deer) and the type of forage.

$$\lambda_{50,19} = \frac{365.25}{M_{19}} \sum_{i=1}^{I} S_i \, g_i \, n_i$$

where: S_i = soil ingestion rate for species i, g/day

g_i = fraction of total grazing activity that an individual of species i spends grazing over the burial ground

n_i = number of individuals of species i under consideration

M_{19} = mass of soil in compartment 19, g

11. Surface soil to shallow-rooted grass:

$\lambda_{49,m}$: This transfer coefficient will depend on the assumed land usage. If a climax forest is established, then there will be less shallow-rooted grass than if the burial ground were used for pasture and/or crops. Since only a portion of the total shallow-rooted biomass is consumed by herbivores, assume that the remainder is returned to the surface soil (compartment 19).

m = 19-21

$$\lambda_{49,m} = \frac{(CF)(M_v) \times F_m}{\text{Soil mass}}$$

where: C.F. = concentration factor

= pCi/g plant/pCi/g soil for the nuclide of interest

M_v = the growth rate of shallow-rooted grass on the burial ground

Soil mass = the total weight of soil in compartment m

F_m = the fraction of the root mass in compartment m

12. Surface soil to vegetable crops:

$\lambda_{69,m}$: Roots of vegetable crops may penetrate below 4' as seen in the following table.[8]

m = 19-24; 10-12

Vegetable	Maximum root penetration (ft.)
Corn	8'
Spinach	4'
Tomato	5'
Cucumber	4'
Watermelon	4'

$$\lambda_{69,m} = \frac{(CF)(M_V)\ Fm}{\text{Soil mass}}$$

where: terms are defined above under $\lambda_{49,m}$

13. Surface soil to deep-rooted vegetation:

$\lambda_{48,m}$: Similar to above.

$m = 19\text{-}24$ $$\lambda_{48,m} = \frac{C.F. \times M_V \times F_m}{\text{Soil mass in compartment } m}$$

However, the concentration factor (CF) for surface soil to deep-rooted vegetation probably is not the same as the CF for burial soil to deep-rooted vegetation.

14. Deep soil to deep-rooted vegetation:

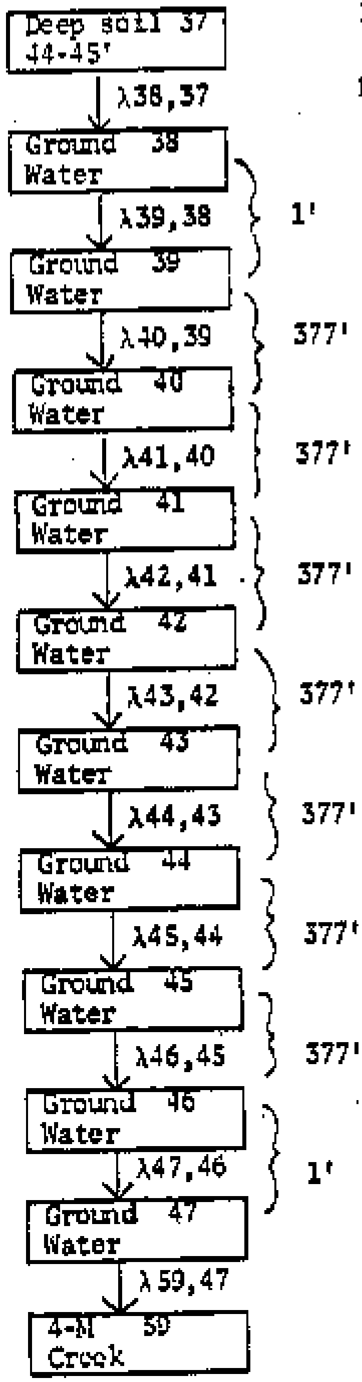
$\lambda_{48,m}$: See discussion for $\lambda_{48,m}$ ($m = 10\text{-}18$)

$m = 25\text{-}37$ $$\lambda_{48,m} = \frac{(CF)(M_V)\ F_m}{M_s}$$

$m = 25\text{-}37$

15. Shallow ground water to 4 Mile Creek:

The shallow ground water is subdivided horizontally into 10 compartments:



$\lambda_{39,38}$ to $\lambda_{59,47}$:

Hydrologic transport will move nuclides according to the following equation (see $\lambda_{4,2}$ for discussion):

$$V_{nuclide} = \frac{V_{water}}{1 + K_d R}$$

where: V_{water} = 40 ft/year at the burial ground

R = 4.0 for saturated burial ground soil (See p.3)

$$V_{nuclide} \cong \frac{40 \text{ ft/yr}}{4 K_d} = \frac{10 \text{ ft/yr}}{K_d}$$

$\lambda = V_{nuclide} \div$ (compartment separation, ft.)

16. Shallow ground water to domestic water:

$\lambda_{58,m}$: This pathway will depend on projected land usage. If a farm with shallow well is postulated on the burial ground, then domestic water would come from the shallow ground water. For larger population distributions, no domestic water would come from shallow ground water.

m = 38-47

17. Shallow ground water to deep aquifers:

$\lambda_{57,m}$: Hydrologic transport from shallow ground water to deeper aquifers (the McBean and Congaree) is known to occur. Data from wells screened in the McBean formation will determine the transfer rate to the formation and the flow path and velocity within the formation.

m = 38-47

18. Domestic water to man's G.I. tract:

$\lambda_{65,58}$: This pathway represents people drinking water from some source. The source of water may change depending on the population being considered and on the land-use scenario.

$$\lambda_{65,58} = \frac{\text{(Man's drinking rate)(Population)}}{\text{(Volume of water available for drinking)}}$$

19. Domestic water to surface soil:

$\lambda_{19,58}$: This pathway represents irrigation of crops (a practice not normally done in the southeast except for small family gardens) and disposal of water used for washing, etc. As above, the transfer coefficient will depend on the proposed land use scenario.

$$\lambda_{19,58} = \frac{\text{Volume of water released to surface soil}}{\text{Volume of water available for domestic use}}$$

20. Domestic water to herbivore's G.I. tract:

$\lambda_{50,58}$: This pathway represents watering domestic cattle. The transfer coefficient will depend on the proposed land-use scenario.

$$\lambda_{50,58} = \frac{\text{(Cattle drinking rate)(\# cattle)}}{\text{(Volume of water available for domestic use)}}$$

21. Deep-rooted vegetation to man's G.I. tract:

$\lambda_{65,48}$: This pathway will vary depending on the proposed land use scenario. If the burial ground is used as a farm site, some deep-rooted species (peaches, pears, etc.) may be produced. However, if a climax forest is postulated, although deep-rooted species will be present, their produce will not be consumed by man.

$$\lambda_{65,48} = \text{(man's consumption rate)} \div \text{inventory of deep-rooted species}$$

22. Deep-rooted vegetation to herbivore's G.I. tract:

$\lambda_{50,48}$: This pathway will depend on the proposed land use scenario. Domestic herbivores (cows) would not feed on deep-rooted species; wild herbivores (deer, etc.) may.

23. Deep-rooted vegetation to surface litter:

$\lambda_{68,48}$: This represents fall of leaves, branches, etc., to the ground.

$$\lambda_{68,48} = \text{(Fraction of deep-rooted vegetation that falls as litter each year)}$$

24. Shallow-rooted grass to surface litter:

$\lambda_{68,49}$: This represents death of vegetation.

$$\lambda_{68,49} = 1 - \lambda_{50,49}$$

25. Vegetables to surface litter:

$\lambda_{68,69}$: This represents disposal of unused plant parts to the soil.

$$\lambda_{68,69} = 1 - \lambda_{65,69} - \lambda_{50,69}$$

26. Vegetables to man's G.I. tract:

$\lambda_{65,69}$: This pathway represents consumption of vegetable crops grown on the burial ground by man. This will depend on the proposed land usage.

$$\lambda_{65,69} = \frac{\text{(Consumption rate of vegetables, gm/year per person)(\# people being considered)}}{\text{(Mass of vegetation in compartment 69,g)}}$$

Although the entire vegetable plant assimilates the nuclide, only a portion of the plant is used by man. See $\lambda_{49,m}$ $m = 19\text{-}21$

27. Shallow-rooted grass to herbivore's G.I. tract:

$\lambda_{50,49}$: This pathway represents either cows grazing on pasture or wild animals (deer, etc.) grazing on native vegetation in the burial ground.

$$\lambda_{50,49} = \sum_{i=1}^{I} V_i\, g_i\, n_i \div \text{Biomass}$$

where: V_i = ingestion rate for shallow-rooted species

Other terms are defined as in $\lambda_{50,10}$.

28. Vegetables to herbivore's G.I. tract:

$\lambda_{50,69}$: This represents either cattle feeding on farm produce (i.e. corn) or deer eating vegetable crops.

$$\lambda_{50,69} = \sum_{i=1}^{I} V_i g_i n_i \div \text{Biomass}$$

where: terms are defined in $\lambda_{50,49}$

29. Herbivore's G.I. tract to blood:

$\lambda_{52,50}$: This pathway represents nuclide absorption from the G.I. tract.

$\lambda_{52,50}$ = fraction of nuclide absorbed by G.I. tract

30. Herbivore's G.I. tract to surface soil:

$\lambda_{19,50}$: This pathway represents excretion of nuclide from the G.I. tract in feces.

$\lambda_{19,50}$ = fraction of nuclide that is not absorbed from the G.I. tract.

31. Herbivore's lungs to G.I. tract:

$\lambda_{50,51}$: This pathway represents clearance of particles from the lungs and swallowing them. Assume the clearance rate is the same for all herbivores.

$$\lambda_{50,51} = F_c$$

where: F_c = fraction of nuclide inhaled that is cleared to the G.I. tract.

32. Herbivore's lungs to blood:

$\lambda_{52,51}$: This pathway represents absorption of nuclide into the bloodstream from the lungs. Assume the absorption rate is the same for all herbivores.

$$\lambda_{52,51} = F_A$$

where: F_A = fraction of nuclide inhaled that is absorbed by blood.

33. Herbivore's lungs to surface soil:

$\lambda_{19,51}$: This represents either the death and decay on the ground of native herbivores or the disposal to the ground of unused tissue from butchering cattle or other herbivores. It is assumed that the total amount of nuclide in compartment 51 is distributed among the different species in proportion to their body weight.

$$\lambda_{19,51} = \sum_{i=1}^{I} \frac{\left(F_{D_i} + \left(F_{B_i} \quad U_{lung_i}\right)\right) \cdot N_i \, m_i}{\Sigma N_i \, m_i}$$

where: F_{D_i} = the annual fraction of herbivore species i that dies naturally

F_B = the fraction of the herbivore population that is butchered each year

U_{lung} = the fraction of lung tissue that is waste

N_i = number of herbivores of species i

m_i = mass of individual herbivore of species i

34. Herbivore's blood to muscle:

$\lambda_{53,52}$: This represents transport of nuclide from the bloodstream to muscle tissue. Assume the transport rate is the same for all herbivores.

$$\lambda_{53,52} = F_M$$

where: F_M = fraction of nuclide transferred from blood to muscle

35. Herbivore's blood to liver:

$\lambda_{54,52}$: This represents transport of nuclide from the bloodstream to the liver. Assume the transport rate is the same for all herbivores.

$$\lambda_{54,52} = F_l$$

where: F_l = fraction of nuclide transferred from blood to liver.

36. Herbivore's blood to milk:

$\lambda_{55,52}$: This represents transport of nuclide from the bloodstream to herbivore's milk. Assume the transport rate is the same for all herbivores.

$$\lambda_{55,52} = F_{milk}$$

where: F_{milk} = fraction of nuclide transferred from blood to milk.

37. Herbivore's blood to surface soil:

$\lambda_{19,52}$: Similar to $\lambda_{19,51}$

$$\lambda_{19,52} = \sum_{i=1}^{I} \frac{(F_{D_i} + F_B) * N_i m_i}{\Sigma N_i m_i}$$

where: symbols are defined as in $\lambda_{19,51}$

38. Herbivore's muscle to man's G.I. tract:

$\lambda_{65,53}$: This pathway will depend on proposed land usage.

$$\lambda_{65,53} = \sum_{i=1}^{I} \frac{E_i f_i}{M_i} P$$

where: E_i = consumption rate per person of flesh from species i.[2]

f_i = fraction of total flesh of species i that man ingests that comes from animals that have grazed over the burial ground.

M_i = total muscle mass of species i.

P = human population being considered

39. Herbivore's muscle to surface soil:

$\lambda_{19,53}$: Similar to $\lambda_{19,51}$

$$\lambda_{19,53} = \sum_{i=1}^{I} \frac{(F_{D_i} + F_B * U_{muscle}) * N_i m_i}{\Sigma N_i m_i}$$

where: symbols are defined as in $\lambda_{19,51}$

40. Herbivore's liver to man's G.I. tract:

$\lambda_{65,54}$: This pathway will depend on the proposed land usage. The total herbivore population must be specified as well as the total human population.

$$\lambda_{65,54} = \sum_{i=1} \frac{L_i f_i}{l_i} P$$

where: L_i = consumption rate per person of liver from species i.

l_i = total liver mass of species i

Other symbols are as in $\lambda_{65,53}$

41. Herbivore's liver to surface soil

$\lambda_{19,54}$: Similar to $\lambda_{19,51}$

$$\lambda_{19,54} = \sum_{i=1}^{I} \frac{F_D + F_B + U_{liver} + N_i m_i}{\Sigma N_i m_i}$$

where: symbols are as in $\lambda_{19,51}$

42. Herbivore's milk to man's G.I. tract:

$\lambda_{65,55}$: This represents drinking of milk by people. Both herbivore and human populations, must be specified.

$$\lambda_{65,55} = \frac{P \sum_{i=1}^{I} C_i}{\sum_{i=1}^{I} VM_i I_i}$$

where: P = # persons being considered

C_i = consumption rate of milk from species i, ℓ/year/person

VM_i = volume of milk produced by an individual of species i

I_i = # of individuals of species I

43. Herbivore's milk to surface soil:

$\lambda_{19,55}$: Similar to $\lambda_{19,51}$

$$\lambda_{19,55} = \sum_{i=1}^{I} \frac{(F_D + F_B) * N_i m_i}{\Sigma N_i m_i}$$

where: symbols are as in $\lambda_{19,51}$

44. Airborne dust to man's respiratory tract:

$\lambda_{66,56}$: The total volume of the airborne dust compartment must be specified. The total population must be specified.

$$\lambda_{66,56} = \frac{I \times P \times F_D}{V_{56}}$$

where: I = inhalation rate, m^3/year/person[1]

P = # of people

F_D = fraction of inhaled particles deposited in lung (F_D = 0.25)[5]

V_{56} = volume of air in compartment 56, m^3

45. Airborne dust to herbivore's respiratory tract:

$$\lambda_{51,56} = \sum_{i=1}^{I} \frac{I_i \times H_i \times F_{D_i}}{V_{56}}$$

where: I_i = inhalation rate of species I, m^3/individual/year

H_i = # of herbivores of species i

F_{D_i} = fraction of inhaled particles deposited in lung of species i

V_{56} = volume of air in compartment 56, m^3

46. Airborne dust to shallow-rooted grass:

$\lambda_{49,56}$: This pathway represents deposition of dust onto exterior surfaces of grass.

$$\lambda_{49,56} = \frac{D \times A_{grass}}{V_{56}}$$

where: D = Deposition velocity of dust onto plant surfaces[3]

A_{grass} = area of exposed foliage

V_{56} = total volume of compartment 56

47. Airborne dust to vegetables:

$$\lambda_{69,56} = \frac{D * A_{veg}}{V_{56}}$$

where: terms are defined in $\lambda_{49,56}$

48. Airborne dust to deep-rooted plants:

$\lambda_{48,56}$: Same as above for shallow-rooted plants.

$$\lambda_{48,56} = \frac{D \times A_{veg}}{V_{56}}$$

49. Airborne dust to surface soil:

$\lambda_{19,56}$: This pathway represents deposition of dust onto the ground surface.

$$\lambda_{19,56} = \frac{V_d * A_{19}}{V_{56}}$$

where: V_d = deposition velocity onto ground surface

A_{19} = area of ground (This will depend on the scenario studied)

V_{56} = total volume of compartment 56

50. Deep aquifers to Four Mile Creek water:

$\lambda_{59,57}$: Hydrologic transport to Four Mile (and Upper Three Runs) Creek from the deeper aquifers (McBean, Ellenton and Congaree) will occur. The flow paths and water velocities are not well known. The flow path from the burial ground to 4 Mile Creek in the McBean formation is estimated to be 3000-4000 ft and the travel time to be 75-1000 years.

$$V_{nuclide} = \frac{V_w}{1+K_d R}$$

where: symbols are defined in item 15.

then: $\lambda_{59,57} = \dfrac{V_w}{1 + K_d R} \div$ (length of flow path)

51. Deep aquifers to domestic water:

$\lambda_{58,57}$: Home water supply wells in this area are usually in the McBean or Congaree aquifers. If a farmstead supply well is postulated on the burial site, the transfer coefficient would be:

$$\lambda_{58,57} = \frac{\text{(volume of water pumped per year)}}{\text{(total volume of aquifer)}}$$

52. Four-Mile Creek Water to stream seston:

$\lambda_{60,59}$: This path represents the sorption of nuclide by suspended sediment. Nuclide sorption is represented by the distribution coefficient (K_d):

$$K_d = \frac{f_s}{f_w} \times \frac{V_w}{M_s}$$

where: f_s and f_w = the fraction of nuclide in the sediment and water phases, respectively

V_w = volume of water

M_s = mass of sediment

Let S = sediment load of stream = g sediment/ml

therefore, $$f_s = \frac{K_d S}{1 + K_d S}$$

$$\lambda_{60,59} = \frac{K_d S}{1 + K_d S}$$

53. Four-Mile Creek water to fish:

$\lambda_{64,59}$: This pathway represents the assimilation of nuclide from stream water by fish.

Let CF be the concentration factor for fish

= pCi/g fish/pCi/ℓ water

$$\lambda_{64,59} = \frac{CF\ M\ P}{V_{59}}$$

where: CF = concentration factor for fish

M = average weight of individual fish, g/fish

P = # of fish

V_{59} = flow rate of stream, ℓ/year

54. Four-Mile Creek water to man's G.I. tract:

$\lambda_{65,59}$: This pathway represents direct ingestion of stream water by man while swimming.

$$\lambda_{65,59} = \frac{S \times V_s}{V_{59}}$$

where: S = # of swims per year

V_s = volume of water ingested per swim

V_{59} = volume of stream

55. Four-Mile Creek water to domestic water:

$\lambda_{58,59}$: This represents the use of creek water for drinking, etc. This will depend on the land-use scenario, but is improbable as local water supplies are from wells.

56. Four-Mile Creek water to Savannah River water:

$\lambda_{61,59}$: This represents transport of stream water into the river. It is assumed that all of the creek water gets into the river, except that diverted by other uses.

$$\lambda_{61,59} = 1 - \lambda_{60,59} - \lambda_{64,59} - \lambda_{65,59} - \lambda_{58,59}$$

57. Stream seston to man's G.I. tract:

$\lambda_{65,60}$: This represents accidental ingestion of seston by man while swimming in the creek.

$$\lambda_{65,60} = \frac{S \times M_s}{M_{60}}$$

where: M_s = weight of seston ingested per swim

S = # swims per year

M_{60} = total weight of seston in stream

58. Stream seston to river seston:

$\lambda_{62,60}$: This represents the transport of stream seston to the Savannah River.

$$\lambda_{62,60} = 1 - \lambda_{65,60} - D$$

where: D = fraction of suspended sediment (seston) that is deposited on the stream bottom

59. Savannah River Water to man's G.I. tract:

$\lambda_{65,61}$: This represents direct ingestion of river water while swimming.

$$\lambda_{65,61} = \frac{S * V_s}{V_{61}}$$

See $\lambda_{65,59}$

60. Savannah River water to fish:

$$\lambda_{64,61} = \frac{CF\ M\ P}{V_{61}}$$

See $\lambda_{64,59}$ for definition of symbols.

61. Savannah River water to river seston:

$$\lambda_{62,61} = \frac{K_d S}{1 + K_d S}$$

where: S = sediment load of river (g/ml)

62. Savannah River water to domestic water:

$\lambda_{58,61}$: This represents the use of Savannah River water for drinking, etc. This will depend on the population under study. Obviously, a local population at the burial ground would not be affected by Savannah River water. However, populations along the river, such as Port Wentworth, Ga., presently obtain drinking water from the river.

63. Savannah River water to ocean sink:

$\lambda_{63,61}$: This represents the transport of nuclide from the river to the ocean, where it is assumed to be unavailable to man.

$$\lambda_{63,61} = 1 - \lambda_{65,61} - \lambda_{64,61} - \lambda_{62,61} - \lambda_{58,61}$$

64. River seston to man's G.I. tract:

$$\lambda_{65,62} = \frac{S \times M_s}{M_{62}}$$

See $\lambda_{65,60}$ for definition of symbols.

65. River seston to island top soil:

$\lambda_{19,62}$: Sediment is dredged from the mouth of the Savannah River and is dumped on Hutchinson's island and Barnwell island. These islands are farmed and the sediment dumped onto the islands must be considered as surface soil.

66. River seston to ocean sink:

$$\lambda_{63,62} = 1 - \lambda_{65,62} - \lambda_{19,62} - D$$

where: D is the fraction of suspended sediment (seston) that is deposited on the river bottom.

67. Fish to man's G.I. tract:

$\lambda_{65,64}$: Represents ingestion of fish by people.

$$\lambda_{65,64} = \frac{I\,P}{M}$$

where: I = weight of fish ingested per person per year

P = # of people

M = total mass of fish

68. Man's G.I. tract to dose-to-man:

$\lambda_{67,65}$: This represents the effect of ingestion of a nuclide on eventual dose to man. The transfer coefficient will vary depending on the critical organ chosen for dose estimation and on the nuclide. If a bone dose is calculated, this pathway represents the assimilation of the nuclide from the G.I. tract and into bone.

69. Man's G.I. tract to surface soil:

$\lambda_{19,65}$: This represents excretion of ingested nuclide in feces.

$$\lambda_{19,65} = F_E$$

where: F_E = the fraction of nuclide that is not absorbed by the G.I. tract

70. Man's respiratory tract to man's G.I. tract:

$\lambda_{65,66}$: This represents clearance of inhaled particles from the respiratory tract and swallowing them.

$$\lambda_{65,66} = F_{cleared}$$

where: $F_{cleared}$ = the fraction of inhaled particles that are cleared to the G.I. tract

71. Man's respiratory tract to dose-to-man:

$\lambda_{67,66}$: This represents the effect of inhalation of a nuclide on eventual dose to man. The transfer coefficient will vary depending on the critical organ chosen for dose estimation and on the nuclide. If a bone dose is calculated, this pathway represents the assimilation of the nuclide from the respiratory tract into the skeleton.

72. External radiation dose to man:

Instead of movement of a nuclide between compartments, this represents radiation of people by nuclides in compartments 19 (surface soil), 56 (airborne dust), 59 (Four-mile Creek water) and 61 (Savannah River water). The dose is calculated by multiplying the concentration of nuclide in soil, air or water by the appropriate dose rate factor as listed below, and by the estimated duration of contact with the compartment (hours/year).

External Whole Body Dose Rate Factors[9]

Nuclide	Immersion in Water	Submersion in Air	Above Ground Surface
^{90}Sr	0.213Rem/hour/μCi/ml	0.243Rem/hr/μCi/g	0.224Rem/hour/μCi/cm^2
^{137}Cs	0.193	0.220	0.144
^{238}Pu	0.010	0.006	0.010
^{239}Pu	0.017	0.010	0.002

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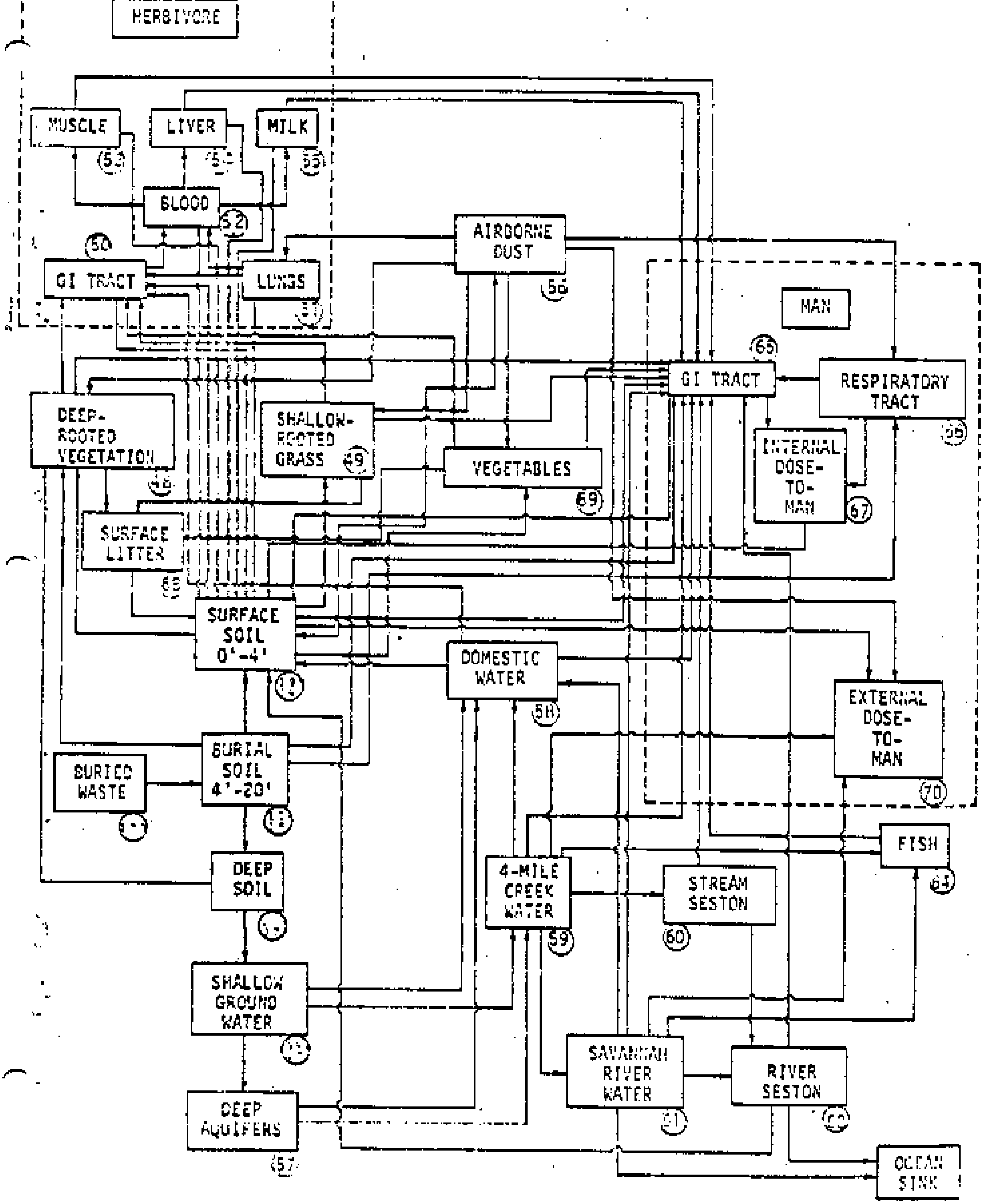
RADIONUCLIDE TRANSPORT MODEL



TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-78-398

June 16, 1978

MEMORANDUM

TO: E. L. ALBENESIUS

FROM: E. L. WILHITE *E L Wilhite*

DOSE TO MAN PROJECTION FOR PLUTONIUM IN BURIED WASTE

Scenario 1: Farm on the Burial Ground

Summary

The maximum average lifetime dose from plutonium in buried solid waste, if the SRP burial ground is used as a farm, is 0.4 rem/person/year 200 years after plant shutdown (predominantly from ^{238}Pu). This dose is to a limited population of four people living continuously on the burial ground and obtaining all of their food and water from the farm. After 900 years, the maximum average lifetime dose is 0.8 rem/person/year (predominantly from ^{239}Pu). Results of a parameter sensitivity analysis show that estimated dose to man is strongly dependent on plutonium oxidation state. For ^{239}Pu, hydrologic pathways are most important, while for ^{238}Pu, terrestrial pathways are more important.

Introduction

Solid waste contaminated with alpha-emitting transuranium (TRU) nuclides, with beta/gamma emitting activation and fission products, and with tritium, has been buried at the SRP burial ground since 1953. To aid planning for the eventual decommissioning of the burial ground, the long term dose to man from each type of waste must be estimated. The dose projections will provide guidance in choosing alternatives for a burial ground decommissioning plan. Such alternatives may include limiting the total curie quantity of a particular nuclide or group of nuclides in the burial ground; exhumation of a portion of the buried wastes (such as the unencapsulated TRU waste); or, establishing a minimum period of custodial control of the burial ground to allow for decay of certain nuclides. Dose to man estimations will be made by means of a mathematical model.

The conceptual nuclide transport model is diagrammed in Figure 1. Each block in the diagram represents an environmental compartment that may contain nuclides from buried waste. The arrows indicate the direction of nuclide movement between compartments. The general model is described in Reference 1. To apply the model, a postulated future use of the burial ground (scenario) must be specified. This report is the first in a series that will describe model results for several scenarios such as:

- a farm on the burial ground with very localized utilization of farm produce and a small affected population (this report).
- a farm on the burial ground with wide distribution of farm produce and a large affected population.
- a forest on the burial ground for recreational/commercial use and a large affected population.

Scenario Description

The basis for this scenario is the assumption that a farm will be established on the ~200 acre burial ground 100 years after plant shutdown. It is further assumed that a family of four lives continuously on this farm and obtains all of its food supply from the farm. The family also obtains its water supply from a well screened in the Barnwell formation. Land usage is assumed to be as follows:

- vegetable garden - 2 acres
- pasture - 150 acres, supporting 40 cattle
- fruit, shade & misc. trees - 48 acres

It is also assumed that a population of 60 deer reside in the vicinity and occasionally intrude on the farm to forage.

Transfer coefficients for this scenario are described in detail in the Appendix. Transfer coefficients were estimated using the best available literature and site data. Values for transfer coefficients are listed in Table 3.

Parameter Sensitivity Analysis

To determine which parameters of the model are most important in estimating nuclide transport and eventual dose to man, a parameter sensitivity analysis was done. In this analysis, values for selected parameters are varied to determine their effect on estimated dose to man. Twenty-three parameters were tested. Parameter values were varied according to a twenty-eight run Plackett-Burman[2] experimental design. Table 1 lists the selected parameters, their test values, and test results. Test results are based on the highest dose commitment* calculated for a single year. Dose commitments were calculated for one million years after plant shutdown for each test run.

For ^{239}Pu, only three parameters were signficant at the 95% confidence level. They were (in decreasing order of importance) the rate of plutonium transfer from man's gastro-intestinal tract to bone, the plutonium soil/water distribution coefficient (K_d), and the rate of hydrologic transport of soil particles.

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*The dose commitment is the radiation dose that will be received by a person over a period of seventy years if no additional plutonium assimilation occurs. The organ chosen for dose calculation was the skeleton.

For ^{238}Pu, thirteen parameters were significant. The six most important parameters (listed in order of decreasing importance) were:

- rate of Pu transfer from man's gastro-intestinal tract to bone
- soil/plant concentration factor for Pu
- soil ingestion rate of deer
- length of control period after plant shutdown
- plutonium leach rate from buried waste
- man's consumption rate of vegetables

In both cases, the most important parameter was the rate of plutonium transfer from the gastro-intestinal tract to bone. For ^{239}Pu, the other important parameters were related to hydrologic transport. The other significant parameters for ^{238}Pu were generally for terrestrial pathways. The different parameter significance for ^{238}Pu and ^{239}Pu is due to the difference in half-lives. Plutonium-238 decays before the hydrologic pathway can become significant. This effect is illustrated in Figure 2 which shows the estimated annual amount of plutonium deposited in man's skeleton as a function of time for trial 6 of the experimental design. The maximum deposition occurs at about 150 years for ^{238}Pu and at about 400 years for ^{239}Pu.

For both ^{238}Pu and ^{239}Pu, several of the most significant parameters (Pu transfer to bone, K_d, and soil/plant concentration factor) depend on the plutonium oxidation state. The plutonium oxidation state will, in turn, depend on the waste/soil/ground water environment. Parameters such as Eh (redox potential), pH, organic complexing agents, etc. will influence the plutonium oxidation state. To accurately project dose to man from plutonium in buried solid waste, parameters influencing plutonium oxidation state must be studied in aged waste and in the soil/ground water system.

Dose Projection

The maximum average lifetime dose from plutonium that could occur under the assumptions of this scenario was calculated using the transfer coefficients listed in the Appendix. The plutonium source term used was 500 Ci ^{239}Pu and 2600 Ci ^{238}Pu, the estimated plutonium content of unencapsulated alpha waste in the SRP burial ground. Results are shown in Table 2. The estimated doses under this scenario are ~2 and ~4 times the ICRP guide[3] of 170 mrem/year to the general population for ^{238}Pu and ^{239}Pu, respectively.

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TABLE 1

PARAMETER SENSITIVITY ANALYSIS

	Parameter	Test Values[1] Low Value	High Value	Significance Probability[2] ^{238}Pu	^{239}Pu
1.	Control period after plant shutdown	20.	500.	>99%(4)[3]	65%
2.	Pu distribution coefficient (K_d)	160.	1,600.	55	96 (2)[3]
3.	Erosion rate	2.3×10^{-5}	1.0×10^{-3}	35	55
4.	Pu leach rate	0.01	0.10	>99 (5)	15
5.	Soil particle hydrologic transport rate	0.00068	0.0068	>99	96 (3)
6.	Soil/plant concentration factor	1×10^{-5}	1×10^{-4}	>99 (2)	85 (6)
7.	Probability of intrusion into buried waste	0.125	0.50	>99	75
8.	Rate of suspension of surface soil into air	0.5	5.0	75	5
9.	Man's vegetable consumption rate	1000.	5000.	>99 (6)	15
10.	Rate of Pu transfer from man's respiratory tract to bone	0.028	0.28	70	35
11.	Rate of Pu transfer from man's G.I. tract to bone	1.35×10^{-5}	1.35×10^{-2}	>99 (1)	>99 (1)
12.	Man's soil ingestion rate	0.01	1.0	45	1 ✓
13.	Soil ingestion rate of cattle	200.	2000.	40	10
14.	Soil ingestion rate of deer	1.0	10.	>99 (3)	10
15.	Man's consumption rate of herbivore muscle	300 (cow) 13 (deer)	3000 (cow) 130 (deer)	>99	5
16.	Man's consumption rate of herbivore liver	13 (cow) 0.6 (deer)	130 (cow) 6 (deer)	>99	85 (5)
17.	Dust deposition velocity onto plant surfaces	315	3150	>99	10✓
18.	Water/fish concentration factor	0.01	0.1	70	55
19.	Water transport rate from Barnwell aquifer to McBean aquifer	1×10^{-6}	1×10^{-4}	>99	55
20.	Man's fruit consumption rate	1,100	11,000	>99	55
21.	Annual time man swims in Four-Mile Creek	2	20	35	55
22.	Annual time man swims in Savannah River	4	40	55	55
23.	Man's fish consumption rate	46.5	465	70	91 (4)

1. Units for parameter values are in the Appendix.
2. Probability that parameter significance is not caused by chance.
3. Relative ranking of six most significant parameters.

TABLE 2

PROJECTED DOSE TO MAN FROM PLUTONIUM IN BURIED SOLID WASTE[1]

Nuclide	Maximum Average Lifetime Dose, Rem/person/yr[2]	Time At Which Maximum Occurs, Years After Plant Shutdown
^{238}Pu	0.4	200
^{239}Pu	0.8	900

1. Under the assumptions of Scenario 1, farm on the burial ground.
2. The following source term was used: ^{238}Pu = 2600 Ci, ^{239}Pu = 500 Ci.

Table 3

Values of Transfer Coefficients

$\lambda_{n,m}$	Year^{-1}
10,1	0.01
10,11	5.0×10^{-12}
10,24	1.2×10^{-3}
11,2	0.01
11,10	8.1×10^{-4}
11,12	8.4×10^{-13}
12,3	0.01
12,11	6.2×10^{-4}
12,13	2.8×10^{-14}
13,4	0.01
13,12	6.2×10^{-4}
13,14	2.6×10^{-17}
14,5	0.01
14,13	6.2×10^{-4}
14,15	2.6×10^{-17}
15,6	0.01
15,14	6.2×10^{-4}
15,16	2.6×10^{-17}
16,7	0.01
16,15	6.2×10^{-4}
16,17	2.6×10^{-17}
17,8	0.01
17,16	6.2×10^{-4}
17,18	2.6×10^{-17}
18,9	0.01
18,17	8.1×10^{-4}
19,20	2.6×10^{-9}
19,50	.99997
19,51	.052
19,52	.052
19,53	.031
19,54	.031
19,55	.052
19,58	6.8×10^{-8}

$\lambda_{n,m}$	Year^{-1}
19,65	.99997
19,67	.0143
19,68	0.1
20,19	2.5×10^{-3}
20,21	6.5×10^{-10}
21,20	2.5×10^{-3}
21,22	2.2×10^{-10}
22,21	2.5×10^{-3}
22,23	1.3×10^{-11}
23,22	1.6×10^{-3}
23,24	1.7×10^{-11}
24,23	1.2×10^{-3}
24,10	5.6×10^{-12}
25,18	.00091
26,25	.00068
27,26	.00068
28,27	.00068
29,28	.00068
30,29	.00068
31,30	.00068
32,31	.00068
33,32	.00068
34,33	.00068
35,34	.00068
36,35	.00068
37,36	.00091
38,37	.00025
39,38	.0062
40,39	1.6×10^{-5}
41,40	1.6×10^{-5}

$\lambda_{n,m}$	Year^{-1}
42,41	1.6×10^{-5}
43,42	1.6×10^{-5}
44,43	1.6×10^{-5}
45,44	1.6×10^{-5}
46,45	1.6×10^{-5}
47,46	.0062
48,10	1.2×10^{-12}
48,11	6.0×10^{-13}
48,12	6.0×10^{-13}
48,13	3.9×10^{-13}
48,14	3.9×10^{-13}
48,15	3.9×10^{-13}
48,16	3.9×10^{-13}
48,17	3.4×10^{-13}
48,18	3.4×10^{-13}
48,19	4.5×10^{-12}
48,20	3.8×10^{-12}
48,21	5.1×10^{-12}
48,22	2.8×10^{-12}
48,23	1.2×10^{-12}
48,24	1.2×10^{-12}
48,25	0
48,26	0
48,27	0
48,28	0

$\lambda_{n,m}$	Year^{-1}
48,29	0
48,30	0
48,31	0
48,32	0
48,33	0
48,34	0
48,35	0
48,36	0
48,37	0
48,56	0.11
49,19	1.0×10^{-8}
49,20	2.5×10^{-9}
49,21	8.0×10^{-10}
49,56	.64
50,19	1.5×10^{-4}
50,48	5.5×10^{-3}
50,49	.57
50,51	.625
50,58	6×10^{-8}
50,69	.16
51,56	2.0×10^{-4}
52,50	3×10^{-5}
52,51	.375
53,52	.07
54,52	.12

Continuation of Table 3

$\lambda_{n,m}$	Year^{-1}	$\lambda_{n,m}$	Year^{-1}	$\lambda_{n,m}$	Year^{-1}	$\lambda_{n,m}$	Year^{-1}
55,52	.007	59,47	1.0	65,60	7.3×10^{-10}	69,21	1.5×10^{-10}
56,19	4.6×10^{-5}	59,57	2.9×10^{-7}	65,61	1.6×10^{-12}	69,22	1.5×10^{-10}
		60,59	.008	65,62	1.6×10^{-12}	69,23	1.8×10^{-10}
57,38	1×10^{-6}	61,59	.992	65,64	4.0×10^{-5}	69,24	6.1×10^{-11}
57,39	1×10^{-6}	62,60	.9	65,66	.933	69,56	2.7×10^{-3}
57,40	1×10^{-6}	62,61	.031	65,69	.061		
57,41	1×10^{-6}	63,61	.969	66,10	1.9×10^{-13}		
57,42	1×10^{-6}	63,62	.9	66,11	5.8×10^{-14}		
57,43	1×10^{-6}	64,59	8.6×10^{-6}	66,12	1.9×10^{-14}		
57,44	1×10^{-6}	64,61	1.3×10^{-6}	66,13	9.2×10^{-15}		
57,45	1×10^{-6}	65,10	6.3×10^{-14}	66,14	1.9×10^{-15}		
57,46	1×10^{-6}	65,11	1.9×10^{-14}	66,15	1.9×10^{-15}		
57,47	1×10^{-6}	65,12	6.3×10^{-15}	66,16	1.9×10^{-15}		
58,38	1.6×10^{-4}	65,13	3.2×10^{-15}	66,17	1.9×10^{-15}		
58,39	0	65,14	6.3×10^{-16}	66,18	3.9×10^{-15}		
58,40	0	65,15	6.3×10^{-16}	66,56	2.4×10^{-6}		
58,41	0	65,16	6.3×10^{-16}	67,65	1.4×10^{-5}		
58,42	0	65,17	6.3×10^{-16}	67,66	0.028		
58,43	0	65,18	1.3×10^{-15}	68,48	.019		
58,44	0	65,19	7.4×10^{-11}	68,49	.42		
58,45	0	65,48	.0034	68,69	.78		
58,46	0	65,53	.10	69,10	5.4×10^{-11}		
58,47	0	65,54	.14	69,11	9.1×10^{-12}		
58,57	0	65,55	.16	69,12	3.0×10^{-13}		
58,59	0	65,58	1.6×10^{-7}	69,19	1.5×10^{-10}		
58,61	0	65,59	7.3×10^{-10}	69,20	1.5×10^{-10}		

FIGURE 1

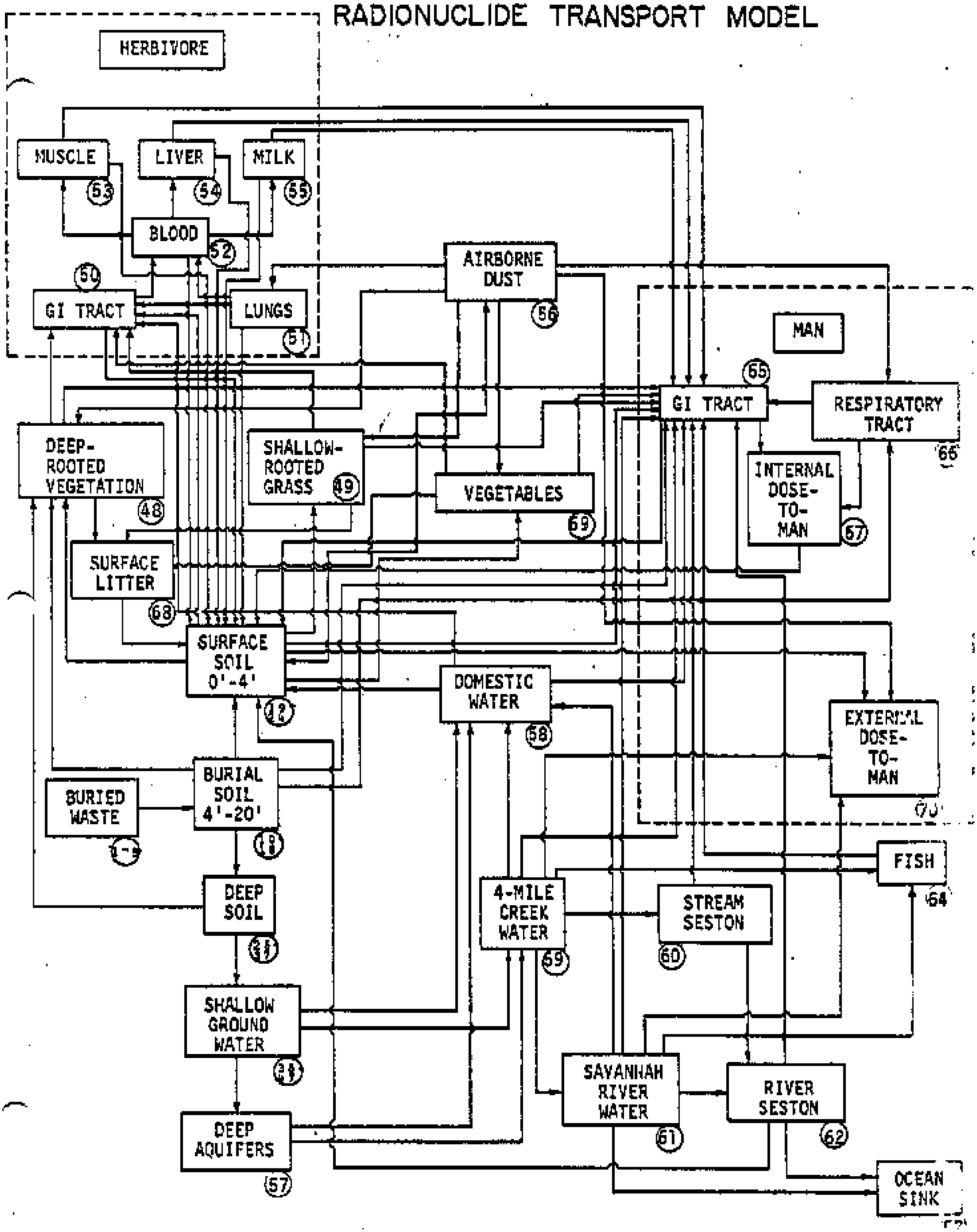
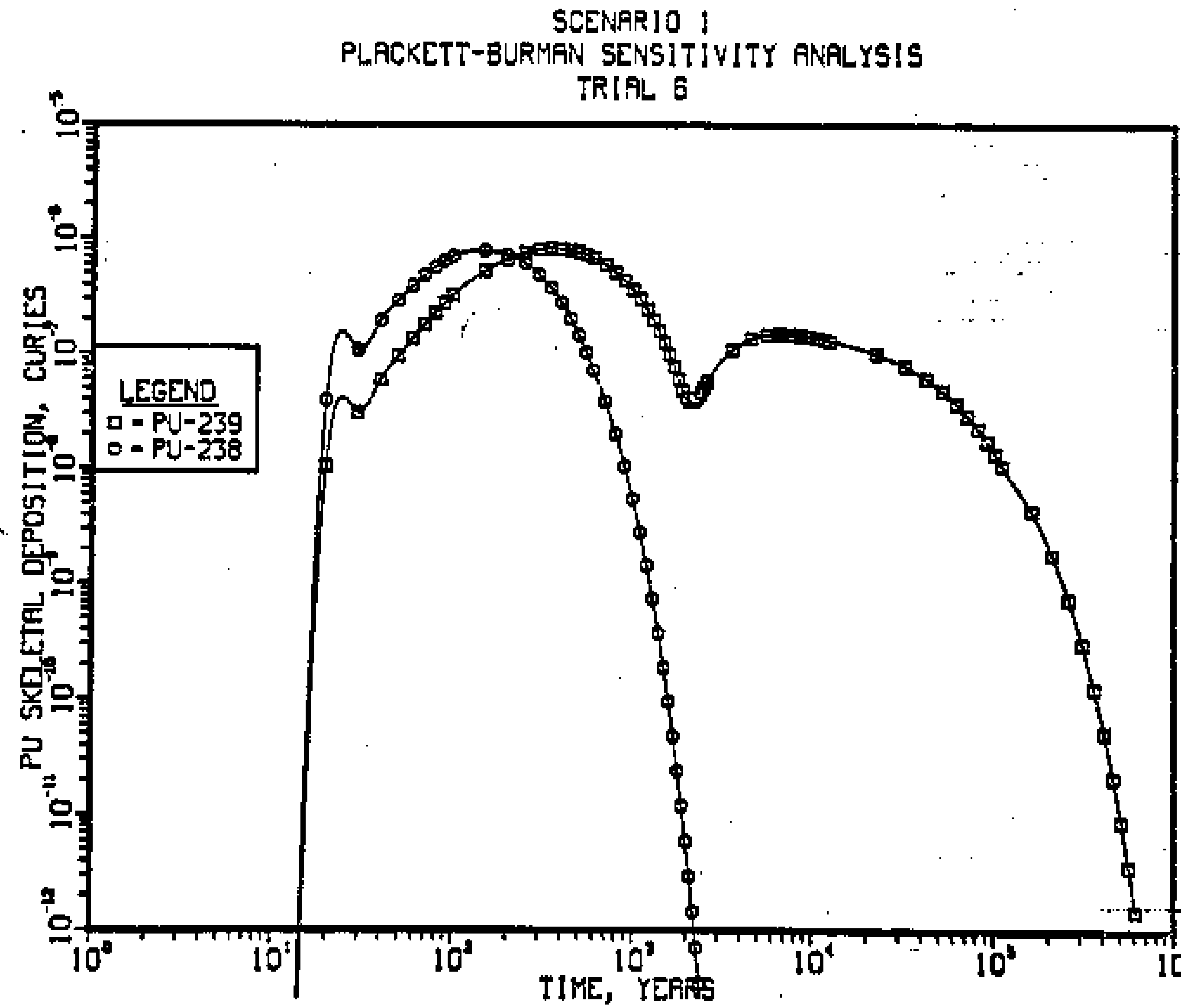

RADIONUCLIDE TRANSPORT MODEL
HERBIVORE
MUSCLE
53
LIVER
54
MILK
55
BLOOD
52
50
GI TRACT
LUNGS
51
AIRBORNE DUST
56
MAN
65
GI TRACT
RESPIRATORY TRACT
66
INTERNAL DOSE-TO-MAN
67
DEEP-ROOTED VEGETATION
48
SHALLOW-ROOTED GRASS
49
VEGETABLES
SURFACE LITTER
68
SURFACE SOIL 0'-4'
DOMESTIC WATER
58
EXTERNAL DOSE-TO-MAN
BURIED WASTE
BURIAL SOIL 4'-20'
DEEP SOIL
FISH
64
4-MILE CREEK WATER
59
STREAM SESTON
60
SHALLOW GROUND WATER
SAVANNAH RIVER WATER
61
RIVER SESTON
62
DEEP AQUIFERS
57
OCEAN SINK

FIGURE 2


SCENARIO 1
PLACKETT-BURMAN SENSITIVITY ANALYSIS
TRIAL 6
LEGEND
□ - PU-239
○ - PU-238
PU SKELETAL DEPOSITION, CURIES
TIME, YEARS

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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-80-237

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January 28, 1980

TO: E. L. ALBENESIUS

FROM: D. J. FAUTH DJF

UPDATED DOSE-TO-MAN PROJECTION FOR PLUTONIUM FROM BURIED WASTE

INTRODUCTION

Radioactive waste has been buried at the SRP burial ground since 1953. This waste includes alpha-emitting transuranium (TRU) nuclides, beta/gamma-emitting activation and fission products, and tritium. The long term dose-to-man from the waste must be estimated so the eventual decommissioning of the burial ground can be planned. The dose projection will provide guidance in choosing alternatives for burial ground decommissioning. A mathematical model has been developed[1] that will estimate the projected dose-to-man. This memorandum updates a previous[2] dose-to-man estimate for plutonium as a result of recent mathematical refinements and improvements to the data base.

SUMMARY

Use of the home-farm scenario for the disposition of the burial ground results in an estimate of the maximum dose-to-man per year to be 0.130 rem/person. The dose is to a limited population of four people who live continuously on the farm and obtain their food and water on the farm. This dose would occur from ^{239}Pu. The predominant pathway for plutonium is downward to the ground water from where it then is transported to man in well water.

MODEL DESCRIPTION

Figure 1 diagrams the conceptual nuclide transport model. Each block in the diagram represents an environmental compartment that may contain radionuclides that were in the buried waste. Some compartments have been subdivided to better simulate the migration of nuclides through the environment. Reference 1 describes the general model.

We have postulated a future use of the burial ground (scenario) to apply the model. The basis for the scenario is the assumption that a family will establish a farm on the ~200-acre burial ground 100 years after plant shutdown. The family (four people) lives continuously on this farm. They obtain all of their food from vegetables and fruit grown on the grounds and from animals grazing on the burial grounds. The family also obtains its water supply from a well drilled in the Barnwell formation. Land use is assumed as follows:

- vegetable garden - 2 acres
- fruit, shade and miscellaneous trees - 48 acres
- pasture - 150 acres

The pasture supports 40 cattle. Deer (60) occasionally intrude on the farm to forage.

The range of nuclide movement between compartments is represented by transfer coefficients. The transfer coefficients for plutonium have been determined from literature and SRL laboratory and field studies. The transfer coefficients have units of yrs^{-1}. Differential equations incorporating these transfer coefficients were constructed in the following form for all 69 compartments.

$$\frac{dQ_n}{dt} = \sum_{m=1}^{69} Q_m\lambda_{n,m} - \sum_{m=1}^{69} Q_n\lambda_{m,n} - Q_n\lambda_R$$

Q_n = Quantity of nuclide in compartment n

t = Time

$\lambda_{m,n}$ = Fraction of nuclide transferred from compartment n to compartment m/per year

λ_R = Fraction of nuclide decaying per year

The equations were simultaneously solved by using a finite difference method. The equations were solved yearly for 1.8 million years. The transfer coefficients that were used in the Pu study and their source are listed in Table 1. (The calculation of these transfer coefficients is described in Reference 2.)

MODEL RESULTS

The plutonium skeletal concentration is projected in Figure 2. The equation used to calculate dose from bone concentration is also shown in Figure 2. The critical organ for plutonium is the skeleton because of the Pu assimilation by the bone and resulting long-term retention.[3] The isotopes plotted are Pu-238 and Pu-239, the major plutonium isotopes in our buried wastes. The curve for Pu-238 has one maximum at 4 mrem/yr/person at 120 years. This dose results from the radioisotope migrating upward to the surface and then to man. Transports include vegetation uptake (shallow-rooted and deep-rooted), erosion, and human intrusion. These transports reach a maximum and the dose per year would remain constant but decay causes the dose to decrease to an infinitesimal amount after 4,000 years.

For Plutonium-239 the concentration-time curve has two maxima. The first maximum occurs in the same time period as for Pu-238. The main transports for Pu-239 in this time are, as expected, the same as ^{238}Pu's transports. The second maximum that occurs after 38,000 years results in the maximum dose of 130 mrem/yr/person. Pu-238 after 38,000 years (427 half lives) would not contribute to the dose. The reason for this much higher maximum (130 mrem vs. 4 mrem) is that rain infiltration would cause most of the plutonium to migrate downward through the soil. After 38,000 years plutonium has reached the ground-water system and been transported to the surface in wells drilled into the burial site. Plutonium has also slowly moved with the ground water to Four Mile Creek and the Savannah River. Once in the water system, Pu is more easily transported to man in all the surface and supersurface compartments.

The critical uptake mechanism for the body changes for plutonium as the transports change. In the first several thousand years, over 95% of the plutonium in the skeleton originated in the respiratory tract. This changes dramatically as Pu reaches the water system and by 38,000 years ingested Pu is the critical uptake mechanism with over 99% of the plutonium in the skeleton originating in the gastrointestinal tract. This scenario predicts that from 120 to 5×10^6 times as much Pu is ingested than is inhaled; however, the transfer coefficient for Pu assimilation in the skeleton from the respiratory tract is 2000 times the transfer coefficient for migration from the gastrointestinal tract to the skeleton.[4]

The home-farm scenario we use here is a worst-case situation. To be more certain of the maximum dose possibilities the transfer coefficients used here are conservative; i.e., cause radionuclide to reach man faster. More realistic scenarios for future of the burial ground would be

- a farm whose products are widely distributed over a large affected populace
- a forest growing up over the burial ground after the end of the surveillance period that might be for recreation and commercial use.

Although dose from plutonium waste is the prime concern from Savannah River solid waste, other nuclides may contribute to the dose-to-man. Using this same scenario, other radionuclides present in Savannah River Plant solid waste are being modeled to determine the human dose affect.

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DJF:ewb

TABLE I

VALUES OF TRANSFER COEFFICIENTS

$\lambda_{n,m}$	Year^{-1}	Ref.
10,1	0.01	5
10,11	5.0×10^{-12}	8,9,10
10,24	1.3×10^{-3}	7
11,2	0.01	5
11,10	8.4×10^{-4}	7
11,12	8.4×10^{-13}	8,9,10
12,3	0.01	5
12,11	6.3×10^{-4}	7
12,13	2.8×10^{-14}	8,9,10
13,4	0.01	5
13,12	6.3×10^{-4}	7
13,14	2.6×10^{-17}	8,9,10
14,5	0.01	5
14,13	6.3×10^{-4}	7
14,15	2.6×10^{-17}	8,9,10
15,6	0.01	5
,14	6.3×10^{-4}	7
15,16	2.6×10^{-17}	8,9,10
16,7	0.01	5
16,15	6.3×10^{-4}	7
16,17	2.6×10^{-17}	8,9,10
17,8	0.01	5
17,16	6.3×10^{-4}	7
17,18	2.6×10^{-17}	8,9,10
18,9	0.01	5
18,17	8.4×10^{-4}	7
19,20	2.6×10^{-9}	8,9,10,11
19,50	.99993	4
19,51	.049	17,18
19,52	.052	17,18
19,53	.031	16,17,18
19,54	.031	18
19,55	.052	18
19,56	.3115	11,14
19,58	6.8×10^{-8}	26
19,65	.99993	4
19,67	.0143	3
,68	0.1	25

$\lambda_{n,m}$	Year^{-1}	Ref.
20,19	2.5×10^{-3}	7
20,21	6.6×10^{-10}	8,9,10,11
21,20	2.5×10^{-3}	7
21,22	2.2×10^{-10}	8,9,10,11
22,21	2.5×10^{-3}	7
22,23	1.3×10^{-11}	8,9,10,11
23,22	1.7×10^{-3}	7
23,24	1.7×10^{-11}	8,9,10
24,23	1.3×10^{-3}	7
24,10	5.6×10^{-12}	8,9,10
25,18	9.1×10^{-4}	6
26,25	6.8×10^{-4}	6
27,26	6.8×10^{-4}	6
28,27	6.8 x 10-4	6
29,28	6.8×10^{-4}	6
30,29	6.8×10^{-4}	6
31,30	6.8×10^{-4}	6
32,31	6.8×10^{-4}	6
33,32	6.8×10^{-4}	6
34,33	6.8×10^{-4}	6
35,34	6.8×10^{-4}	6
36,35	6.8×10^{-4}	6
37,36	9.1×10^{-4}	6
38,37	2.5×10^{-4}	6
39,38	6.3×10^{-3}	6
40,39	1.7×10^{-5}	6
41,40	1.7×10^{-5}	6

$\lambda_{n,m}$	Year^{-1}	Ref.
42,41	1.7×10^{-5}	6
43,42	1.7×10^{-5}	6
44,43	1.7×10^{-5}	6
45,44	1.7×10^{-5}	6
46,45	1.7×10^{-5}	6
47,46	6.2×10^{-8}	6
48,10	1.2×10^{-12}	9
48,11	6.0×10^{-13}	9
48,12	6.0×10^{-13}	9
48,13	3.9×10^{-13}	9
48,14	3.9×10^{-13}	9
48,15	3.9×10^{-13}	9
48,16	3.9×10^{-13}	9
48,17	3.4×10^{-13}	9
48,18	3.4×10^{-13}	9
48,19	4.5×10^{-12}	8,9,10
48,20	3.8×10^{-12}	8,9,10
48,21	3.1×10^{-12}	8,9,10
48,22	2.8×10^{-12}	8,9,10
48,23	1.2×10^{-12}	8,9,10
48,24	1.2×10^{-12}	8,9,10
48,56	0.10	19
49,19	1.0×10^{-8}	8,9,10,11
49,20	2.5×10^{-9}	8,9,10,11
49,21	8.0×10^{-10}	8,9,10,11
49,56	.585	
50,19	1.5×10^{-4}	11,14
50,48	5.5×10^{-3}	7
50,49	.57	11,17
50,51	.594	4
50,58	6×10^{-8}	17
50,59	2.1×10^{-6}	17
50,69	.1598	11,17
51,56	1.8×10^{-4}	4
52,50	3×10^{-5}	4
52,51	.356	4
53,52	.07	4
54,52	.12	4

TABLE 1 - Contd.

VALUES OF TRANSFER COEFFICIENTS

n,m	Year^{-1}	Ref.
5,52	7.0×10^{-8}	4
6,19	4.6×10^{-5}	11,14
7,38	1×10^{-6}*	
7,39	1×10^{-6}*	
7,40	1×10^{-6}*	
7,41	1×10^{-6}*	
7,42	1×10^{-6}*	
7,43	1×10^{-6}*	
7,44	1×10^{-6}*	
7,45	1×10^{-6}*	
7,46	1×10^{-6}*	
7,47	1×10^{-6}*	
8,38	1.7×10^{-4}*	2
9,47	.99993	6
9,57	2.9×10^{-7}	6
0,59	8.0×10^{-1}	5,20
9	.9919	5,16,19, 20,21
2,60	.9	19,20
2,61	.031	6,20
3,61	.969	6,16,20,23
3,62	.9	12,13,20,23
4,59	8.6×10^{-6}	16
4,61	1.3×10^{-6}	16,23
5,10	6.3×10^{-14}	6,13
5,11	1.9×10^{-14}	6,13
5,12	6.3×10^{-15}	6,13
5,13	3.2×10^{-15}	6,13
5,14	6.3×10^{-16}	6,13
5,15	6.3×10^{-16}	6,13
5,16	6.3×10^{-16}	6,13
5,17	6.3×10^{-16}	6.13

$\lambda_{n,m}$	Year^{-1}	Ref.
65,17	6.3×10^{-16}	6,13
65,18	1.3×10^{-15}	6,13
65,19	7.4×10^{-11}	11,14
65,20	3.8×10^{-14}	6,12,13
65,21	2.5×10^{-14}	6,12,13
65,22	2.5×10^{-14}	6,12,13
65,23	1.0×10^{-14}	6,12,13
65,24	1.0×10^{-14}	6,12,13
65,48	3.4×10^{-8}	7,11
65,53	.10	16,17
65,54	.14	15
65,55	.16	16,17
65,58	1.6×10^{-7}	3
65,59	7.3×10^{-10}	19,21
65,60	7.3×10^{-10}	19,20
65,61	1.6×10^{-12}	22,23
65,62	1.6×10^{-12}	20,23
65,64	4.0×10^{-5}	24
65,66	.933	4
65,69	0.61	11,16
66,10	1.9×10^{-14}	6,12,13
66,11	4.2×10^{-14}	6,12,13
66,12	1.9×10^{-14}	6,12,13
66,13	9.7×10^{-16}	6,12,13
66,14	1.9×10^{-16}	6,12,13
66,15	1.9×10^{-15}	6,12,13
16,16	1.9×10^{-15}	6,12,13
16,17	1.9×10^{-16}	6,12,13
66,18	3.8×10^{-15}	6,12,13
66,19	1.2×10^{-10}	6,12,13
66,20	1.2×10^{-10}	6,12,13
66,21	7.7×10^{-11}	6,12,13
66,22	7.7×10^{-11}	6,12,13
66,23	3.1×10^{-11}	6,12,13
66,24	3.1×10^{-11}	6,12,13
66,56	2.2×10^{-8}	4
67,65	1.4×10^{-8}	4
67,66	0.028	17
68,48	.019	15
68,49	.42	11,17
68,69	.779	11,16,17

$\lambda_{n,m}$	Year^{-1}	Ref.
69,10	5.4×10^{-11}	8,9,10,11
69,11	9.1×10^{-12}	8,9,10,11
69,12	3.0×10^{-13}	8,9,10,11
69,19	1.5×10^{-10}	8,9,10,11
69,20	1.5×10^{-10}	8,9,10,11
69,21	1.5×10^{-10}	8,9,10,11
69,22	1.5×10^{-10}	8,9,10,11
69,23	1.8×10^{-10}	8,9,10,11
69,24	6.1×10^{-11}	8,9,10,11
69,56	2.5×10^{-3}	19

*Assumed Value

FIGURE 1

RADIONUCLIDE TRANSPORT MODEL

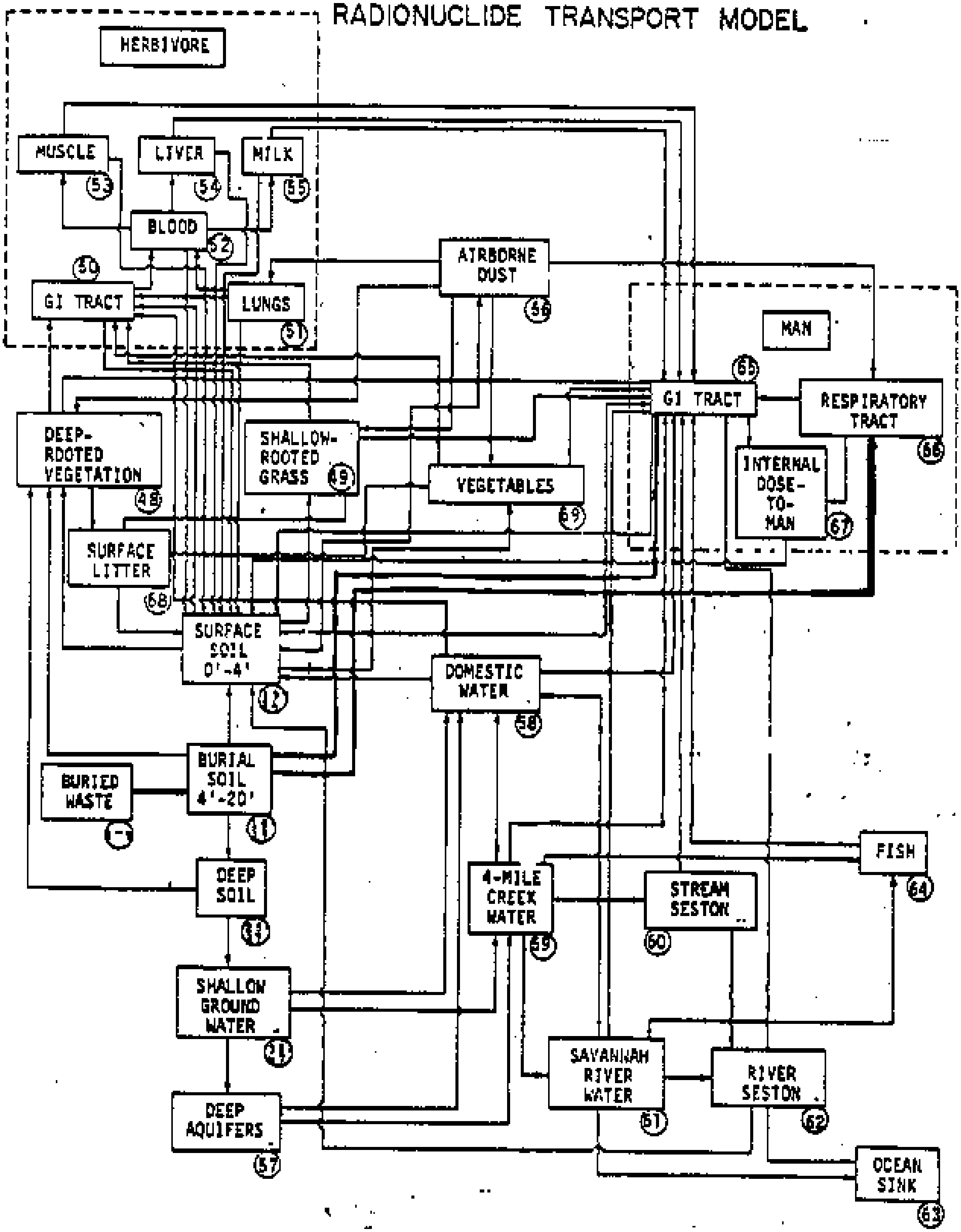
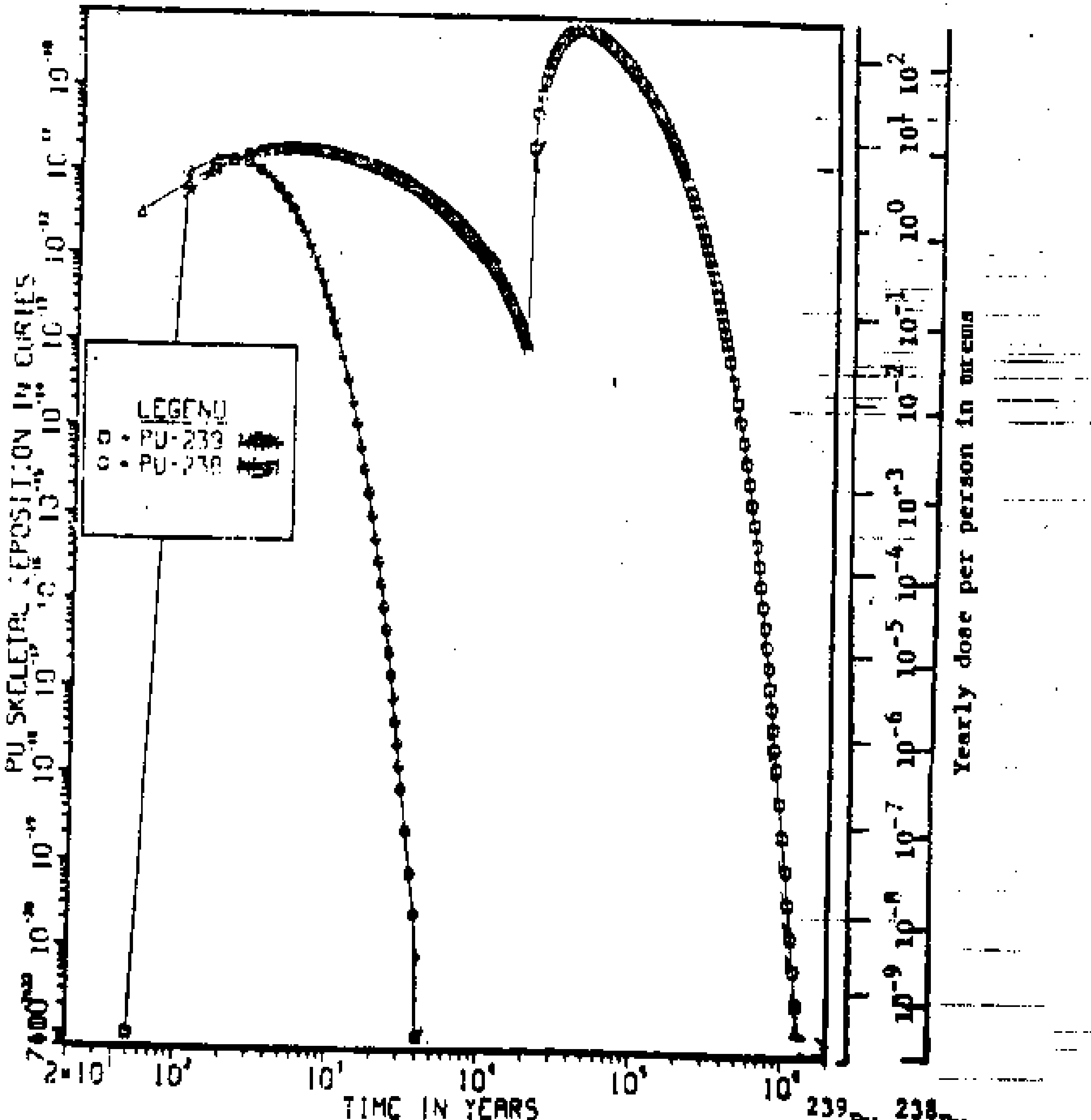


FIGURE 2
PU 239(500 CURIES) PU-238(2600 CURIES)



dose (mrem/person/yr) = $\frac{X \text{ curies (from graph)}}{4 \text{ persons}} \times \frac{3.7\times10^{10} \text{ dis}}{\text{sec}\cdot\text{Ci}} \times \text{dose factor}\left(\frac{\text{MeV}}{\text{dis}}\right) \times \frac{1.6\times10^{-6} \text{ erg}}{\text{MeV}} \times \frac{1 \text{ g-rem}}{100 \text{ erg}} \times \frac{3.156\times10^{7} \text{ s}}{\text{yr}}$

from Reference 3

	^{238}Pu	^{239}Pu
dose factors $\left(\frac{MeV}{dis}\right)$	284	266

APPENDIX B

USER'S GUIDE FOR THE DOSTOMAN COMPARTMENTAL MODEL

DPST-81-549

CC: J. D. Spencer
E. L. Albenesius
J. R. Wiley
C. M. King
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DOCUMENTATION AND USER'S GUIDE FOR "DOSTOMAN" -
A PATHWAYS COMPUTER MODEL OF RADIONUCLIDE MOVEMENT

By: R. W. Root, Jr.

TABLE OF CONTENTS

DPST-81-549

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

MEMORANDUM

July 13, 1981

TO: E. L. ALBENESIUS

FROM: R. W. ROOT, JR.

TIS FILE
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DOCUMENTATION AND USER'S GUIDE FOR "DOSTOMEN" - A PATHWAYS COMPUTER MODEL OF RADIONUCLIDE MOVEMENT

ABSTRACT

This report documents the mathematical development and the computer implementation of the Savannah River Laboratory computer code used to simulate radionuclide movement in the environment. The user's guide provides all the necessary information for the prospective user to input the required data, execute the computer program, and display the results.

INTRODUCTION

Solid waste contaminated with radionuclides has been buried at the Savannah River Plant (SRP) burial ground since 1953. The radionuclides include alpha-emitting transuranium (TRU) nuclides, tritium and beta- and gamma-emitting activation and fission products. To evaluate current operating limits for burial of this waste and to aid planning for the eventual decommissioning of the burial ground, the long-term dose to man from each type of waste must be estimated. The dose projections will provide guidance in choosing alternatives for a burial ground decommissioning plan. Such alternatives may include exhuming selected segments of the waste to reduce the long-lived radionuclide inventory or providing additional backfill over the waste trenches. The sensitivity of dose projections to the length of institutional control over the burial ground will provide an estimate of the minimum time period such control must be maintained.

To provide these estimates of long term dose to man, a mathematical model has been developed at Savannah River Laboratory (SRL). The model consists of compartments which represent different portions of the environment, including vegetation, herbivores, ground water, atmosphere, surface water, and man. Movement of radionuclides between compartments is controlled by transfer coefficients, which specify the fraction of radionuclides entering or leaving a compartment during a specified time period. Sources and sinks independent of the natural radionuclide movement are provided for.

MODEL DESCRIPTION

The general form of the equation was derived by personnel at the Oak Ridge National Laboratory for a study to predict the uptake of selected radioactive species by cows.[1] Later refinements were made by personnel at SRL.

The data required to run the model include all those factors which influence the rate of movement of radionuclides in the environment. Such hydrologic, geochemical, and lithologic information as water table disposition, ion distribution coefficients, bulk density, and porosity must be known. The radionuclide inventory must be defined as an initial condition for a simulation. Data must also be available on plant and animal concentration factors. Site-specific data is desirable; however, considerable information may be obtained from the literature. Details of how the transfer coefficients are determined for each compartment interaction have been discussed by Wilhite.[2, 3]

The model has been used to project the radioactive dose to man assuming a small subsistence farm is established on the burial ground during the post-operational period. Results of this work have been published[4, 5, 6, 7] and the reader is referred to these for an application of the model to a hypothetical but plausible situation.

THEORETICAL DEVELOPMENT

The approach used in the DOSTOMAN model employs a single equation that considers only the movement of radionuclides through the system. Such factors as water and wind velocity are accounted for in the transfer coefficients.

Formulation of the Basic Equation

The equation governing radionuclide movement accounts for the four factors determining the radionuclide inventory in a compartment: 1) transfer in from other compartments, 2) transfer out to other compartments, 3) source or sink terms, and 4) radioactive decay. These factors are all included in the following generalized linear differential equation:

$$\frac{dQ_n}{dt} = \sum_{m=1}^{N} \lambda_{n,m} Q_m - \sum_{m=1}^{N} \lambda_{m,n} Q_n - \lambda_R Q_n \pm S_n \qquad (1)$$

where: Q_n represents the quantity of nuclide in compartment n (curies), Q_m represents the quantity of nuclide in compartment m (curies), $\lambda_{n,m}$ is the transfer coefficient for the transport of radionuclides from compartment m to compartment n (year^{-1}), λ n,m is the transfer coefficient for the transport of radionuclide from compartment n to compartment m (year^{-1}), λ_R is the decay constant for the radionuclide (year^{-1}), S_n is a source or sink term in compartment n (curies/year), and N is the maximum number of compartments under consideration.

Thus, the first term to the right of the equal sign in the equation is the sum of all input rates to compartment n, the second term is the sum of all loss rates from compartment n, the third term is the loss from compartment n due to radioactive decay, and the fourth term is the gain or loss in compartment n due to sources or sinks, respectively.

Expansion and Solution of the Equations

Equation (1) can be specified for compartment n=1 as

$$\sum_{m=1}^{N} \lambda_{1,m}Q_m - \sum_{m=1}^{N} \lambda_{m,1}Q_1 - \lambda_R Q_1 + S_1 = \frac{Q_1 - Q_1^{\circ}}{\Delta t} \quad (2)$$

where Q_1° is the radionuclide inventory in compartment 1 at the beginning of the time step and all other terms are described above. Equation (2) is then partially expanded to:

$$\lambda_{1,1}Q_1 + \lambda_{1,2}Q_2 + \ldots + \lambda_{1,N}Q_N - Q_1 \sum_{m=1}^{N} \lambda_{m,1} - \lambda_R Q_1 + S_1 = \frac{Q_1 - Q_1^{\circ}}{\Delta t}$$

Isolating Q_1 terms gives

$$\left[\lambda_{1,1} - \sum_{m=1}^{N} \lambda_{m,1} - \frac{1}{\Delta t} - \lambda_R\right] Q_1 + \lambda_{1,2}Q_2 + \ldots + \lambda_{1,N}Q_N + S_1 = \frac{-Q_1^{\circ}}{\Delta t}$$

Analogously, for compartment n=2,

$$\lambda_{2,1}Q_1 + \left[\lambda_{2,2} - \sum_{m=1}^{N} \lambda_{m,2} - \frac{1}{\Delta t} - \lambda_R\right] Q_2 + \lambda_{2,3}Q_3 + \ldots + \lambda_{2,N}Q_N + S_2 = \frac{-Q_1^{\circ}}{\Delta t}$$

The equation can be generalized, then, for compartment n, as

$$\lambda_{n,1}Q_1 + \ldots + \lambda_{n,n-1}\, Q_{n-1} + \left[\lambda_{n,n} - \sum_{m=1}^{N} \lambda_{m,n} - \frac{1}{\Delta t} - \lambda_R\right] Q_n +$$

$$\lambda_{n,n+1}\, Q_{n+1} + \ldots + \lambda_{n,N}Q_N + S_n = \frac{-Q_n^{\circ}}{\Delta t}$$

where n=1,2,...N

The result of this expansion is a set of simultaneous, linear differential equations which defines the radionuclide inventory in compartment n (n=1,2...,N) with time as a function of transfer mechanisms ($\lambda_{n,m}$), radioactive decay (λ_R), sources and sinks (S_n), the initial radionuclide inventory (Q°_n), and the time increment (Δt). This set of simultaneous equations can be defined in matrix terms as A·X=B

where

$$A = \begin{bmatrix} \left[\lambda_{1,1} - \sum_{m=1}^{N} \lambda_{m,1} - \frac{1}{\Delta t} - \lambda_R\right] & \lambda_{1,2} & \cdots & \lambda_{1,N} \\ \lambda_{2,1} & \left[\lambda_{2,2} - \sum_{m=1}^{N} \lambda_{m,2} - \frac{1}{\Delta t} - \lambda_R\right] & \cdots & \lambda_{2,N} \\ \vdots & \vdots & & \vdots \\ \lambda_{N,1} & \lambda_{N,2} & \cdots & \left[\lambda_{N,N} - \sum_{m=1}^{N} \lambda_{m,N} - \frac{1}{\Delta t} - \lambda_R\right] \end{bmatrix}$$

$$X = \begin{bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ \cdot \\ Q_N \end{bmatrix} \qquad (4)$$

$$B = \begin{bmatrix} -Q_1^\circ/\Delta t - S_1 \\ -Q_2^\circ/\Delta t - S_2 \\ \cdot \\ \cdot \\ \cdot \\ -Q_N^\circ/\Delta t - S_N \end{bmatrix} \qquad (5)$$

The solution to this equation is therefore $X=A^{-1}B$ and is accomplished by Gauss-Jordan elimination.[8] The result is the value for Q_n at time t for each compartment n (n=1,2,...N). This value for Q_n is the radionuclide inventory averaged over the entire compartment n.

COMPUTER IMPLEMENTATION

The computer program consists of a main program (module DOSTOMAN) and seven subroutines (Figure 1).

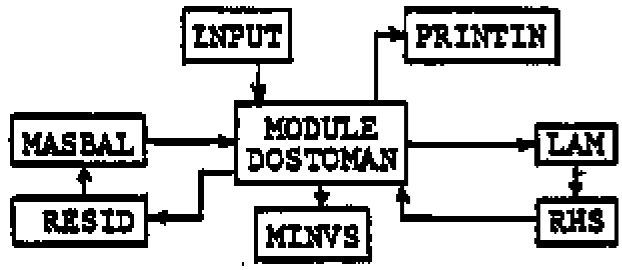

FIGURE 1. Flow Chart of DOSTOMAN

DOSTOMAN performs the main control function by coordinating the input and output of data and the calculations of compartment radionuclide inventories. The entire module is run for each time step specified and subroutines are called in clockwise order in Figure 1, beginning with subroutine INPUT.

Module DOSTOMAN is divided into two basic sections: 1) calculation of radionuclide inventories in compartments assuming transfer coefficients are time independent; either continuous exponential or Gaussian functions with time or discontinuous step functions and 2) calculation of inventories assuming that some component of a transfer coefficient changes either additively or geometrically during the period being simulated.

Subroutine INPUT reads in the initial data from seven records. These data include: radioactive decay constant, number of compartments, number of compartments with sources or sinks, time step, values and compartment locations of sources or sinks, initial compartment radionuclide inventories, transfer coefficient components, time functions to control the application of the transfer coefficients, and factors to perturb components of transfer coefficients, if applicable. Other input records give plotting and editing specifications. The only calculations performed in this subroutine involve the transfer coefficients, which are of the form $A \cdot V^X$. The individual components A, V, and X are read at this time and the transfer coefficients are calculated. If requested, all input data is printed by PRINTIN.

In the main program, all transfer coefficients, sources, and sinks are corrected for time dependence, if any, and the coefficient matrix is set up. Subroutine LAM is then called to calculate the terms on the diagonal in the A matrix (equation (3)). This involves summing the λ's from m=1 to m=N and subtracting $\frac{1}{\Delta t}$ and λ_R. After this calculation, coefficients of the A matrix are ready for the solution of the simultaneous equations.

Subroutine RHS is then called to set up the right-hand side of the simultaneous equations - the B matrix in equation (5). This involves making each term (B_n) in the B matrix equal to $-Q_n/\Delta t$ where n=1,...N. If compartment n contains a source or sink, the time dependence of the source or sink is accounted for and the B_n are adjusted accordingly:

$$B_n = \frac{-Q_n^\circ}{\Delta t} - S_n \quad (n=1,\ldots,N)$$

Upon returning to the main program, the matrices A, X, and B are ready for solution by matrix inversion. Solution is accomplished by calling subroutine MINVS*, which calculates the determinant and the inverse of the A matrix (the values) for the matrix problem A X=B and finds the solution vector X. Upon return from MINVS, matrix A contains the inverse matrix; therefore, the original matrix A is destroyed. Matrix B then contains the solution vector X (in this case, the Q_n). The solution is accomplished by the standard Gauss-Jordan elimination method. Details of this method can be found in matrix algebra texts.[9] The Q_n values are then printed and any requested plots are made.

Two means of evaluating the numerical stability of the code are included in the program. Subroutine RESID determines the difference (residual) between the calculated values for the right-hand and the left- hand sides of the set of simultaneous equations solved by matrix inversion in subroutine MINVS. The subroutine RHS uses the values calculated at a particular time; therefore, the difference between the two sides of each equation is a measure of how accurate the solution is. Ideally, the residual should be zero; some small residual can be accounted for by round-off and truncation errors in the calculations and is usually insignificant.

An initial inventory is provided to the system by the Q_n° values. If no sources or sinks add or remove radionuclides from the system during the run, this initial amount of radionuclide must be maintained throughout the run, adjusted, of course, for radioactive decay. Subroutine MASBAL calculates the state of mass balance by summing all of the Q_n values at a particular time and comparing the total to the sum of initial Q_n° values. Ideally, the deviation from mass balance should be zero; again, round-off and truncation errors may contribute to a small deviation.

At this point in the program, time is incremented by either a specified or a calculated time step and the model is rerun to calculate Q_n values for a new time. This is done until the specified simulation time is achieved or the number of time steps is consumed.

The second part of module DOSTOMAN calculates radionuclide inventories if any component of a transfer coefficient is to be changed, or perturbed, during the run. Specifications for such perturbations, if

---

* MINVS is an IBM-supplied scientific subroutine.

any, are read in subroutine INPUT. If a perturbation of a transfer coefficient is to occur, the original transfer coefficient values are read in and the perturbation is calculated. The perturbation may be geometric or additive in nature and the Q_n values resulting from the perturbation are calculated only for steady-state conditions. The same calculation method for Q_n is used here as was used for the first part of module DOSTOMAN. Q_n values are then printed out.

The program listing of module DOSTOMAN and relevant subroutines is provided in Appendix A. The definitions of variables are given in Appendix B.

TEST CASES

The following test cases are included to demonstrate the capability and options of the code. They should not be interpreted as answers to specific physical problems.

Test Case 1

A three-compartment model was set up with radionuclide movement allowed from compartment 1 to compartment 2, from compartment 2 to compartment 3, and from compartment 3 to compartment 1. All transfer coefficients had a value of 1 (i.e., all radionuclide inventory in the compartment was transferred each year). An initial inventory of 10 curies was provided to compartment 1 while no inventory was provided to compartments 2 and 3. No sources, sinks, or radioactive decay were allowed. The case was run for 50 years of simulated time with a time step of 1.5 years.

Time vs. concentration plots for each compartment are shown in Figure 2. As expected, after a period of time all compartment inventories approached the same value. In this case it was one-third of the initial system radionuclide inventory, or 3.333 curies in each compartment.

Test Case 2

This case was the same as Test Case 1 except that radioactive decay was allowed at the rate of 1 per year. All other parameters remained the same, except that the time step for this case was 0.08 years. Time vs. concentration plots for this case are shown in Figure 3. Radionuclides circulated through the system but gradually declined in concentration, approaching zero with time.

Test Case 3

This case was the same as Test Case 1 but sources or sinks were provided in 2 compartments. Compartment 2 had a sink of strength -10 curies/year and compartment 3 had a source of +10 curies/year. Also, no initial radionuclide inventory was provided to any compartment.

Time vs concentration plots are shown in Figure 4. The material being supplied to compartment 3 is gradually spread evenly through the system. Therefore, the inventories in compartments 1 and 3 approach 3.333 curies and the amount of loss from compartment 2 is reduced to -6.666 curies. Note however, that a negative activity is aphysical, and is allowed here only for test purposes.

Test Case 4

This case was the same as Test Case 1 but the transfer coefficient between compartments 3 and 1 was subjected to a time function. The transfer coefficient was allowed to decrease in strength exponentially at a rate of 1 per year, beginning at time zero.

Time vs. concentration plots are shown in Figure 5. Transfer from compartment 3 to compartment 1 gradually declines, causing all inventory to accumulate in compartment 3. Inventories in compartments 1 and 2 approach zero.

Test Case 5

This case was the same as Test Case 1 but the transfer coefficient between compartments 2 and 3 was subjected to a time function. The transfer coefficient was allowed to increase in strength in a linear manner at the rate of 1 + time.

Time vs. concentration plots are shown in Figure 6. Transfer from compartment 2 to compartment 3 gradually increases, causing inventory to diminish in compartment 2 and gradually approach equality in compartments 1 and 3.

Test Case 6

This case was the same as Test Case 1 but two sources were provided to each compartment. The sources all had strength +10 curies/year for the first 40 years of simulated time and then declined to +0.5 curies/year for the remainder of the simulation.

Time vs. concentration plots are shown in Figure 7. The inventories in all compartments rise rapidly until 40 years, after which they continue to rise but at a much lower rate.

USER'S GUIDE

General

The dose-to-man model is presently programmed to run under the SRL JOSHUA data management system. JOSHUA is an operating system which provides the data handling services required to accomplish extensive scientific calculations on a large data base. Input to the model is by pre-formatted templates; input is entered at specific locations on templates in response to a data request, rather than simply on the lines of a card. For general batch-run use of the model it is only necessary to specify the appropriate format in all READ statements in the main program and in subroutine INPUT and in all PRINT statements in subroutine PRNTIN.

Data Input

The data input templates, or records, are discussed individually below in the order in which they are called in subroutine INPUT or, for plotting routines, in the order in which they are called in the main program. The format of the templates and sample input values are also shown.

INPUT.DOSTOMAN.GENERAL.TEST0001
The "TEST0001" in the name of this record is an eight unit string of alphanumeric characters (always beginning with a letter) which is used as a job name. The format for the first page of the "GENERAL" record is:

```
4420.INPUT.DOSTOMAN.GENERAL.TEST0001

CASE NAME :CASE0001
RADIOACTIVE DECAY CONSTANT FOR ISOTOPE :1.0000E-03
NUMBER OF COMPARTMENTS :   3
NUMBER OF COMPARTMENTS WITH SOURCE OR SINK TERMS :   1
```

"CASE NAME" is, like the job name, an eight alphanumeric character string (always beginning with a letter) which defines a specific case associated with the job name. For this example a "CASE NAME" of "CASE0001" is used. The radioactive decay constant is read in exponential form and must be in units compatible with the transfer coefficients discussed later (generally as year^{-1}). The total number of compartments in the model is specified, up to 999. The number of compartments in the model with source or sink terms is specified, up to the total number of compartments in the model. If there are no sources or sinks, there is only one page to the "GENERAL" record. If there are sources or sinks the second page has the format:

```
4420.INPUT.DOSTOMAN.GENERAL.TEST0001

SPECIFY THE COMPARTMENT NUMBER OF EACH COMPARTMENT WHICH
CONTAINS A SOURCE OR SINK TERM.
      INDEX                  COMPARTMENT NUMBER
        1                         :  1
```

The "INDEX" is supplied automatically by the code. The compartment number of each compartment containing a source or sink is given in the right-hand column, one to a line. For this example a source or sink term occurs in compartment 1; the nature of the source or sink is provided in a later record.

INPUT.DOSTOMAN.CASE0001.TIMESTEP

The time step specifications are made in the "TIMESTEP" record, which has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.TIMESTEP

DO YOU WANT TO USE AUTOMATIC TIME STEP SELECTION? : NO  (YES/NO)
IF NO, GO TO THE NEXT PAGE. IF YES, COMPLETE THE FOLLOWING.

SPECIFY MAXIMUM PERMISSIBLE CHANGE IN CONCENTRATION
PER TIME STEP :0.0000E 00
SPECIFY THE SIZE OF THE FIRST TIME STEP :0.0000E 00  (SECS)
```

The code will generate its own time steps if "YES" is selected in the first line. If automatically selected, the following equation is used:

$$\Delta t_{K+1} = \frac{\varepsilon \Delta t_K}{\Delta Q_{max}}$$

where ε = maximum desired change in any Q_n per time step,

Δt_K = previous time step size, and

ΔQ_{max} = maximum absolute change in Q_n in any compartment during the previous time step.

Note that Δt_{K+1} increases if $\Delta Q_{max} < \varepsilon$ and decreases if $\Delta Q_{max} > \varepsilon$.

Alternatively, the user may select "NO" in the first line; if so, the second page of the "TIMESTEP" record has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.TIMESTEP

DEFINITION--A TIME DOMAIN IS AN INTERVAL OF TIME SUBDIVIDED
INTO AN ARBITRARY NUMBER OF EQUAL SIZE TIME STEPS
SPECIFY THE NUMBER OF TIME DOMAINS DESIRED :  2  (MAX IS 10)
     MAXIMUM NUMBER OF TIMESTEPS IN ALL DOMAINS IS 1000
     DOMAIN INDEX    NO. OF TIMESTEPS        TIMESTEP SIZE(SECS)
          1               : 10                  :1.5000E 00
          2               : 10                  :3.0000E 00
```

The time steps may be divided into a maximum of 10 time domains, each with a user-specified number of time steps of a given duration. For this example, this simulation will run for 10 time steps of 1.5 seconds each and then for 10 time steps of 3 seconds each, for a total simulated time of 45 seconds. Alternatively, the same simulated time could be obtained by one domain of 10 time steps that are 4.5 seconds each.

INPUT.DOSTOMAN.CASE0001.LAMBDA-Q.n

For each compartment, the non-zero interactions between that compartment and all other compartments are specified. This record has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.LAMBDA-Q.3

SPECIFY THE NUMBER OF NON-ZERO LAMBDA-Q TERMS FOR THIS
COMPARTMENT : 2
SPECIFY THE NON-ZERO LAMBDAS BELOW
     INDEX           N  ,   M
       1           : 3  ,  : 2
       2           : 1  ,  : 3
```

For this example, the interactions for compartment 3 are specified. They are two in number: transfer into compartment 3 from compartment 2 and transfer from compartment 3 into compartment 1.

INPUT.DOSTOMAN.CASE0001.SOURCE.OR.SINK.TERMS.n

The sources and/or sink terms for compartment n, if any, are specified in the "SOURCE.OR.SINK.TERMS" record which has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.SOURCE.OR.SINK.TERMS.1

SPECIFY THE NUMBER OF SOURCE OR SINK TERMS IN THIS
COMPARTMENT : 1     (MAX IS 10)
THE GENERAL FORM IS
          S(T)=0   T<T1
              =SMAX     T1<T<T2
              =0        T>T2
INDEX         SMAX          T1              T2
  1        :1.0000E 00   :0.0000E 00      :1.0000E 05
```

Repeated injection and withdrawal of radioactivity in any compartment is permitted during arbitrary time intervals, provided that the time intervals do not overlap. For example, in compartment n there may be up to 10 sources or sinks of the form

$$
\begin{aligned}
S_n &= S^*_{n,1} && t_1 < t \le t_2 \\
&= S^*_{n,2} && t_3 < t \le t_4,\ t_3 > t_2 \\
&\ \vdots \\
&= S^*_{n,M} && t_{2M-1} < t \le t_{2M},\ t_{2M-1} > t_{2M-2}
\end{aligned}
$$

where $M \le 10$ and $S^*_{n,m}$ (curies/year) are non-zero only within their respective time intervals. For the example above, compartment 1 has a single source of strength 1 curie/year which operates from time = 0 seconds to time = 1×10^5 seconds. A sink is specified by a negative sign preceding the value given in SMAX. The "INDEX" is automatically provided by the code.

INPUT.DOSTOMAN.CASE0001.INITIAL.VALUES

Selected compartments may have an initial inventory of radionuclides, which is then distributed during the simulation. The initial inventories are given in the "INITIAL.VALUES" record, which has the format:

```
            4429.INPUT.DOSTOMAN.CASE0001.INITIAL.VALUES

     NUMBER OF COMPARTMENTS:  5
          COMPARTMENT INDEX           INITIAL VALUE
                  1                    :0.0000E 00
                  2                    :1.0000E 10
                  3                    :0.0000E 00
```

For this example, compartment 2 has an initial inventory of 1×10^{10} curies, while compartments 1 and 2 initially have no radioactivity.

INPUT.DOSTOMAN.CASE0001.LAMBDA.n.m

The rate of transfer of radionuclides between compartments is controlled by transfer coefficients, or lambdas.

$$\lambda_{n,m} = \text{LAMBDA.n.m}$$

specifies the transfer coefficient for movement from compartment m to compartment n and is the fraction of activity in compartment m moving to compartment n during a given time period. The "LAMBDA" record has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.LAMBDA.2.1

LAMBDA IS A SUMMATION OF THE FORM
.     LAMBDA=A(I)*V(I)**(X(I))        I=1,IX
SPECIFY IX : 2          (MAX IS 7)
    INDEX              A                 V                -X
      1          :1.0000E 00      :1.0000E 00      :1.0000E 00
      2          :5.0000E-01      :2.0000E 00      :-.1000E 01
```

Considerable flexibility is introduced into the model by permitting the transfer coefficients $\lambda_{n,m}$ to be expressed as a polynominal in terms of arbitrary variables $V_{i,n,m}$. Thus,

$$\lambda_{n,m} = \sum_{i=1}^{N} \left(a_i V_{i,n,m}^{X_i} \right) \qquad N \leq 7$$

where a_i, X_i = arbitrary coefficients and exponents, respectively, for the variable $V_{i,n,m}$.

For the example above, the transfer coefficient for movement from compartment 1 to compartment 2 is defined. Thus,

$$\lambda_{2,1} = 1.0 \times 1.0^{1.0} + 0.5 \times 2.0^{-1.0} = 1.25 \text{ year}^{-1}$$

The "INDEX" is provided automatically by the code.

INPUT.DOSTOMAN.CASE0001.TIME.FUNCTION

The transfer coefficients can be made time - dependent through selection of one of the following three functional forms:

A polynomial form

$$f_{n,m}(t) = \sum_{j=1}^{J} A_j \, t^{j-1}, J \leq 4$$

where A_j = arbitrary coefficients and
t = time;

an exponential form

$$f_{n,m}(t) = e^{at}$$

where a = arbitrary coefficient and
t = time;

and a step-function form

$$f_{n,m}(t) = f_{n,m} \text{ for } t_1 \leq t \leq t_2 \text{ and}$$

$$f_{n,m}(t) = 0 \text{ for } t < t_1 \text{ and } t > t_2$$

where $f_{n,m}$ = a fraction and
t_1, t_2 = times.

The expression for the transfer coefficient then becomes

$$\lambda_{n,m} = f_{n,m}(t) \sum_{i=1}^{N_{n,m}} A_i \, V_{i,n,m}^{X_i}.$$

The first page of the "TIME.FUNCTION" record has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.TIME.FUNCTION

        1ST QUALIFIER = ?CASE = CASE NAME

SPECIFY THE NUMBER OF TIME DEPENDENT LAMBDAS :  1 (MAX IS 100)
```

Up to 100 time-dependent lambdas may be specified.

The second page has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.TIME.FUNCTION

FOR LAMBDA (N,M) :  3  :  2 PLACE AN 'X' BESIDE THE DESIRED
FUNCTIONAL FORM AND SUPPLY THE REQUESTED CONSTANTS.
  --POLYNOMIAL :     F(T) = A(1) + A(2)*T + A(3)*T**2 + A(4)*T**3
        SPECIFY  A(1)=:0.000E 00     A(2)=:0.000E 00
                 A(3)=:0.000E 00     A(4)=:0.000E 00
  --EXPONENTIAL :X     F(T) = EXP(A*T)
        SPECIFY  A=:1.000E-02
  --STEP :     F(T)    = 0, T<T1;     = FMAX, T1<T<T2;     = 0, T>T2
        SPECIFY  NUMBER OF STEP FUNCTIONS : 0 (MAX IS 8)
      RE-SPECIFY NUMBER OF STEP FUNCTIONS : 0 (TO READ TEMPLATE)
```

For this example, the exponential form of the time function was selected. Therefore:

$$\lambda_{3,2}(t) = \lambda_{3,2}\, e^{a \cdot a \cdot t}$$

(i.e., the transfer coefficient increases exponentially with time). Alternatively, a polynominal form or a step form could be selected, if appropriate.

INPUT.DOSTOMAN.CASE0001.PLOT.

This record has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.PLOT

NUMBER OF PLOTS DESIRED:  1
   PLOT INDEX        COMPARTMENT NUMBERS TO BE PLOTTED
       1              : 1       : 2       : 3     : 0
```

and allows results to be plotted using the appropriate hardware. In this example, the radionuclide inventory vs. time data for all three compartments would be plotted on the same graph. Alternatively, three plots could be requested, with data from each compartment appearing on its own plot.

INPUT.DOSTOMAN.CASE0001.EDIT

The "EDIT" record controls the printing of input data and specifies the perturbing of lambdas. It has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.EDIT

DO YOU WANT ALL INPUT RECORDS PRINTED? :YES   (YES/NO)

IF YOU WANT AN EDIT OF ALL COMPARTMENT VALUES VERSUS TIME,
SPECIFY THE DESIRED EDIT FREQUENCY AS EVERY : 1 (NTH) TIME
STEP.

IF YOU WANT TO PERTURB SOME OF THE LAMBDAS AFTER RUNNING THE
CURRENT PROBLEM, PLACE AN 'X' IN THE FOLLOWING FIELD :X
  NOTE--ONLY A STEADY STATE CALCULATION WILL BE PERFORMED FOR
        EACH PERTURBATION.
```

If "YES" is stated on the first line then all input records will be printed with the results. Not all simulation results have to be printed: the second line allows the user to request a specific interval for results to be printed (e.g., every 20th time step). In this example, the results for each time step will be printed.

In some cases it may be desirable to see the effects of perturbing a variable in a lambda (i.e., during the course of a simulation a variable of a lambda changes in a regular fashion). This option is requested here. However, note that the results of this simulation will be given only for a steady-state calculation. Perturbing variables is discussed in more detail below.

INPUT.DOSTOMAN.CASE0001.PERTURB.VARIABLE

The first page of the "PERTURB.VARIABLE" record has the format:

```
        4420.INPUT.DOSTOMAN.CASE0001.PERTURB.VARIABLE

    SPECIFY THE NUMBER OF VARIABLES (NOT LAMBDAS) TO BE
    INCREMENTED : 2  (MAX IS 20)
```

For this example, two variables (the $V_{i,n,m}$ terms of some lambda or lambdas) will be perturbed. Note that this option is not actually perturbing the lambda itself but only a component of it.

The sensitivity of a given steady-state calculation to the arbitrary variables $V_{i,n,m}$ may be evaluated by perturbing the $V_{i,n,m}$ one at a time, as follows. Let

$$V_{i,n,m} = V^{\circ}_{i,n,m} + (j-1)\,\Delta V_{i,n,m},\quad j = 1,2,3\ldots$$

where $V^{\circ}_{i,n,m}$ = best estimate of $V_{i,n,m}$ and

$\Delta V_{i,n,m}$ = arbitrary increment (or decrement) of $V_{i,n,m}$.

The code will initially compute the activity Q_n in each compartment using $V^{\circ}_{i,n,m}$. After completing this computation, the code will then compute the j^{th} steady-state solution with $V_{i,n,m}$ incremented (or decremented) by $V_{i,n,m}$.

The "PERTURB.VARIABLE" record for the additive perturbation has the format:

```
        4420.INPUT.DOSTOMAN.CASE0001.PERTURB.VARIABLE

    INDEX      1
    SPECIFY VARIABLE AS V(I,N,M) :2  ,:  2  ,:  1
    PLACE AN 'X' BESIDE THE DESIRED FORM
    ADDITIVE:X      V=V(0)+DELY
             SPECIFY V(0)=:2.0000E 00
                     DELV=:1.0000E 00
                     NO. OF INCREMENTS : 3
    GEOMETRIC:A      V=V(0)**N        (N IS AN INTEGER COUNTER)
             SPECIFY V(0)=:1.0000E 00
```

In this example, the second variable in $\lambda_{2,1}$ is initially $V^0_{2,2,1}$ =2, but is then increased by $\Delta V_{2,2,1}$ =1 for each successive steady-state calculation. Therefore, for the first run $V_{2,2,1}$ =2, for the second run $V_{2,2,1}$ =3, for the third run $V_{2,2,1}$ =4, and for the final run $V_{2,2,1}$ =5.

Alternatively, the user may select a geometric perturbation of the form

$$V_{i,n,m} = (V^0_{i,n,m})^N \ , \ N = 1,2,3...$$

The "PERTURB.VARIABLE" record for the geometric perturbation has the format:

```
4420.INPUT.DOSTOMAN.CASE0001.PERTURB.VARIABLE

INDEX     2
SPECIFY VARIABLE AS V(I,N,M) :1  ,:  1  ,:  3
PLACE AN 'X' BESIDE THE DESIRED FORM
ADDITIVE:        V=V(0)+DELV
          SPECIFY V(0)=:0.0000E 00
                  DELV=:0.0000E 00
                  NO. OF INCREMENTS : 0
GEOMETRIC:       V=V(0)**N       (N IS AN INTEGER COUNTER)
           SPECIFY V(0)=:2.0000E 00
                  MAX. VALUE OF N=: 3
```

For this example the first variable in $\lambda_{1,3}$ is initially $V^0_{1,1,3} = (2)^1 = 2$. In the second steady-state calculation $V_{1,1,3} = (2)^2 = 4$ and in the third and final run $V_{1,1,3} = (2)^3 = 8$.

The use of an additive or geometric perturbation requires the presence of at least one constant, non-zero source term S_n if radioactive decay is present. Otherwise, all of the Q_n go to zero as $t \to \infty$. If radioactive decay is not occuring it is only necessary to specify Q^0_n.

The steady-state results may be printed by providing the compartment numbers of interest:

```
4420.INPUT.DOSTOMAN.CASE0001.PERTURB.VARIABLE

SPECIFY THE NUMBER OF COMPARTMENT VALUES TO BE PRINTED :  3
          INDEX              COMPARTMENT NUMBER
            1                       :  1
            2                       :  2
            3                       :  3
```

As mentioned earlier, the perturbed variable option calculates compartment radionuclide inventories only for steady-state conditions. This is accomplished by specifying the time step as $1x10^{20}$ seconds and proceeding with the calculation. A potential error is introduced at this point due to the use of the Taylor approximation:

$$Q_n\,(t-\Delta t) = Q_n(t) - \Delta t\,\frac{dQ_n}{dt}\Big|_t + \frac{(\Delta t)^2}{2!}\,\frac{d^2Q_n}{dt}\Big|_t - \ldots$$

$$\approx Q_n(t) - \Delta t\,\frac{dQ_n}{dt}\Big|_t$$

$$\text{or } \frac{dQ_n}{dt} \approx \frac{Q_n(t) - Q_n\,(t-\Delta t)}{\Delta t}\,.$$

This relationship is accurate, however, only for small Δt ; specifying $\Delta t = 1x10^{20}$ has the effect of making $\frac{dQ_n}{dt} = 0$. In the matrix definition (equation 5)

$$B = \begin{bmatrix} -Q_1^*/\Delta t - S_1 \\ -Q_2^*/\Delta t - S_2 \\ \vdots \quad\quad \vdots \\ -Q_n^*/\Delta t - S_n \end{bmatrix}$$

In the absence of sources or sinks and with $\Delta t = 1x10^{20}$, matrix $B = 0$. The matrix solution is $A \cdot X = B$ and $X = A^{-1} \cdot B$ where A^{-1} = inverse of matrix A.

Then

$$X = \frac{\tilde{A} \cdot B}{|A|}$$

where $\tilde{A}$ = adjoint of matrix A and
$|A|$ = determinant of matrix A.

But $B = 0$; therefore $X = 0$(i.e., $Q_n(t) = 0$).

This may be analytically erroneous, although numerically correct.

A plausible steady-state solution is possible only if there is at least one non-zero term in matrix B. This is accomplished by providing a source or sink term. However, in order to maintain conservation of mass, any source (or sink) must be countered by a sink (or source) of equal magnitude in another compartment.

Plotting Specifications

The following records are called from the main program and relate to the plotting of results. "DISS2D" refers to the two-dimensional plotting capabilities of the "DISSPLA" system at SRL, a set of user-callable subroutines for creating graphical displays of computer data.

INPUT.DISS2D.JOB.TEST0001

This record has the format:

```
     4420.INPUT.DISS2D.JOB.TEST0001
 NUMBER OF PLOTS : 1   (EACH PLOT IS DRAWN ON 6X8 INCH PAGE)

     4420.INPUT.DISS2D.JOB.TEST0001
 NAME OF EACH PLOT
 :TEST

     4420.INPUT.DISS2D.JOB.TEST0001
 IDEN TO APPEAR ON TOP EDGE OF MICROFICHE(PUT $ AT END OF LABEL)
 :
```

This record allows the number and name of all plots and any title on microfiche to be specified.

INPUT.DISS2D.PLOT.plot name

This record allows various plotting specifications to be made. "TEST" in the heading corresponds to the plot name from the "JOB" record immediately above. The format for the template for this record is shown below; for this example the plot name is "1". The first page has the format:

```
:      TEMPLATE.INPUT.DISS2D.PLOT.1

TITLE FOLLOWS (3 LINES) PUT $ AT END OF EACH LINE
LINE 1 :AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
LINE 2 :AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
LINE 3 :AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA


X AND Y AXIS LABELS . PUT $ AT THE END OF EACH LABEL
X AXIS :AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Y AXIS :AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

The plot title and axis labels are specified. The "A's" represent alphanumeric characters. Note that a "$" symbol must be placed at the end of each line or label.

The second and third pages have the format:

```
:      TEMPLATE.INPUT.DISS2D.PLOT.1

OPTIONS-SMOOTH DATA(SEE REP CN SPLINE FITTING) YES=0,NO=1 :I
PRINT INPUT DATA (YES=1, NO=0) :I
MARKER (CONNECT POINTS(YES=+,NO=-);DRAW MARK AT ITH POINT) :II
ELIMINATE DISSPLA BOOKEEPING ON HARDCOPY (YES=0,NO=1) :I
NUMBER OF CURVES ON PLOT(MAX 4) :I
ORIENTATION 6X8(0),8X6(1):I
KIND OF CURVES(LINEAR=1,SEMILOG=2,LOGLOG=3) :I
NO. GRID LINES BETWEEN TICK MARKS ON X AXIS:II ON Y AXIS:II
NO. LOG CYCLES IF APPLICABLE-X AXIS:II   Y AXIS:II
CALCULATE X VALUES FROM XORG,XMAX,AND NO. POINTS(NO=0,YES=1):I
```

```
:      TEMPLATE.INPUT.DISS2D.PLOT.1

XORGIN   :EE.EEEEEE
XMAX     :EE.EEEEEE
YORGIN   :EE.EEEEEE
YMAX     :EE.EEEEEE
TICK MARKS
  UNITS PER INCH ON X AXIS (DEFAULT=0)   :E.EEEEEEEEE
  UNITS PER INCH ON Y AXIS (DEFAULT=0)   :E.EEEEEEEEE
```

Various options regarding curve-fitting, data output, and axis specifications are made on these pages.

The last page of the "PLOT" record has the format:

```
:      TEMPLATE.INPUT.DISS2D.PLOT.1

NO OF X VALUES :IIII (TO CALCULATE X VALUES ,SET X=0)
    X(I)          Y(I)          Y(I+1)        Y(I+2)        Y(I+3)
:EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE
:EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE
:EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE
:EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE :EE.EEEEEEEE
```

Calculated results are entered to be plotted. Time values are entered into column "X(I)" and radionuclide inventories for up to four compartments are entered into columns "Y(I)" thru "Y(I+3)". A plot of the time vs. radionuclide inventory is then generated on the appropriate hardware.

INPUT.DISS2D.LEGEND.job name.plot name

This record provides additional information for the plotting option, specifying the location and wording of the legend which identifies the various curves on a plot. The template for this record is shown below, with a job name of "TEST3881" and a plot name of "1".

```
:    3881.TEMPLATE.INPUT.DISS2D.LEGEND.TEST3881.1

XLEG IS THE NUMBER OF INCHES FROM THE PHYSICAL ORIGIN ON X AXIS.
YLEG IS THE NUMBER OF INCHES FROM THE PHYSICAL ORIGIN ON Y AXIS
DEFAULTS ARE USED IF THIS RECORD IS MISSING OR XLEG=0 AND YLEG=0
 XLEG = :FF.FF  YLEG = :FF.FF  (DEFAULTS ARE XLEG=3. AND YLEG=.2
LEGENDS FOLLOW. TO GET DEFAULTS, SHIFT AND ENTER NOW.
***** END EACH LEGEND WITH $  *******
CURVE 1 :AAAAAAAAAAAAAAAA   (DEFAULT IS CURVE 1$)
CURVE 2 :AAAAAAAAAAAAAAAA   (DEFAULT IS CURVE 2$)
CURVE 3 :AAAAAAAAAAAAAAAA   (DEFAULT IS CURVE 3$)
CURVE 4 :AAAAAAAAAAAAAAAA   (DEFAULT IS CURVE 4$)
```

<u>Samples of Results</u>

Whenever a particular time step result is requested to be printed (in the "EDIT" record) a page similar to the following is produced:

```
                                   HHHHHHHHHHHHHHHH     TIME =  1.5400E+00

COMPARTMENT                                                       Q-VALUES

     I       1.6455D+09  9.1840D+09  3.1555D+09

THE RESIDUAL IN COMPARTMENT   1 IS -1.792000E+03

THE RESIDUAL IN COMPARTMENT   2 IS -6.144000E+03

THE RESIDUAL IN COMPARTMENT   3 IS -3.584000E+03
```

On the top line the time in appropriate units is printed. The radionuclide inventory in each compartment is then printed, with compartment 1 at the left. Up to ten compartment results will be printed on a line, then a new line will be started with compartment 11 at the left.

The "Residual in Compartment" is the difference between the calculated values for the right-hand and the left-hand side of the set of simultaneous equations solved by matrix inversion, as discussed under COMPUTER IMPLEMENTATION. If the numerical errors in the computer calculation are small, the residual will be only a small fraction of the compartment inventory.

When variables are perturbed, an additional printout is made which gives the results of the steady-state calculation, with the format:

```
FOR LAMBDA (  2,  1), VARIABLE 2 HAS BEEN PERTURBED.
THE NEW VALUE OF LAMBDA IS  1.1250D+00. THE NEW VALUE OF VARIABLE  2 IS  4.0000E+00
COMPARTMENT              Q-VALUE
     1                   3.8174D-08
     2                   2.5279D-08
     3                   3.9686D-08

THE RESIDUAL IN COMPARTMENT   1 IS -2.861790E-14

THE RESIDUAL IN COMPARTMENT   2 IS -1.635429E-14

THE RESIDUAL IN COMPARTMENT   3 IS -2.873383E-14
```

The particular lambda and variable being perturbed, the new value of the lambda, and the new value of the variable are given, along with the steady-state results and the "Residual in Compartment" results calculated.

The user is referred to Appendices C and D for some important considerations in running the DOSTOMAN model.

Dose Calculations

The results of running module DOSTOMAN are compartment radionuclides inventories in curies. The inventories are the amount of activity accumulating in or being taken in each year by the compartments in the modeled system. As such, the results from DOSTOMAN do not represent a radiation dose to man. To calculate the radiation dose requires information on the effects of the particular radionuclide on the human body. The method of calculating the dose is discussed briefly below and in detail in reference 10.

The dose rate to an organ or to the body is a function of the amount of radioactive material present. The amount q of radioactive material in the body at any time t can be expressed as:

$$q_t = q_o e^{-\lambda t}$$

where q_t = amount of radioactive material in the body at time t (curies)

q_o = initial amount of radioactive material (initial uptake) (curies)

λ = effective decay constant for the radionuclide ($time^{-1}$)

After radionuclides enter the body they decline in number through radioactive decay and through biological decay (the loss due to natural removal processes in the body). These effects are accounted for by calculating a dose conversion factor (DCF) that converts a radioactivity intake in curies to a dose in rem:

$$DCF = \frac{f_w \; R_d \; (\varepsilon) \; (E)}{e_e (m) (\lambda)} \; (1 - e^{-\lambda t})$$

where f_w = fraction of radionuclide ingested that reaches the organ of interest.

R_d = disintegration rate = 3.7×10^4 dis/sec-Ci

ε = effective energy in organ of interest (MeV/dis)

E = energy conversion factor = 1.6×10^{-6} ergs/MeV

e_e = radiation conversion factor = 100 ergs/gm-rem

m = mass of organ of interest (gms)

λ = effective decay constant (year^{-1}) = $\frac{\ln 2}{t_b} + \frac{\ln 2}{t_r}$

t_b = biological decay half-life (years)

t_r = radioactive decay half-life (years)

Units of the dose conversion factor are rems/curie.

For the situation where persons are residing on the low-level waste burial ground beginning sometime after abandonment of the facility, some quantity of radioactivity is entering the body by ingestion and by inhalation continuously over a period of several years. Depending upon the radionuclide, there will be a residence time for the radionuclide in the body ranging from several days to several years. Therefore, intake of a radionuclide during one year may contribute to the radiation dose for several years. Each year's subsequent intake also may contribute to the dose for several years. Therefore, the radiation dose a person receives during one particular year may be a composite dose with contributions by radiation intake for each of several years.

These incremental contributions of each year's intake to the radiation dose are determined for a specific period. This period is typically 50 or 70 years, representing the time the individual resides over the buried waste. The radiation dose received by an organ or by the body due to one year's intake can be obtained by integrating equation 6 over one-year increments following the year of intake:

$$\text{Dose} = (q_o \times DCF) \int_{t_1}^{t_2} e^{-\lambda t}\, dt = (q_o \times DCF) \left(\frac{1-e^{-\lambda t}}{\lambda}\right)\Bigg|_{t_1}^{t_2}.$$

where Dose = radiation dose received by an organ or the body between time t_1 and time t_2 due to the initial intake of q_o.

Assume that an individual intakes a quantity q_1 of radioactive material during year 1 of a 50-year residence time on the burial ground. For the next several years the individual will receive a decreasing dose every year from this intake due to the exponential decay nature of radioactivity. Thus, a smaller dose will be received during year 2 than during year 1; a smaller dose will be received during year 3 than during year 2; and so on. Assume also that during year 2 the individual intakes a quantity q_2 of radioactive material; similarly, a decreasing dose will be received from this intake for each of the following years. The contribution from each year's intake to each year's dose must then be summed. This summation is done over the full residence time to calculate the dose the individual receives each year.

A computer program was written to make these calculations. Input to the program includes the value of the dose conversion factor, the number of people who are receiving a radiation dose, the effective decay constant, the number of years of residence, and the quantity of radionuclide taken in by the population for each year of residence. A FORTRAN listing of the program is given in Appendix E.

ACKNOWLEDGEMENTS

K. R. Routt, formerly of the Computer Applications Division at SRL was responsible for writing the computer program which comprises the DOSTOMAN model. Karen English, co-operative student from University of Tennessee - Knoxville, wrote the computer program to radioactively decay inventories calculated by DOSTOMAN.

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FIGURE 2. TEST CASE 1 RESULTS

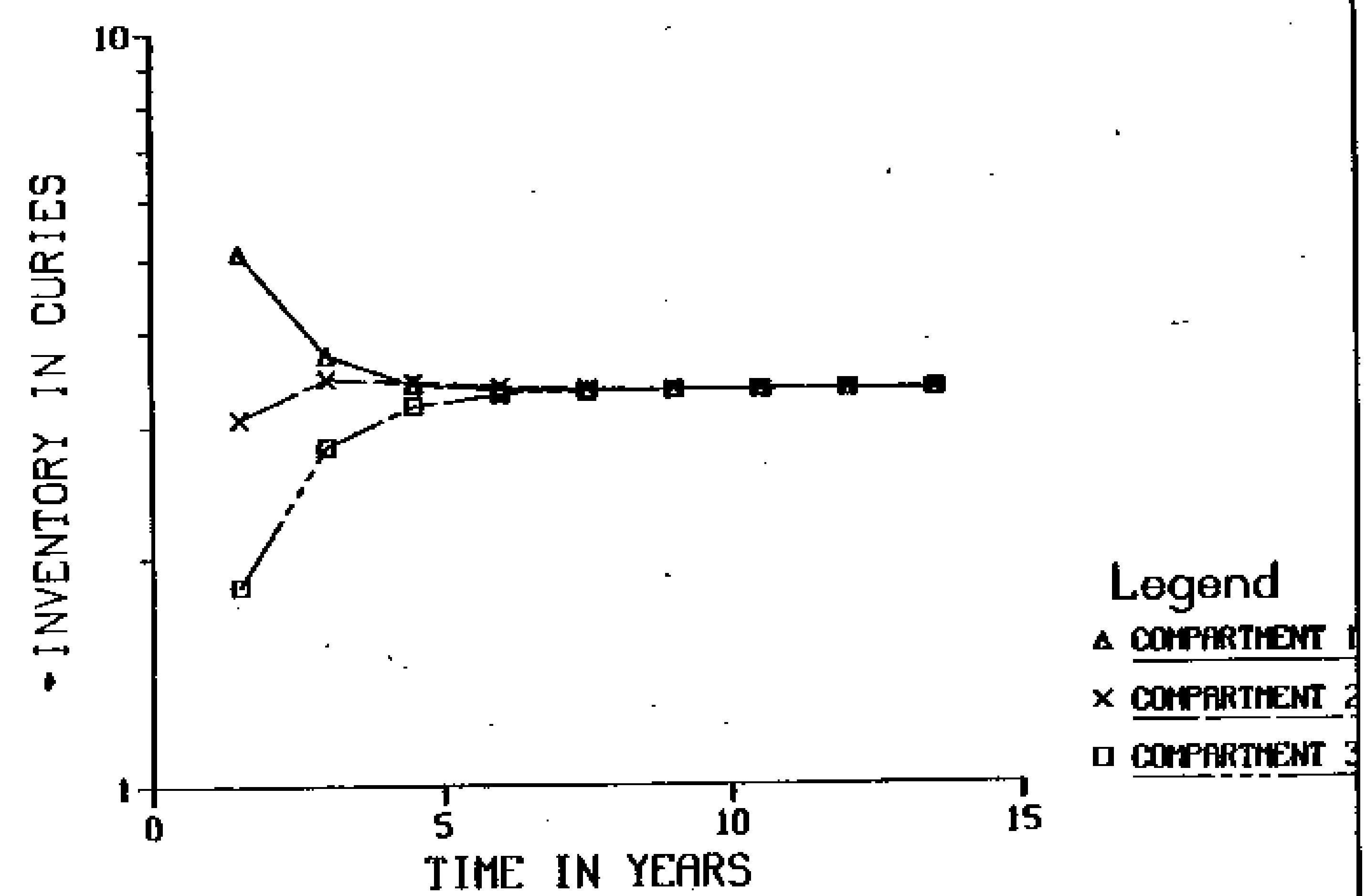


FIGURE 3. TEST CASE 2 RESULTS

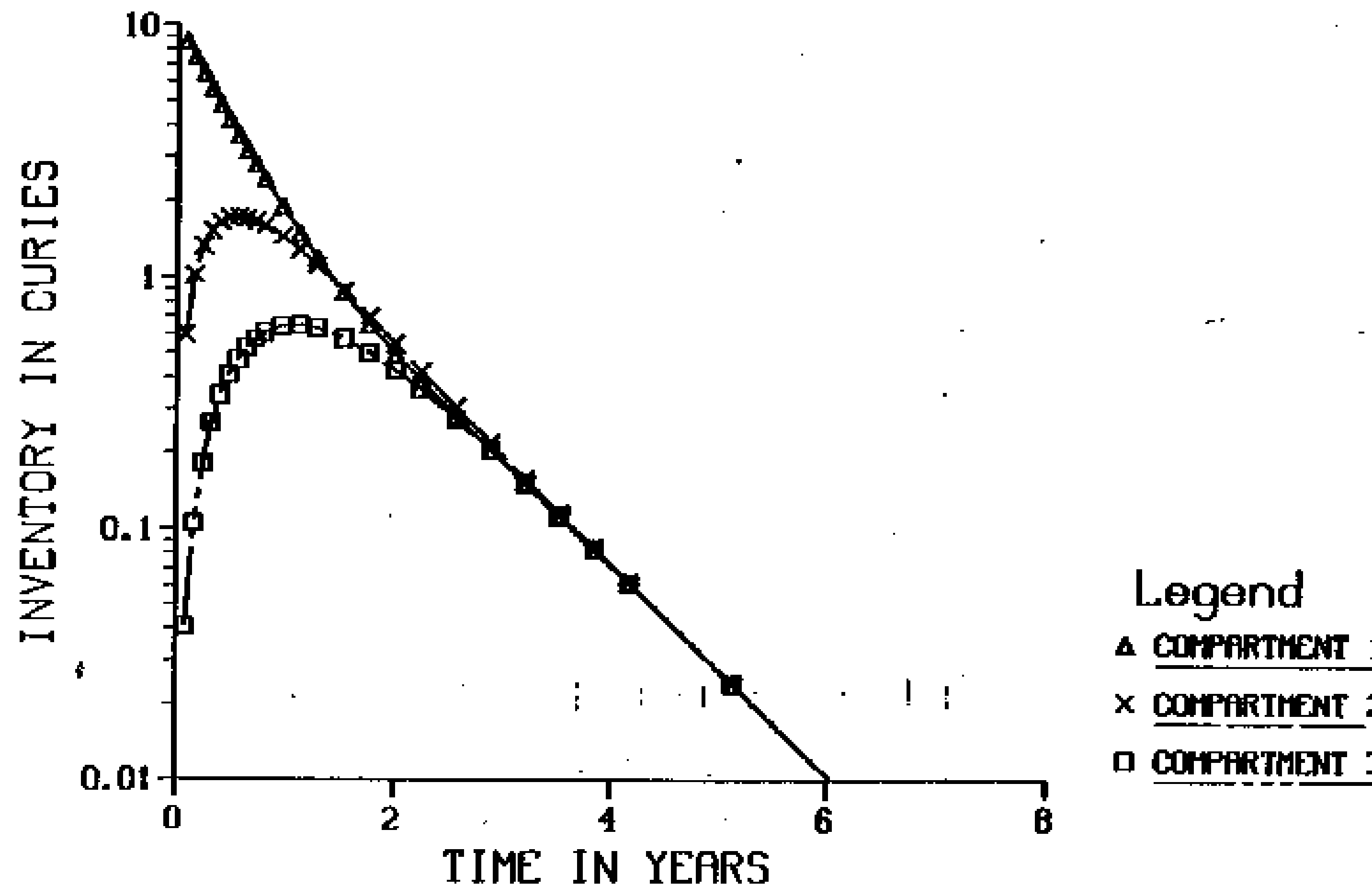


FIGURE 4. TEST CASE 3 RESULTS

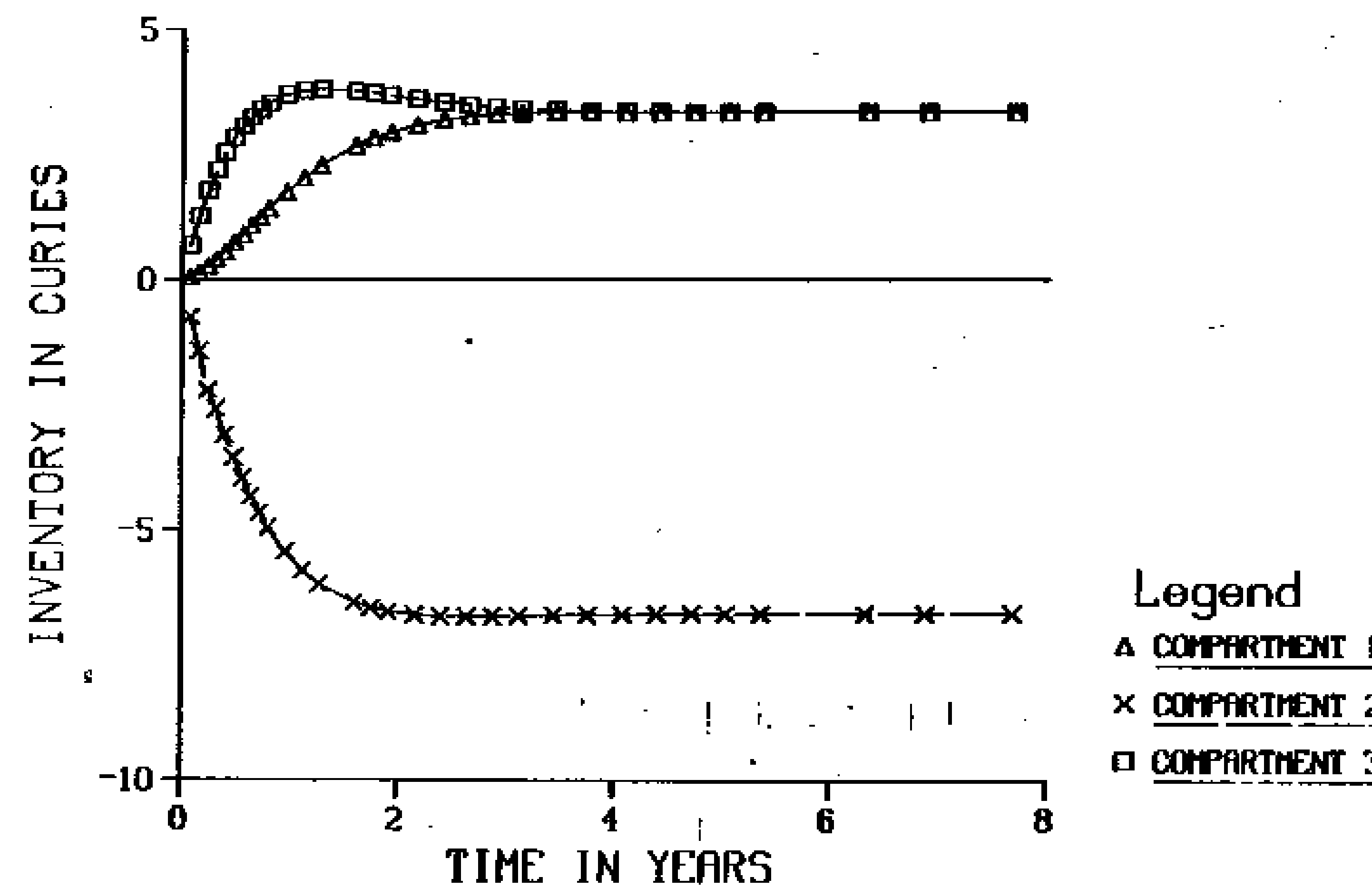


FIGURE 5. TEST CASE 4 RESULTS

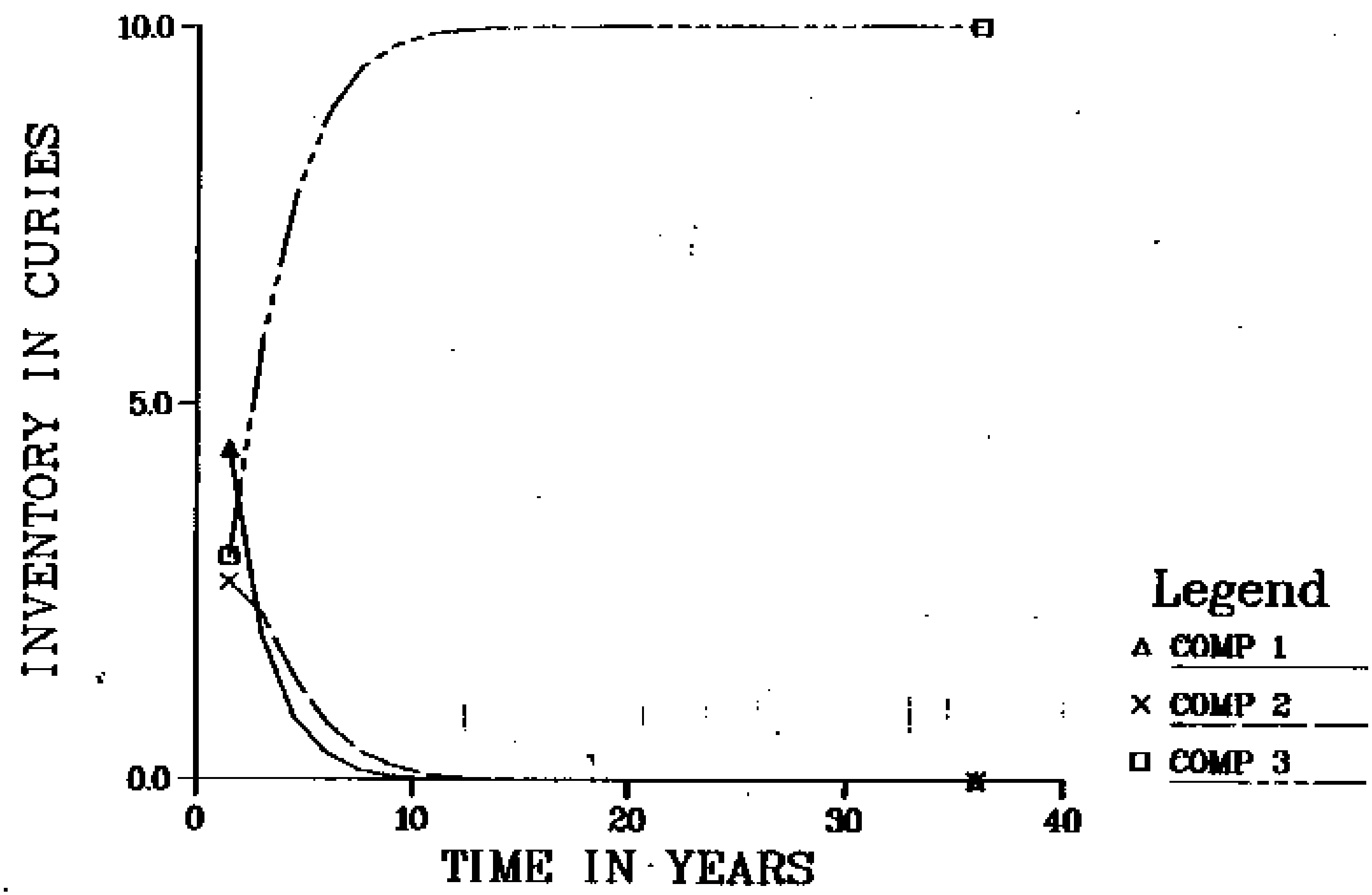


FIGURE 6. TEST CASE 5 RESULTS

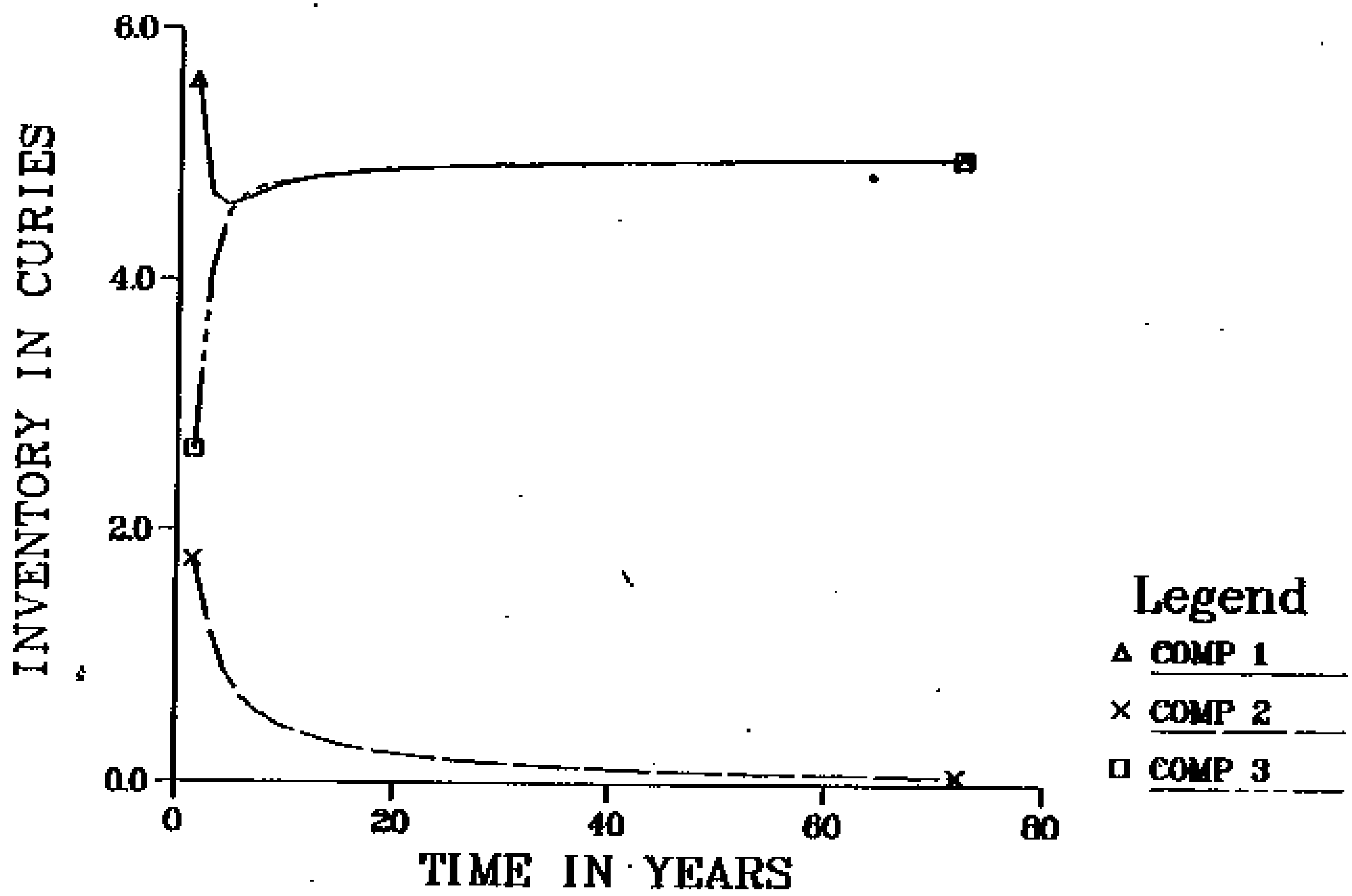
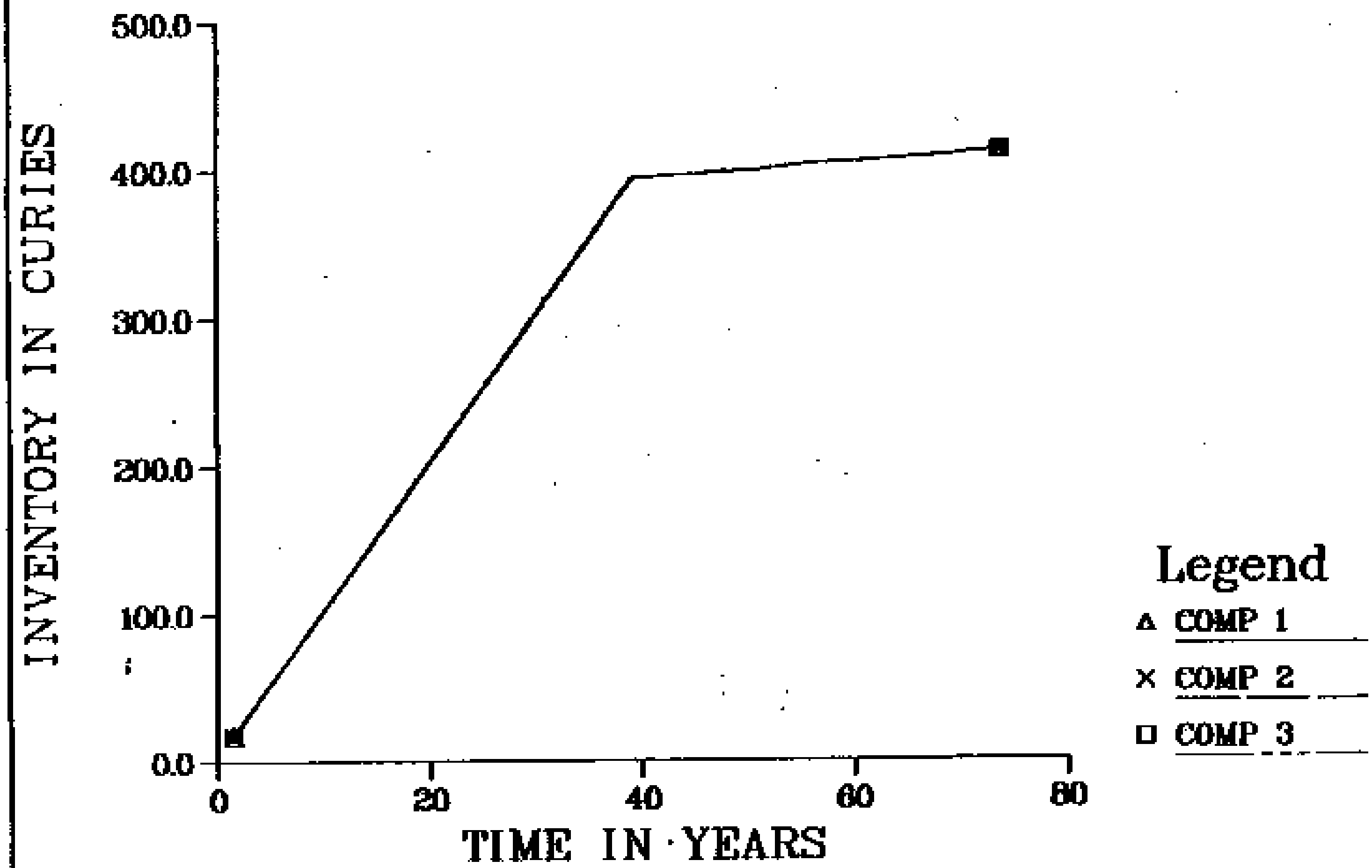


FIGURE 7. TEST CASE 6 RESULTS



```
C     ************************************************************************
C     DIMENSION STATEMENTS FOR PROGRAM VARIABLES
C     ************************************************************************

      DODEFINE

      REAL*8 CASE,LAMBDA(100,100),DET,Q(100),QOLD(100),QZERO(100),
     *B(100),FMAX(10,100)
      REAL*4 SMAX(10,100),T1(10,100),T2(10,100),
     *A1(100),A2(100),A3(100),A4(100),A5(100),
     *X1(100),X2(100),LAMB(100,100),A(7),V(7),X(7),
     *X4(20),VOADD(20),
     *DELV(20),X5(20),VOGEO(20),SOURCE(100),LAMBDS,DTID(10),DT(1000),
     *X3(100),FT1(10,100),FT2(10,100)
      INTEGER*2 N(100,100),M(100,100),NTRMSX(100),NCOMS(100),
     *NSST(100),NTDL(100),MTDL(100),IOFV(20),NOFV(20),MOFV(20),NMAX(20)
     *,ICOMPR(50),NICRX(20),NSTEP(10),NTH
      INTEGER*4 NFMAXX(100)
      COMMON/BLK1/CASE,LAMBDA,DET,Q,QOLD,QZERO,B
      COMMON/BLK2/
     *SMAX,T1,T2,X1,A1,A2,A3,A4,A5,X2,LAMB,A,V,X,X4,VOADD,DELV,
     *X5,VOGEO,DTID,TFLAG,EPS,DELT1,DT,PINPUT,PERTUR,RDLAM,DELT,TIME,
     *SOURCE
      COMMON/BLK3/
     *NEDIT,IPRINT,NCOMX,NCSX,NCOMPX,NOTDLX,NVTRIX
      COMMON/BLK4/
     *N,M,NTRMSX,NCOMS,NSST,NTDL,MTDL,IOFV,NOFV,MOFV,NMAX,ICOMPR,NICRX,
     *NSTEP,NTH
      COMMON/BLK5/ TES,XX
      COMMON/BLK6/ICTBP(25,4),NPLOTX
      COMMON/BLK7/X3,NFMAXX,FMAX,FT1,FT2
```

```
C     **********************************************************************
C     INPUT DATA
C     **********************************************************************

      SUBROUTINE INPUT
      INCLUDE (DODEFINE)
      READ('INPUT'.'DOSTOMAN'.'GENERAL'.@JOB,ERR=901)
     *CASE,RDLAM,NCOMX,NCSX,(NCOMS(NCS),NCS=1,NCSX)
      READ('DEBUG'.'DOSTOMAN'.CASE,ERR=910) IPRINT
      IF(IPRINT.EQ.2) WRITE(6,601) CASE,RDLAM,NCOMX,NCSX,(NCOMS(NCS),
     *NCS=1,NCSX)
601   FORMAT(1H ,'CASE=',A8,' RDLAM=',G12.4,' NCOMX=',I4,
     *' NCSX=',I4/,T2,'NCOMS=',(T9,10I4/))
910   READ('INPUT'.'DOSTOMAN'.CASE.'TIMESTEP',ERR=902)
     *TFLAG,EPS,DELT1,NDOMX,(NSTEP(NDOM),DTID(NDOM),NDOM=1,NDOMX)
      IF(TFLAG.EQ.YES) GO TO 10
      NTH=0
      DO 9 NDOM=1,NDOMX
      NX=NSTEP(NDOM)
      DO 9 NN=1,NX
      NTH=NTH+1
9     DT(NTH)=DTID(NDOM)
      IF(IPRINT.EQ.2) WRITE(6,603) (DT(NN),NN=1,NTH)
603   FORMAT(1H0,'TIMESTEPS',(1H ,10G12.4))
10    DO 3 NCOM=1,NCOMX
      READ('INPUT'.'DOSTOMAN'.CASE.'LAMBDA-Q'.NCOM,ERR=809)
     *NTX,(N(NT,NCOM),M(NT,NCOM),NT=1,NTX)
      IF(IPRINT.EQ.2) WRITE(6,602) NTX,(N(NT,NCOM),M(NT,NCOM),NT=1,NTX)
602   FORMAT(1H0,'NTX=',I4,T16,'N',T23,'M'/,(1H ,T15,I3,T22,I3))
3     NTRMSX(NCOM)=NTX
100   IF(NCSX.EQ.0) GO TO 4
      DO 8 NCS=1,NCSX
      NCOMSS=NCOMS(NCS)
      READ('INPUT'.'DOSTOMAN'.CASE.'SOURCE'.'OR'.'SINK'.'TERMS'.NCOMSS,
     *ERR=903) NSSX,(SMAX(NSS,NCS),T1(NSS,NCS),T2(NSS,NCS),
     *NSS=1,NSSX)
      IF(IPRINT.EQ.2) WRITE(6,607) NCOMSS,NSSX,(SMAX(NSS,NCS),
     *T1(NSS,NCS),T2(NSS,NCS),NSS=1,NSSX)
607   FORMAT(1H0,'NCOMSS=',I4,' NSSX=',I4,T28,'SMAX',T41,'T1',T54,'T2',
     *(1H ,T25,G10.4,T37,G10.4,T50,G10.4))
8     NSST(NCS)=NSSX
4     READ('INPUT'.'DOSTOMAN'.CASE.'INITIAL'.'VALUES',ERR=904)
     *NDUM,(QOLD(NCOM),NCOM=1,NCOMX)
      IF(IPRINT.EQ.2) WRITE(6,604) (QOLD(NCOM),NCOM=1,NCOMX)
604   FORMAT(1H0,'INITIAL VALUES'/,(1H ,10G12.4))
      READ('INPUT'.'DOSTOMAN'.CASE.'INITIAL'.'VALUES',ERR=904)
     *NDUM,(QZERO(NCOM),NCOM=1,NCOMX)
      DO 1 NN=1,NCOMX
      DO 1 MM=1,NCOMX
1     LAMBDA(NN,MM)=0.0
      DO 5 NCOM=1,NCOMX
      NTX=NTRMSX(NCOM)
      DO 5 NT=1,NTX
      NN=N(NT,NCOM)
      MM=M(NT,NCOM)
      IF(LAMBDA(NN,MM).GT.0.0) GO TO 5
      READ('INPUT'.'DOSTOMAN'.CASE.'LAMBDA'.NN.MM,ERR=905)
     *NVX,(A(NV),Y(NV),X(NV),NV=1,NVX)
      DO 6 NV=1,NVX
```

```
C     ***********************************************************************
C     DEFINE LAMBDAS ON THE MAIN DIAGONAL
C     ***********************************************************************

      SUBROUTINE LAM
      INCLUDE (DODEFINE)
      DO 1 NN=1,NCOMX
      SUM=0.0
      DO 2 MM=1,NCOMX
      IF(MM.EQ.NN) GO TO 2
      SUM=SUM+LAMBDA(MM,NN)
2     CONTINUE
1     LAMBDA(NN,NN)=-SUM-RDLAM-1.0/DELT
      IF(IPRINT.NE.2) RETURN
      DO 3 NN=1,NCOMX
      WRITE(6,601) (LAMBDA(NN,MM),MM=1,NCOMX)
3     CONTINUE
601   FORMAT(1H0,'SUBROUTINE LAM - THE LAMBDA(N,M) ARE',
     * (1H ,10G12.4))
      RETURN
      END
```

MODULE

```
C     ******************************************************************
C     MODULE DOSTOMAN - MAIN PROGRAM
C     ******************************************************************

      REAL*8 LAMBST(100,100),DETST,BST(100),LTITLE(7)/7*'        '/,
     *PNAME(200),Y(4)
      REAL*4 C(6)/6*0.0/,XTEMP(200),YTEMP(4,200)
      INTEGER*2 I2(6)/6*0/
      INCLUDE (DOSEFINE)
C---------GET INPUT DATA
      CALL INPUT
      IF(PINPUT.EQ.YES) CALL PRNTIN
      TIME=0.0
      DELT=DT(1)
      IF(IFLAG.EQ.YES) DELT=DELT1
      ITSTEP=1
C---------DEFINE LAMBDA ON THE MAIN DIAGONAL
6     TIME=TIME+DELT
      IF(IPRINT.EQ.2) WRITE(6,606) TIME,DELT
606   FORMAT(1H0,'TIME=',G12.4,' DELT=',G12.4)
C---------UPDATE TIME DEPENDENT LAMBDAS
      IF(NOTDLX.EQ.0) GO TO 3
      DO 2 NOTDL=1,NOTDLX
      IF(X1(NOTDL).EQ.XX) LAMBDA(NTDL(NOTDL),MTDL(NOTDL))=
     *LAMB(NTDL(NOTDL),MTDL(NOTDL))*(A1(NOTDL)+
     *A2(NOTDL)*TIME+A3(NOTDL)*TIME**2+A4(NOTDL)*TIME**3)
      IF(X2(NOTDL).EQ.XX) LAMBDA(NTDL(NOTDL),MTDL(NOTDL))=
     *LAMB(NTDL(NOTDL),MTDL(NOTDL))*EXP(A5(NOTDL)*TIME)
      IF(X3(NOTDL).NE.XX)GOTO2
      NNNNNN=NFMAXX(NOTDL)
      DO1000 NFMAX=1,NNNNNN
      IF((TIME.GE.FT1(NFMAX,NOTDL)).AND.
     *                              (TIME.LE.FT2(NFMAX,NOTDL)))GOTO800
      GOTO1000
  800 LAMBDA(NTDL(NOTDL),MTDL(NOTDL))=
     *                 LAMB(NTDL(NOTDL),MTDL(NOTDL))*FMAX(NFMAX,NOTDL)
      GOTO2
 1000 CONTINUE
      IF(TIME.GT.FT2(NFMAXX(NOTDL),NOTDL))
     *                              LAMBDA(NTDL(NOTDL),MTDL(NOTDL))=0.0
      IF(TIME.LT.FT1(1,NOTDL))
     *                              LAMBDA(NTDL(NOTDL),MTDL(NOTDL))=0.0
2     CONTINUE
      IF(IPRINT.EQ.2) WRITE(6,601) ((LAMBDA(NN,MM),NN=1,NCOMX),
     *MM=1,NCOMX)
601   FORMAT(1H0,'TIME PERTURBED LAMBDAS',(1H ,10G12.4))
C---------UPDATE TIME DEPENDENT SOURCE AND SINK TERMS
3     IF(NCSX.EQ.0) GO TO 40
      DO 5 NCS=1,NCSX
      NSSX=NSST(NCS)
      DO 5 NSS=1,NSSX
      IF(TIME.LT.T1(NSS,NCS)) SOURCE(NCOMS(NCS))=0.0
      IF(TIME.GT.T1(NSS,NCS).AND.TIME.LE.T2(NSS,NCS))
     *SOURCE(NCOMS(NCS))=SMAX(NSS,NCS)
      IF(TIME.GT.T2(NSS,NCS)) SOURCE(NCOMS(NCS))=0.0
5     CONTINUE
      IF(IPRINT.EQ.2) WRITE(6,602) (SOURCE(NCOM),NCOM=1,NCOMX)
```

```
602    FORMAT(1H0,'SOURCES',(1H ,10G12.4))
   40 CALL LAM
       IF(IPRINT.EQ.2) WRITE(6,606) TIME,DELT
C---------DEFINE RIGHT HAND SIDE OF EQUATIONS
       CALL RHS
       IF(IPRINT.EQ.2) WRITE(6,606) TIME,DELT
C---------SAVE LAMBDA. KEEP B AND NCOMX OUT OF THE ARGUMENT STRING OF
C          MINVS
       DO 14 NN=1,NCOMX
       BST(NN)=B(NN)
       DO 14 MM=1,NCOMX
14     LAMBST(NN,MM)=LAMBDA(NN,MM)
       NCOMXS=NCOMX
       DETST=DET
       IF(IPRINT.EQ.2) WRITE(6,606) TIME,DELT
C---------SOLVE FOR Q
       CALL MINVS(LAMBST,NCOMXS,100,DETST,BST,I)
       IF(IPRINT.EQ.2) WRITE(6,606) TIME,DELT
C---------MOVE B INTO Q
       DO 18 NCOM=1,NCOMX
18     Q(NCOM)=BST(NCOM)
C---------CHECK FOR DESIRED EDIT FREQUENCY
       IF(NEDIT.EQ.0) GO TO 19
       IF(.NOT.(ITSTEP.EQ.1.OR.MOD(ITSTEP,NEDIT).EQ.1
      *.OR.NEDIT.EQ.1)) GO TO 19
C---------PRINT Q IN ALL COMPARTMENTS
       WRITE(6,603) TIME
603    FORMAT(1H1,T37,'****************      TIME =',1PE12.4,
      *'      ****************'//,T2,'COMPARTMENT',T63,'Q-VALUES'/)
       IMAX=NCOMX/10
       IF(MOD(NCOMX,10).NE.0) IMAX=IMAX+1
       DO 8 I=1,IMAX
       IL=1+10*(I-1)
       IU=10*I
       IF(IU.GT.NCOMX) IU=NCOMX
       WRITE(6,604) I,(Q(NCOM),NCOM=IL,IU)
604    FORMAT(1H ,T5,I3,4X,10(1PE12.4))
8      CONTINUE
19     IF(DABS(DETST).LT.1.0E-03) WRITE(6,607) DETST
607    FORMAT(1H0,'DETERMINANT WAS',1PE13.5)
C---------EXTRACT DATA FOR PLOTTING
       READ('INPUT'.'DISS2D'.'JOB'.$JOB,ERR=904) NPLOTX,(PNAME(I),
      *I=1,NPLOTX)
       IF(NPLOTX.EQ.0) GO TO 904
       NPTS=1
       DO 20 NPLOT=1,NPLOTX
       DO 22 I=1,4
       Y(I)=0.0
       IF(ICTBP(NPLOT,I).EQ.0) GO TO 22
       Y(I)=Q(ICTBP(NPLOT,I))
22     CONTINUE
       IF(ITSTEP.EQ.1) GO TO 23
       READ('INPUT'.'DISS2D'.'PLOT'.PNAME(NPLOT),ERR=903)
      *((LTITLE(I),I=1,7),J=1,5),(I2(J),J=1,6),IKIND,
      *(I2(J),J=1,4),IXAUTO,(C(J),J=1,0),NPTS,(XTEMP(MM),
      *(YTEMP(I,MM),I=1,4),MM=1,NPTS)
       NPTS=NPTS+1
       IF(NPTS.GT.200) GO TO 905
23     XTEMP(NPTS)=TIME
       DO 24 I=1,4
```

```
      LAMBDA(NN,MM)=LAMBDA(NN,MM)+A(NV)*V(NV)**X(NV)
6     LAMB(NN,MM)=LAMBDA(NN,MM)
      IF(IPRINT.EQ.2) WRITE(6,605) NCOM,NN,MM,LAMBDA(NN,MM)
605   FORMAT(1H ,T2,'NCOM=',I3,' NN=',I3,' MM=',I3,' LAMBDA(NN,MM)=',
     *G12.4)
5     CONTINUE
      READ('INPUT'.'DOSTOMAN'.CASE.'TIME'.'FUNCTION',ERR=906) NOTDLX
      IF(NOTDLX.EQ.0) GO TO 7
      READ('INPUT'.'DOSTOMAN'.CASE.'TIME'.'FUNCTION',ERR=906)
     *NOTDLX,((NTDL(NOTDL),MTDL(NOTDL),X1(NOTDL),A1(NOTDL),
     *A2(NOTDL),A3(NOTDL),A4(NOTDL),X2(NOTDL),A5(NOTDL),
     *X3(NOTDL),NFMAXX(NOTDL),NDUMMY,((FMAX(NFMAX,NOTDL),
     *FT1(NFMAX,NOTDL),FT2(NFMAX,NOTDL)),NFMAX=1,NDUMMY)),
     *NOTDL=1,NOTDLX)
7     NPLOTX=0
      READ('INPUT'.'DOSTOMAN'.CASE.'PLOT',ERR=911) NPLOTX
      IF(NPLOTX.EQ.0) GO TO 911
      READ('INPUT'.'DOSTOMAN'.CASE.'PLOT',ERR=912) NPLOTX,
     *((ICTBP(J,I),I=1,4),J=1,NPLOTX)
911   READ('INPUT'.'DOSTOMAN'.CASE.'EDIT',ERR=907)
     *PINPUT,NEDIT,PERTUR
      IF(IPRINT.EQ.2) WRITE(6,608) (NTRMSX(NCOM),NCOM=1,NCOMX)
608   FORMAT(1HO,'INPUT'/,1H ,'NTRMSX=',(10G12.4))
      IF(PERTUR .NE.XX)  RETURN
      READ('INPUT'.'DOSTOMAN'.CASE.'PERTURB'.'VARIABLE',ERR=908)
     *NVTBIX,(IOFV(NVTBI),NOFV(NVTBI),MOFV(NVTBI),
     *X4(NVTBI),VOADD(NVTBI),DELV(NVTBI),NICRX(NVTBI),X6(NVTBI),
     *VOGEO(NVTBI),NMAX(NVTBI),NVTBI=1,NVTBIX),
     *NCOMPX,(ICOMPR(NCOMP),NCOMP=1,NCOMPX)
      RETURN
901   STOP 1 'ERROR IN READING INPUT.DOSTOMAN.GENERAL.$JOB'
902   STOP 2 'ERROR IN READING INPUT.DOSTOMAN.?CASE.TIMESTEP'
903   STOP 3 'ERROR IN READING INPUT.DOSTOMAN.?CASE.SOURCE.OR.SINK.TERM '
     *S'
904   STOP 4 'ERROR IN READING INPUT.DOSTOMAN.?CASE.INITIAL.VALUES'
905   STOP 5 'ERROR IN READING INPUT.DOSTOMAN.?CASE.LAMBDA.?N.?M'
906   STOP 6 'ERROR IN READING INPUT.DOSTOMAN.?CASE.TIME.FUNCTION'
907   STOP 7 'ERROR IN READING INPUT.DOSTOMAN.?CASE.EDIT'
908   STOP 8 'ERROR IN READING INPUT.DOSTOMAN.?CASE.PERTURB.VARIABLE'
909   STOP 9 'ERROR IN READING INPUT.DOSTOMAN.?CASE.LAMBDA-Q.?NCOM'
912   STOP 12 'ERROR IN READING INPUT.DOSTOMAN.?CASE.PLOT'
      END
```

```
      YTEMP(I,NPTS)=Y(I)
      IF(Y(I).LE.0.1E-20)YTEMP(I,NPTS)=0.1E-20
24    CONTINUE
      WRITE('INPUT'.'DISS2D'.'PLOT'.PNAME(NPLOT),ERR=003)
     *((LTITLE(I),I=1,7),J=1,5),(I2(J),J=1,6),IKIND,
     *(I2(J),J=1,4),IXAUTO,(C(J),J=1,6),NPTS,(XTEMP(MM),
     *(YTEMP(I,MM),I=1,4),MM=1,NPTS)
20    CONTINUE
C---------CHECK RESIDUALS
904   CALL RESID
C---------CHECK MASS BALANCE
      CALL MASBAL
C---------COMPUTE NEW TIME AND DELTA-T
      IF(TFLAG.NE.YES) GO TO 1
      DELQMX=0.0
      QMAX=0.0
      DO 7 NCOM=1,NCOMX
      IF(DABS(Q(NCOM)-QOLD(NCOM)).GT.DELQMX)
     *DELQMX=DABS(Q(NCOM)-QOLD(NCOM))
      IF(DABS(Q(NCOM)).GT.QMAX) QMAX=DABS(Q(NCOM))
7     CONTINUE
      IF(DELQMX.LE.0.001*QMAX)  GO TO 15
      DELT=EPS*DELT/DELQMX
1     ITSTEP=ITSTEP+1
      IF(TFLAG.NE.YES) DELT=DT(ITSTEP)
C---------MOVE Q INTO QOLD
4     DO 12 NCOM=1,NCOMX
12    QOLD(NCOM)=Q(NCOM)
      IF(TFLAG.NE.YES.AND.ITSTEP.GT.NTS) GO TO 15
      GO TO 6
C---------START PERTURBATION OF VARIABLES IN LAMBDA(N,M)
15    IF(PERTUR.NE.XX)  STOP
      IF(IPRINT.EQ.2) WRITE(6,608) NVTBIX
608   FORMAT(1H0,'MAIN---------NVTBIX=',I4)
      DO 9 NVTBI=1,NVTBIX
      NN=NOFV(NVTBI)
      MM=MOFV(NVTBI)
      READ('INPUT'.'DOSTOMAN'.CASE.'LAMBDA'.NN.MM,ERR=001)
     *NVX,(A(NV),V(NV),X(NV),NV=1,NVX)
      IF(X5(NVTBI).EQ.XX) NCRX=NMAX(NVTBI)
      IF(X4(NVTBI).EQ.XX) NCRX=NICRX(NVTBI)
      DO 11 NCR=1,NCRX
      LAMBDA(NN,MM)=0.0
      DO 10 NV=1,NVX
      IF(IOFV(NVTBI).EQ.NV.AND.X4(NVTBI).EQ.XX)
     *LAMBDA(NN,MM)=LAMBDA(NN,MM)+A(NV)*(VOADD(NVTBI)+(NCR-1)*
     *DELV(NVTBI))**X(NV)
      IF(IOFV(NVTBI).EQ.NV.AND.X5(NVTBI).EQ.XX)
     *LAMBDA(NN,MM)=LAMBDA(NN,MM)+A(NV)*(VOCEO(NVTBI)**NCR)**X(NV)
      IF(IOFV(NVTBI).NE.NV) LAMBDA(NN,MM)=LAMBDA(NN,MM)+A(NV)*
     *V(NV)**X(NV)
10    CONTINUE
      TIME=1.0E+20
      DELT=1.0E+20
C---------DEFINE LAMBDA ON THE MAIN DIAGONAL
      CALL LAM
C---------DEFINE RIGHT HAND SIDE OF EQUATIONS
      READ('INPUT'.'DOSTOMAN'.CASE.'INITIAL'.'VALUES',ERR=002)
     *NDUM,(QOLD(NCOM),NCOM=1,NCOMX)
      CALL RHS
```

```
C     ******************************************************************
C     CALCULATE SYSTEM MASS BALANCE
C     ******************************************************************

      SUBROUTINE MASBAL
      INCLUDE (BODEFINE)
C---------OMIT MASS BALANCE CHECK IF THERE ARE SOURCE OR SINK TERMS
      IF(NCSX.NE.0) RETURN
C---------SUM INITIAL AND CURRENT CONCENTRATIONS
      SUMI=0.0
      SUMC=0.0
      DO 5 NCOM=1,NCOMX
      SUMC=SUMC+Q(NCOM)
5     SUMI=SUMI+QZERO(NCOM)
C---------CHECK MASS BALANCE
      IF(RDLAM*TIME.LT.276.0) BAL=SUMI*EXP(-RDLAM*TIME)-SUMC
      IF(RDLAM*TIME.GE.276.0) BAL=-SUMC
      IF(ABS(BAL).GT.ABS(0.002*SUMC)) WRITE(6,601) TIME,BAL
601   FORMAT(1H0,'MASS BALANCE AT TIME=',G18.5,' IS',G18.5)
      RETURN
      END
```

```
C     ******************************************************************
C     PRINT OUT INPUT DATA
C     ******************************************************************

      SUBROUTINE PRNTIN
      INCLUDE (DODEFINE)
      PRINT('INPUT'.'DOSTOMAN'.'GENERAL'.$JOB,ERR=900)
      'INPUT'.'DOSTOMAN'.CASE->Z
      DO 8 NCOM=1,NCOMX
      PRINT(Z.'LAMBDA-Q'.NCOM,ERR=901)
8     CONTINUE
      PRINT(Z.'TIMESTEP',ERR=908)
      IF(NCSX.EQ.0) GO TO 4
      DO 2 NCS=1,NCSX
      NCOMSS=NCOMS(NCS)
      PRINT(Z.'SOURCE'.'OR'.'SINK'.'TERMS'.NCOMSS,ERR=902)
2     CONTINUE
4     PRINT(Z.'INITIAL'.'VALUES',ERR=903)
      DO 1 NCOM=1,NCOMX
      NTX=NTRMSX(NCOM)
      DO 9 NT=1,NTX
      NNNX=N(NT,NCOM)
      MMMX=M(NT,NCOM)
      IF(MMMX.NE.NCOM) GO TO 9
      PRINT(Z.'LAMBDA'.NNNX.MMMX,ERR=909)
9     CONTINUE
1     CONTINUE
      PRINT(Z.'TIME'.'FUNCTION',ERR=905)
      GO TO 5
905   WRITE(6,600)
600   FORMAT(1H0,'DID NOT FIND INPUT.DOSTOMAN.?CASE.TIME.FUNCTION')
5     PRINT(Z.'EDIT',ERR=906)
      PRINT(Z.'PERTURB'.'VARIABLE',ERR=907)
      GO TO 6
907   WRITE(6,601)
601   FORMAT(1H0,'DID NOT FIND INPUT.DOSTOMAN.?CASE.PERTURB.VARIABLE')
6     PRINT('INPUT'.'DISS2D'.'JOB'.$JOB,ERR=910)
      GO TO 10
910   WRITE(6,608)
608   FORMAT(1H0,'DID NOT FIND INPUT.DISS2D.JOB.?JOB')
10    PRINT(Z.'PLOT',ERR=911)
      RETURN
911   WRITE(6,611)
611   FORMAT('0DID NOT FIND INPUT.DOSTOMAN.?CASE.PLOT')
      RETURN
900   STOP 0 'ERROR IN PRINTING INPUT.DOSTOMAN.GENERAL.?$JOB'
901   STOP 1 'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.LAMBDA-Q.?NCOM'
902   WRITE(6,602)
602   FORMAT(1H0,'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.SOURCE.OR.',
     *'SINK.TERMS.?NCOMSS')
      STOP 2
903   STOP 3 'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.INITIAL.VALUES'
906   STOP 6 'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.EDIT'
908   STOP 8 'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.TIMESTEP'
909   WRITE(6,610) NNNX,MMMX
610   FORMAT(1H0,'ERROR IN PRINTING INPUT.DOSTOMAN.?CASE.LAMBDA.',I3,'.',
     *I3)
      STOP
      END
```

```
C     **********************************************************************
C     CALCULATE COMPARTMENT RESIDUALS
C     **********************************************************************

      SUBROUTINE RESID
      INCLUDE (DODEFINE)
      IF(IPRINT.EQ.2) WRITE(6,602) NCOMX,RDLAM,(Q(NCOM),NCOM=1,NCOMX),
     *(SOURCE(NCOM),NCOM=1,NCOMX),((LAMBDA(NN,MM),MM=1,NCOMX),
     *NN=1,NCOMX),(QOLD(NCOM),NCOM=1,NCOMX),DELT
602   FORMAT(1H0,'SUBROUTINE RESID----NCOMX=',I4,' RDLAM=',G12.4/,
     *T2,'Q'/,(1H ,10G12.4))
      DO 1 NCOM=1,NCOMX
      RLHS=-RDLAM*Q(NCOM)+SOURCE(NCOM)
      DO 2 I=1,NCOMX
      IF(I.EQ.NCOM) GO TO 2
      RLHS=RLHS+LAMBDA(NCOM,I)*Q(I)-LAMBDA(I,NCOM)*Q(NCOM)
2     CONTINUE
      RRHS=(Q(NCOM)-QOLD(NCOM))/DELT
      RES=RLHS-RRHS
      IF(ABS(RES).GE.0.001*ABS(RHS)) WRITE(6,601) NCOM,RES
601   FORMAT(1H0,'THE RESIDUAL IN COMPARTMENT',I4,' IS',
     *1PE14.6)
1      CONTINUE
       RETURN
       END
```

```
C     **********************************************************************
C     CALCULATE RIGHT-HAND SIDE OF MATRIX
C     **********************************************************************

      SUBROUTINE RHS
      INCLUDE (DODEFINE)
      DO 1 NCOM=1,NCOMX
      B(NCOM)=-QOLD(NCOM)/DELT
      SOURCE(NCOM)=0.0
      IF(NCSX.EQ.0) GO TO 1
      DO 2 NCS=1,NCSX
      IF(NCOMS(NCS).NE.NCOM) GO TO 2
      NSSX=NSST(NCS)
      DO 3 NSS=1,NSSX
      IF(TIME.GT.T1(NSS,NCS).AND.TIME.LE.T2(NSS,NCS))
     *SOURCE(NCOM)=SMAX(NSS,NCS)
3     CONTINUE
      B(NCOM)=B(NCOM)-SOURCE(NCOM)
2     CONTINUE
1     CONTINUE
      IF(IPRINT.NE.2) RETURN
      WRITE(6,601) DELT,(NCOM,QOLD(NCOM),B(NCOM),SOURCE(NCOM),
     *NCOM=1,NCOMX)
601   FORMAT(1H0,'SUBROUTINE RHS'/,T2,'DELT=',G12.4/,
     *T3,'NCOM',T14,'QOLD',T30,'B',T41,'SOURCE'/,
     *(1H ,T4,I3,T10,G12.4,T28,G12.4,2X,G12.4))
      RETURN
      END
```

APPENDIX B DEFINITIONS OF DOSE-TO-MAN MODEL VARIABLES

A(NV) Component of LAMBDA(NN,MM).

A1(NOTDL) First coefficient in the polynomial form of a time function. Used in varying LAMBDA(NN,MM) with time.

A2(NOTDL) Second coefficient in the polynomial form of a time function. Used in varying LAMBDA(NN,MM) with time.

A3(NOTDL) Third coefficient in the polynomial form of a time function. Used in varying LAMBDA(NN,MM) with time.

A4(NOTDL) Fourth coefficient in the polynomial form of a time function. Used in varying LAMBDA(NN,MM) with time.

A5(NOTDL) Rate constant in the exponential form of a time function. (1/Time)

B(NCOM) A designator for -QOLD(NCOM)/DELT. (Curies/Time)

B(NN) A designator for B(NCOM). (Curies/Time)

BAL Deviation of the system mass balance. (Curies)

BST(NN) A designator for B(NN). (Curies)

C(J) Designators to specify plot features.

CASE Case name; up to 8 alphanumeric characters.

DELQMX Maximum change in concentration between time steps when automatic time step is specified. (Curies)

DELT A designator for DT(1) or DELT1. (Time)

DELT1 The size of the first time step when the automatic time step option is used. (Time)

DELV(NVTBI) Incremental change in the V(NV) value of a LAMBDA (NN,MM) being perturbed additively.

DET The determinant of matrix A, the matrix of transfer coefficients.

DETST A designator for DET.

DT(NTD) A designator for DTID(NDOM). (Time)

DTID(NDOM) The size of the time step in each time domain. (Time)

EPS Maximum permissible change in concentration per time step if the automatic time step option is used.(Curies/Time)

FT1(NFMAX,NOTDL) Beginning of step time function period. (Time)

FT2(NFMAX,NOTDL) End of step time function period. (Time)

I A counter.

ICOMPR(NCOMP) Compartment numbers of compartments which have been perturbed and whose radionuclide inventory values are to be printed.

ICTRP(NPLOTX,I) Compartment numbers for compartments for which concentration vs. time plots are to be made.

IKIND Designator to specify type of curve to be plotted (linear=1, semilog=2, and loglog=3).

IL A counter; 1+10*(I-1).

IMAX A counter; NCOMX/10.

IOFV(NVTBI) The index or number of the V(NV)-component of a LAMBDA(NN,MM) to be perturbed.

IPRINT A designator to print the input values of several variables. If IPRINT=2 then all input variables are printed.

ITSTEP A counter for time step incrementing.

IU A counter; 10*I.

IXAUTO A designator to specify X (time) values on plots. (YES or NO).

I2(J) Designators to specify plot features.

J A counter.

LAMB(NN,MM) A designator for LAMBDA(NN,MM). (1/Time)

LAMBDA(NN,MM) The transfer coefficient between compartments MM and NN; it has the form A(NV)*V(NV)**X(NV). (1/Time)

LAMBST(NN,MM) A designator for LAMBDA(NN,MM). (1/Time)

LTITLE(I) Title and x- and y-axis labels for plots.

M(NT,NCOM) Compartment number of the sending compartment in the LAMBDA-Q record.

MM A counter; 1 to NCOMX.

MMM A counter; 1 to NCOMX.

MMMX A designator for M(NT,NCOM).

MOD(ITSTEP,NEDIT) A FORTRAN function subprogram.

MOFV(NVTBI) The compartment number of the sending compartment of a LAMBDA(NN,MM) being perturbed.

MTDL(NOTDL) Compartment number of the sending compartment when specifying the time function of a LAMBDA(NN,MM).

N(NT,NCOM) Compartment of the receiving compartment in the LAMBDA-Q record.

NCOM A counter; 1 to NCOMX.

NCOMP A counter for ICOMPR(NCOMP); 1 to NCOMPX.

NCOMPX Number of compartment values to be printed for compartments which have been perturbed.

NCOMS(NCS) Compartment numbers for compartments with source or sink terms.

NCOMSS A designator for NCOMS(NCS).

NCOMX Number of compartments in the model.

NCOMXS A designator for NCOMX.

NCR A counter; 1 to NCRX.

NCRX A designator for NMAX(NVTBI) and NICRX(NVTBI).

NCS A counter for NCOMS(NCSX); 1 to NCSX.

NCSX Number of compartments with source or sink terms.

NDOM A counter for DTID(NDOM) and NSTEP(NDOM); 1 to NDOMX.

NDOMX The number of time domains desired when time steps are specified individually.

NDUM Number of compartments when designating initial inventory values.

NDUMMY A counter.

NEDIT Time frequency with which compartment inventories are to be printed.

NFMAX A counter; 1 to NDUMMY.

NFMAXX(NOTDL) Number of step functions in a step time function.

NICRX(NVTBI) Number of incremental changes to be made in the V(NV) value of a LAMBDA(NN,MM) being perturbed additively.

NMAX(NVTBI) Exponential factor used in the V(NV) value of a LAMBDA(NN,MM) being perturbed geometrically.

NN A counter; 1 to NCOMX, 1 to NX, or 1 to NTH.

NNN A counter; 1 to NCOMX.

NNNNNN A designator for NFMAXX(NOTDL). Specifies the number of step functions.

NNNX A designator for N(NT,NCOM).

NOPV(NVIBI) The compartment number of the receiving compartment of a LAMBDA(NN,MM) being perturbed.

NOTDL A counter; 1 to NOTDLX.

NOTDLX Number of time-dependent lambdas. Used when specifying time functions.

NPLOT A counter; 1 to NPLOTX.

NPLOTX Number of concentration vs. time plots desired.

NPTS Number of X (time) values on a plot.

NSS A counter for SMAX,T1, and T2; 1 to NSSX.

NSST(NCS) A designator for NSSX.

NSSX The number of source or sink terms in a compartment.

NSTEP(NDOM) The number of time steps in each domain.

NT A counter for N(NT,NCOM) and M(NT,NCOM); 1 to NTX.

NTDL(NOTDL) Compartment number of the receiving compartment when specifying the time function of a LAMBDA(NN,MM)

NTM A counter for DT.

NTRMSX(NCOM) A designator for NTX.

NTX The number of non-zero lambdas associated with a compartment

NV A counter for A,V, and X; 1 to NVIBIX and 1 to NVX.

NVIBI A counter; 1 to NVIBIX.

NVIBIX Number of compartments with lambdas to be incremented when perturbing a LAMBDA(NN,MM) after running a simulation.

NVX Number of components (A(NV)*V(NV)**X(NV) used to calculate a LAMBDA(NN,MM).

NX A designator for NSTEP(NDOM).

PERTUR A designator to specify whether or not selected lambdas are to be perturbed after running a simulation.

PINPUT A designator used to specify whether or not all input records are to be printed with the output. (YES or NO)

PNAME Name of each plot to be made. Up to 8 alphanumeric characters.

Q(NCOM) Compartment inventory calculated at the end of a time step. (Curies)

QMAX A designator for concentration. (Curies)

QOLD(NCOM) Radionuclide inventory in a compartment at the beginning of a time step, other than for the first time step. (Curies)

QZERO(NCOM) Radionuclide inventory initially in a compartment. (Curies)

RDLAM Radioactive decay constant. (1/Time)

RES Residual (difference) between the calculated values for the right- and left-hand sides of the simultaneous equations. (Curies/Time).

RLHS The calculated value on the left-hand side of the simultaneous equations. (Curies/Time)

RRHS The calculated values on the right-hand side of the simultaneous equations. (Curies/Time)

SMAX(NSS,NCS) Fractional strength of a compartment source or sink. (Curies/Time)

SOURCE(NCOMS(NCS)) Input into a compartment in addition to qzero (NCOM). (Curies)

SUM The sum of LAMBDA(NN,MM) when defining lambdas on the main diagonal of the matrix. (1/Time)

SUMC Sum of current concentrations. (Curies)

SUMI Sum of initial concentrations. (Curies)

TFLAG A designator to specify whether or not automatic time step selection is desired. (YES or NO)

TIME Total simulated time. (Time)

T1(NSS,NCS) Beginning of the source or sink period. (Time)

T2(NSS,NCS) End of the source or sink period. (Time)

V(NV) Component of LAMBDA(NN,MM).

VOADD(NVTBI) The initial V(NV) value of a LAMBDA(NN,MM) being perturbed additively.

VOGEO(NVTBI) The initial V(NV) value of a LAMBDA(NN,MM) being perturbed geometrically.

VPRINT A designator for perturbed variables.

X(NV) Exponential component of LAMBDA(NN,MM).

X1(NOTDL) A flag used when designating a polynomial form for the time function of a LAMBDA(NN,MM).

X2(NOTDL) A flag used when specifying the exponential form for the time function of a LAMBDA(NN,MM).

XB(NOTBL) A flag used when specifying the step form for the time function of a LAMBDA(NN,MM).

X4(NVTRI) A flag that specifies an additive form change for a LAMBDA(NN,MM) being perturbed.

X5(NVTRI) A flag that specifies a geometric form change for a LAMBDA(NN,MM) being perturbed.

XTEMP(MM) Time designation for plotting purposes. (Time)

XX A general flag designation.

Y(I) A designator for Q(NCOM).

YES A general flag designator.

YTEMP(MM) Concentration designation for plotting purposes. (Curies)

APPENDIX C PRACTICAL CONSIDERATIONS FOR APPLICATION

I. Radioactive Decay

The DOSTOMAN computer model is subject to numerical errors because it is a finite-difference approximation of essentially continuous functions. Under certain conditions, these errors will appear as large mass imbalances. Large errors in mass balance typically occur when values of the radioactive decay constant are large relative to the values of the transfer coefficients. Coefficient values are typically on the order of 10^{-3} to 10^{-7} per year, wherbas the radioactive decay constants of such relatively short half-lived nuclides as strontium-90 and cesium-137 are on the order of 10^{-2} per year.

In order to avoid the errors imposed by these magnitude differences it is best to impose radioactive decay separately from the DOSTOMAN model. For this purpose the radioactive decay constant is set to zero in the "INPUT.DOSTOMAN.GENERAL" record. The simulation is then run and the undecayed radionuclide inventories for the desired compartments are filed in a JOSHUA system job data set. A separate computer program has been written to perform radioactive decay on these undecayed results. The program listing for this computer code is given in Appendix D. The decay constant for the specific radionuclide of interest is entered directly in the program. The program then reads the time in years and the compartment inventories and calculates the decayed results.

II. Computer Run Sequence

Determining the radiation dose to man using the DOSTOMAN model requires the running of a sequence of three computer porgrams, with other computer work providing plots of data. An example sequence of runs follows:

Step 1

Provide the necessary input data to the DOSTOMAN program, including time step size, transfer coefficients, initial compartment inventories, and the like. This data entry is done in the JOSHUA system using records with a job name (e.g., SR014420) and a case name (e.g., SCENARO4). The job is submitted for execution and the results are automatically loaded to a job data set with the job name SR014420. The main results of interest are from Compartment 65. These results have a record name (e.g., INPUT.DISS2D.PLOT.SR-90). As discussed in Section I of this Appendix, these results have not yet been subjected to radioactive decay.

APPENDIX C PRACTICAL CONSIDERATIONS FOR APPLICATION, cont'd

Step 2

The results in job data set SR014420 are then called by the computer program given in Appendix D and radioactive decay is calculated. This computer program resides in an edit library (e.g., T5115.EDIT.DATA) and has a specific member name (e.g., DECAYSR). When the member DECAYSR is submitted for execution, the decayed results are read automatically into another edit library member (e.g., T5115.EDIT.DATA(SR90NEW)). These results are then available for plotting or for calculating the radiation dose to man.

Step 3

If it is desired to plot the results in member SR90NEW using the TELL-A-GRAF graphics system at SRL, certain appropriate commands must be specified. Details of these commands are provided in appropriate references.[11] The data is first moved to a new member (e.g., T5115.EDIT.DATA(SRCURIES)), the TELL-A-GRAF system is called, and the desired plots are made.

Step 4

If a dose calculation is to be made, it is necessary to move the decayed results from Compartment 65 to another member (e.g., T5115.EDIT.DATA(SRINTAKE)). The results from the first 100 years - which are all essentially zero - are removed and the radionuclide inventories for each of the next X years are typed by hand into the member. A value for the dose commitment factor, the number of people receiving the radiation dose, the effective decay constant of the radionuclide in the body, and the number of years of residence are specified. More details on this are provided in the USER'S GUIDE under "Dose Calculations". The intake data are then ready for determining the radiation dose.

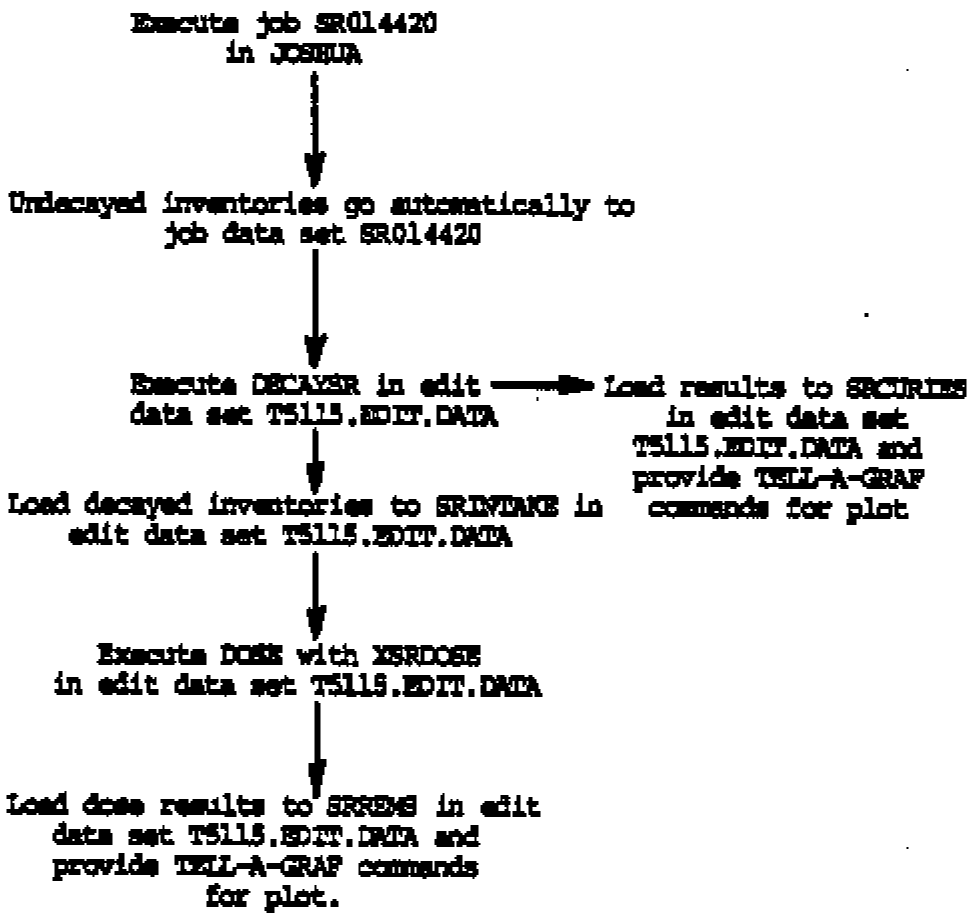
Step 5

A computer program was written to calculate the radiation dose for man. The program listing is found in Appendix E and the code is located in an edit library with a member name (e.g., T5115.EDIT.DATA(DOSE)). The program DOSE is executed by calling a member with the appropriate JCL commands (e.g., T5115.EDIT.DATA(XSRDOSE)) and submitting it. The program DOSE then reads the necessary data from member SRINTAKE and calculates the dose to man for each year of residence on the burial ground.

Step 6

If it is desired to plot the dose results, the year and dose data are hand-entered into a new member (e.g., T5115.EDIT.DATA(SRREMS)) and the appropriate TELL-A-GRAF commands are provided.

In order to clarify this sequence of computer runs, a simple flow chart is provided:



All job and case names, job data set names, edit library designations, and member names given above are provided only as examples. Names and designations will depend on the user.

APPENDIX D DECAY PROGRAM LISTING

```
CJ*** MODULE MAIN
                 SUBROUTINE MAIN($MCB   )
CC-------------------------------------------------------------------------
CC----------   PROGRAM TO CALCULATE THE CONCENTRATION  --------------------
CC--  OF STRONTIUM DUE TO THE EFFECTS OF RADIOACTIVE DECAY  --------------
CC---- HALF-LIFE = 27.7 YEARS, LAMBDA = LN2/27.7 = 0.02502 ---------------
CC-------------------------------------------------------------------------
      REAL*8     VALUE,  DECAY(4,200) ,LTITLE(7)/7*'        '/
      REAL*4   C(6)/6*0.0/,  XTEMP(200),  YTEMP(4,200) ,LAMBDA, XPON
      INTEGER*2  I2(6)/6*0/
                 COMMON /$JCOMA/ $JCB(16),$NAMES(18),$BNAMI(8)
                 REAL     *8 $JCB,$NAMES,$JOB,$BADGE,$CDINT,$RAJ
                 REAL     *8 $LNAM0(    4)
                 INTEGER *4 $BNAMI,$JCBI(32),$DSNAM,$RECRD,$SYS,$ERRNO
                 EQUIVALENCE ($JCBI(1),$JOB,$JCB(1)),  ($JCB(2),$BADGE),
     *                       ($JCBI(5),$SYS)          , ($JCBI(6),$ERRNO),
     *                       ($BNAMI(2),$DSNAM)       ,($BNAMI(3),$RECRD)
                 LOGICAL *1     $00,$LGL0(  7)
                 DATA           $LGL0(1)/F/
                 REAL     *8   $00001(4  )
     *    /'INPUT    ' ,'DISS2D  ' ,'PLOT     ' ,'SR-90    '/
                 EQUIVALENCE ($00001(1),$LNAM0(1   ))
                 LOGICAL *1    $L0001(7   )
     *              /Z00,Z04,Z04,Z01,Z02,Z03,Z04/
                 EQUIVALENCE ($L0001(1), $LGL0(1   ))
                 REAL     *8 $MCB(18)
                      CALL $YUDEX ('JIBINIT ',$MCB,$JCB)
CJ*** READ ('INPUT'.'DISS2D','PLOT'.'SR-90' ,ERR=900) ((LTITLE(I),I=1,7)
CJ  *  ,J=1,5),(I2(J),J=1,6),IKIND,(I2(J),J=1,4),IXAUTO,(C(J),J=1,6),NPT
CJ  *  S,(XTEMP(MM),(YTEMP(I,MM),I=1,4),MM=1,NPTS)
                 CALL $YUD2 ($LGL0(2),$LNAM0,1,&900)
                 READ($DSNAM'$RECRD)((LTITLE(I),I=1,7),J=1,5),(I2(J),J=1,
     *           6),IKIND,(I2(J),J=1,4),IXAUTO,(C(J),J=1,6),NPTS,(XTEMP(M
     *           M),(YTEMP(I,MM),I=1,4),MM=1,NPTS)
     *
       LAMBDA=0.02502
       M=1
       DO 210 I=1,4
       N=1
       DO 200 J=1,NPTS
       XPON=LAMBDA*XTEMP(J)
       VALUE=YTEMP(I,J)/EXP(XPON)
       DECAY(M,N)=VALUE
       N=N+1
 200   CONTINUE
       M=M+1
 210   CONTINUE
       WRITE (6,10)
       WRITE (9,260)  (XTEMP(II),   DECAY(1,II), II=1,NPTS)
       WRITE (6,260)  (XTEMP(II),   DECAY(1,II), II=1,NPTS)
       WRITE (9,260)  (XTEMP(JJ),   DECAY(2,JJ), JJ=1,NPTS)
       WRITE (6,260)  (XTEMP(JJ),   DECAY(2,JJ), JJ=1,NPTS)
       WRITE (9,260)  (XTEMP(LL),   DECAY(3,LL), LL=1,NPTS)
       WRITE (6,260)  (XTEMP(LL),   DECAY(3,LL), LL=1,NPTS)


      WRITE (9,260)  (XTEMP(MM),  DECAY(4,MM), MM=1,NPTS)
      WRITE (6,260)  (XTEMP(MM),  DECAY(4,MM), MM=1,NPTS)
260   FORMAT (2(2X,F6.1,X,F27.25))
      GO TO 270
900   WRITE (6,901)
10    FORMAT (1X,'STRONTIUM-90',5X,'65')
C  10 FORMAT (1X,'STRONTIUM-90',5X,'65',5X,'66',5X,'67',5X,'68')
901   FORMAT ('0',///,'THERE IS AN ERROR IN READING INPUT.DISS2D.PLOT.SR
     *-90' )
CJ*** STOP
270             CALL $YUD98
      GO TO 270
      END
```

APPENDIX E DOSE PROGRAM LISTING

```
C---PROGRAM TO CALCULATE ANNUAL DOSE IN REM TO AN INDIVIDUAL WITH A
C---RADIONUCLIDE INTAKE WHICH VARIES FROM YEAR TO YEAR.  DOSE IS FOR
C---A 50-YEAR LIFETIME.
      DIMENSION Q(50),EXPO(50),DOSE(50)
      WRITE (6,110)
      READ (5,101) DCF,NPEOPL,ALAMB,NYEARS
      WRITE (6,101) DCF,NPEOPL,ALAMB,NYEARS
  101 FORMAT (E9.2,I5,E9.2,I5)
  110 FORMAT (4X,'DCF',4X,'POP',1X,'LAMBDA',1X,'YEARS')
      WRITE (6,111)
      DO 1 N=1,NYEARS
      READ (5,102) Q(N)
      WRITE (6,103) N,Q(N)
  102 FORMAT (E9.2)
  111 FORMAT (1X,'YEAR',1X,'INTAKE')
  103 FORMAT (I5,E10.3)
    1 CONTINUE
      WRITE (6,112)
      ALAMB1=1.00
      ALAMB2=1.00
      DO 2 N=1,NYEARS
      ALAMB1=ALAMB * N
      ALAMB2=ALAMB * (N-1)
      EXPO(N) = (1-1/EXP(ALAMB1)) - (1-1/EXP(ALAMB2))
      WRITE (6,104) N,EXPO(N)
  104 FORMAT (I5,E10.3)
  112 FORMAT (1X,'YEAR',1X,'EXPONENT')
      DOSE(N) = 0.00E 00
    2 CONTINUE
      WRITE (6,113)
  113 FORMAT (1X,'YEAR',1X,'DOSE')
      DO 3 N=1,NYEARS
      J=N
      DO 5 I=1,NYEARS
      DOSE(N) = (DCF/NPEOPL) * (Q(I) * EXPO(J)) + DOSE(N)
      WRITE (6,103) N,DOSE(N)
      J = J-1
      IF (J.EQ.0) GO TO 3
    5 CONTINUE
    3 CONTINUE
      STOP
      END
```

```
      DO 16 NNN=1,NCOMX
      BST(NNN)=B(NNN)
      DO 16 MMM=1,NCOMX
16    LAMBST(NNN,MMM)=LAMBDA(NNN,MMM)
      NCOMXS=NCOMX
      DETST=DET
C--------SOLVE FOR Q
      CALL MINVS(LAMBST,NCOMXS,100,DETST,BST,1)
C--------MOVE BST INTO Q
      DO 17 NCOM=1,NCOMX
17    Q(NCOM)=BST(NCOM)
C--------PRINT SELECTED QS ONLY
      IF(X4(NVTBI).EQ.XX) VPRINT=VOADD(NVTBI)+(NCR-1)*DELV(NVTBI)
      IF(X5(NVTBI).EQ.XX) VPRINT=VOGEO(NVTBI)**NCR
      WRITE(6,605) NN,MM,IOFV(NVTBI),LAMBDA(NN,MM),IOFV(NVTBI),VPRINT,
     *(ICOMPR(NCOMP ),Q(ICOMPR(NCOMP )),NCOMP=1,NCOMPX)
605   FORMAT(1H1,'FOR LAMBDA (',I3,',',I3,'), VARIABLE ',I1,' HAS BEEN'
     *,' PERTURBED.'/,T2,'THE NEW VALUE OF LAMBDA IS',1PE12.4,'. THE ',
     *'NEW VALUE OF VARIABLE',I3,' IS',1PE12.4/,T2,'COMPARTMENT',T22,
     *'Q-VALUE'/,(1H ,T5,I3,T20,1PE12.4))
      IF(DABS(DETST).LT.1.0E-08) WRITE(6,607) DETST
C--------CHECK RESIDUALS
      CALL RESID
C--------CHECK MASS BALANCE
      CALL MASBAL
C--------RESET LAMBDA TO ITS ORIGINAL VALUE
      LAMBDA(NN,MM)=LAMB(NN,MM)
11    CONTINUE
9     CONTINUE
      GO TO 18
901   STOP 1 'ERROR IN READING INPUT.DOSTOMAN.?CASE.LAMBDA.?NN.?MM'
902   STOP 2 'ERROR IN READING INPUT.DOSTOMAN.?CASE.INITIAL.VALUES'
903   STOP 3 'ERROR IN READING OR WRITING INPUT.DISS2D.PLOT.?NAME'
905   STOP 5 'TOO MANY TIME STEPS FOR PLOTTING DISS2D DATA'
18    STOP
      END
      BLOCK DATA
      REAL*4 YES/'YES'/,XX/'X'/
      COMMON /BLKB/ YES,XX
      END
```

DP-MS-81-24

Savannah River Laboratory Dose-to-Man Model
Appendix A. Deterministic Studies - SRL Model

by

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in Shallow Ground

APPENDIX A. DETERMINISTIC STUDIES - SRL MODEL

A.1.1 PURPOSE

Solid waste contaminated with radionuclides has been buried at the Savannah River Plant (SRP) burial ground since 1953. The radionuclides include alpha-emitting transuranium (TRU) nuclides, beta- and gamma-emitting activation and fission products, and tritium. To evaluate current operating limits for burial of this waste and to aid planning for the eventual decommissioning of the burial ground, the long-term dose to man from each type of waste must be estimated. The dose projections will provide guidance in choosing alternatives for a burial ground decommissioning plan. Such alternatives may include exhuming selected segments of the waste to reduce the long-lived radionuclide inventory or providing additional backfill over the waste trenches. The sensitivity of dose projections to the length of institutional control over the burial ground will provide an estimate of the minimum time period such control must be maintained.

A.1.2 BASIC DESIGN FEATURES

A mathematical model has been developed to provide estimates of long-term dose to man from buried waste. The model consists of compartments which represent different portions of the environment, including vegetation, herbivores, atmosphere, ground water, surface water, and man. Movement of radionuclides between compartments is controlled by transfer coefficients, which specify the fraction of radionuclide entering or leaving a compartment during a specified time period. Time controls account for the time lag in movement induced by such factors as the delayed presence of man. Sources and sinks independent of the natural radionuclide movement are provided.

The general form of the equation was derived by personnel at the Oak Ridge National Laboratory for a study to predict the uptake of selected radioactive species by cows.[1] Later refinements were made by personnel at the Savannah River Laboratory.

The approach used in the Savannah River Laboratory model for projecting radiation doses to man (named the DOSTOMAN model) employs a single equation that considers only the movement of radionuclides through the system. Such factors as water and wind velocity are accounted for in the transfer coefficients.

A.1.2.1 Formulation of the Basic Equation

The equation governing radionuclide movement accounts for the four factors determining the radionuclide inventory in a compartment: 1) transfer in from other compartments, 2) transfer out to other compartments, 3) source or sink terms, and 4) radioactive decay. These factors are all included in the following generalized linear differential equation:

$$\frac{dQ_n}{dt} = \sum_{m=1}^{N} \lambda_{n,m}Q_m - \sum_{m=1}^{N} \lambda_{m,n}Q_n - \lambda_R Q_n \pm S_n \qquad (1)$$

where Q_n represents the quantity of nuclide in compartment n (curies), Q_m represents the quantity of nuclide in compartment m (curies), $\lambda_{n,m}$ is the transfer coefficient for the transport of radionuclide from compartment m to compartment n (year^{-1}), $\lambda_{m,n}$ is the transfer coefficient for the transport of a radionuclide from compartment n to compartment m (year^{-1}). λ_R is the decay constant for the radionuclide (year^{-1}), S_n is a source or sink term in compartment n (curies/year^{-1}), and N is the maximum number of compartments under consideration. Equation (1) constitutes a finite difference relationship describing the change in radionuclide inventory in compartment n over time.

Thus, the first term to the right of the equal sign in the equation is the sum of all input rates to compartment n, the second term is the sum of all loss rates from compartment n, the third term is the loss from compartment n due to radioactive decay, and the fourth term is the gain or loss in compartment n due to sources or sinks, respectively.

A.1.2.2 Expansion and Solution of the Equations

Equation (1) can be specified for compartment n=1 as

$$\sum_{m=1}^{N} \lambda_{1,m}Q_m - \sum_{m=1}^{N} \lambda_{m,1}Q_1 - \lambda_R Q_1 + S_1 = \frac{Q_1 - Q_1^*}{\Delta t} \qquad (2)$$

where Q_1^* is the radionuclide inventory in compartment 1 at the beginning of the time step and all other terms are described above. Equation (2) is then partially expanded to:

$$\lambda_{1,1}Q_1 + \lambda_{1,2}Q_2 + \ldots + \lambda_{1,N}Q_N - Q_1 \sum_{m=1}^{N} \lambda_{m,1} - \lambda_R Q_1 + S_1 = \frac{Q_1 - Q_1^{\circ}}{\Delta t}$$

Isolating Q_1 terms gives

$$\left[\lambda_{1,1} - \sum_{m=1}^{N} \lambda_{m,1} - \frac{1}{\Delta t} - \lambda_R\right] Q_1 + \lambda_{1,2}Q_2 + \ldots + \lambda_{1,N}Q_N + S_1 = \frac{-Q_1^{\circ}}{\Delta t}$$

Analogously, for compartment n=2,

$$\lambda_{2,1}Q_1 + \left[\lambda_{2,2} - \sum_{m=1}^{N} \lambda_{m,2} - \frac{1}{\Delta t} - \lambda_R\right] Q_2 + \lambda_{2,3}Q_3 + \ldots + \lambda_{2,N}Q_N + S_2 = \frac{-Q_1^{\circ}}{\Delta t}$$

The equation can be generalized, then, for compartment n, as

$$\lambda_{n,1}Q_1 + \ldots + \lambda_{n,n-1} Q_{n-1} + \left[\lambda_{n,n} - \sum_{m=1}^{N} \lambda_{m,n} - \frac{1}{\Delta t} - \lambda_R\right] Q_n +$$

$$\lambda_{n,n+1} Q_{n+1} + \ldots + \lambda_{n,N}Q_N + S_m = \frac{-Q_n^{\circ}}{\Delta t}$$

where n=1,2,...,N.

The result of this expansion is a set of simultaneous, linear differential equations which define the radionuclide inventory in compartment n (n=1,2,...,N) with time as a function of transfer mechanisms ($\lambda_{n,m}$), radioactive decay (λ_R), sources and sinks (S_n), the initial radionuclide inventory (Q_n°), and the time increment (Δt). This set of simultaneous equations can be defined in matrix terms as A·X = B.

where

$$A = \begin{bmatrix} \left[\lambda_{1,1} - \sum_{m=1}^{N} \lambda_{m,1} - \frac{1}{\Delta t} - \lambda_R\right] & \lambda_{1,2} & \cdots & \lambda_{1,N} \\ \lambda_{2,1} & \left[\lambda_{2,2} - \sum_{m=1}^{N} \lambda_{m,2} - \frac{1}{\Delta t} - \lambda_R\right] & \cdots & \lambda_{2,N} \\ \vdots & \vdots & & \vdots \\ \lambda_{N,1} & \lambda_{N,2} & \cdots & \left[\lambda_{N,N} - \sum_{m=1}^{N} \lambda_{m,N} - \frac{1}{\Delta t} - \lambda_R\right] \end{bmatrix} \quad (3)$$

$$X = \begin{bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ \cdot \\ Q_N \end{bmatrix} \qquad (4)$$

$$B = \begin{bmatrix} -Q_1^*/\Delta t - S_1 \\ -Q_2^*/\Delta t - S_2 \\ \cdot \\ \cdot \\ \cdot \\ -Q_N^*/\Delta t - S_N \end{bmatrix} \qquad (5)$$

The solution to this equation is therefore $X = A^{-1}B$ and is accomplished by Gauss-Jordan elimination. The result is the value for Q_n at time t for each compartment n (n=1,2,...N). This value for Q_n is the radionuclide inventory averaged over the entire compartment n.

A.1.3 MODEL ORGANIZATION

Module DOSTOMAN is divided into two basic sections: 1) calculation of radionuclide inventories in compartments assuming transfer coefficients are continuous exponential or Gaussian functions with time or discontinuous step functions and 2) calculation of inventories assuming that some component of a transfer coefficient changes either additively or geometrically during the period being simulated.

Subroutine INPUT reads in the initial data from seven records, including: radioactive decay constant, number of compartments, number of compartments with sources or sinks, time step, values and locations of sources or sinks, initial compartment radionuclide inventory, transfer coefficient components, time functions to control the application of the transfer coefficients, and factors to perturb components of transfer coefficients, if applicable. Other input records give plotting and editing specifications. The only calculations performed in this subroutine involve the transfer coefficients, which are of the form $A \cdot V^X$. The individual components A, V, and X are read at this time and the transfer coefficients are calculated. If requested, all input data is printed by subroutine PRINTIN.

In the main program, all transfer coefficients, sources, and sinks are corrected for time dependence, if any, and the coefficient matrix is set up. Subroutine LAM is then called to calculate the terms on the main diagonal in the A matrix (Equation 3). This involves summing the λ's from m=1 to m=N and subtracting $1/\Delta t$ and λ_R. After this calculation, coefficients of the A matrix are ready for the solution of the simultaneous equation.

Subroutine RHS is then called to set up the right-hand side of the simultaneous equations [i.e., the B matrix in Equation (5)]. This involves making each term (B_n) in the B matrix equal to $-Q_n^*/\Delta t$ where n=1...N. If compartment n contains a source or sink, the time dependence of the source or sink is accounted for and the B_n are adjusted accordingly:

$$B_n = \frac{-Q_n^*}{\Delta t} - S_n \ (n=1...N)$$

Upon returning to the main program, the matrices A, X, and B are ready for solution by matrix inversion. The solution is accomplished by calling subroutine MINVS, which calculates the determinant and the inverse of the A matrix (the λ values) for the matrix problem AX=B and finds the solution vector X. Upon return from MINVS, matrix A contains the inverse matrix; therefore, the original matrix A is destroyed. Matrix B then contains the solution vector X (in this case, the Q_n). The solution is accomplished by the standard Gauss-Jordan elimination method. Details of this method can be found in matrix algebra texts. The Q_n values are then printed and any requested plots are made.

At this point in the program, time is incremented by either a specified or a calculated time step and the model is rerun to calculate Q_n values for a new time. This is done until the specified simulation time is achieved or the number of time steps is consumed.

The second part of module DOSTOMAN calculates radionuclide inventories if any component of a transfer coefficient is to be changed, or perturbed, during the run. Specifications for such perturbations, if any, are read in subroutine INPUT. If a perturbation of a transfer coefficient is to occur, the original transfer coefficient values are read in and the perturbation is calculated. The perturbation may be geometric or additive in nature and the Q_n values resulting from the perturbation are calculated only for steady-state conditions. The same calculation method for Q_n is used here as was used for the first part of module DOSTOMAN. Q_n values are then printed out.

A.1.4 MODEL OPERATING CHARACTERISTICS

As discussed under "Model Organization (Section A.1.3), the DOSTOMAN model calculates the radionuclide inventory in each compartment at the end of every time step specified. The model uses a finite difference technique to solve the simultaneous equations; therefore, there is some possibility of error accumulating during a simulation run. This error can be minimized by controlling the specification of the time steps. If radionuclide movement is occurring quickly, due, for example, to rapid ground-water transport, small time steps (on the order of one year) should be used. Later in the simulation run, larger time steps can be used. In the case of slowly moving radionuclides, such as those highly susceptible to retention in the soil by ion exchange, larger time steps can be used throughout.

The time required to run a simulation with the model will depend greatly on the characteristics of the computer facilities available to the user. On the IBM 360/195 at the Savannah River Laboratory, a simulation involving 200 time steps, 200 transfer coefficients, and 69 separate compartments requires about six minutes of central processing unit time. About 500 K bytes of core are required for such a simulation. Only one radionuclide can be considered in each run: the radioactive decay constant and many of the compartment inventories and transfer coefficients will be specific to that radionuclide.

Two means of evaluating the numerical stability of the code are included in the program. Subroutine RESID determines the difference (residual) between the calculated values for the right- and the left-hand sides of the set of simultaneous equations solved by matrix inversion in subroutine MINVS. The subroutine RHS uses the values calculated at a particular time; therefore, the difference between the two sides of each equation is a measure of how accurate the solution is. Ideally, the residual should be zero; some small residual can be accounted for by round-off and truncation errors in the calculations and is usually insignificant.

An initial inventory is provided to the system by the Q_n values. If no sources or sinks add to or remove from the system during the run, this initial amount of radionuclide must be maintained throughout the run, adjusted, of course, for radioactive decay. Subroutine MASBAL calculates the state of mass balance by summing all of the Q_n values at a particular time and comparing the total to the sum of initial Q_n values. Ideally, the deviation from mass balance should be zero; again, round-off and truncation errors may contribute to a small deviation.

A.1.5 FLOW DIAGRAM

The computer program consists of a main program (module DOSTOMAN) and seven subroutines (Figure 1).

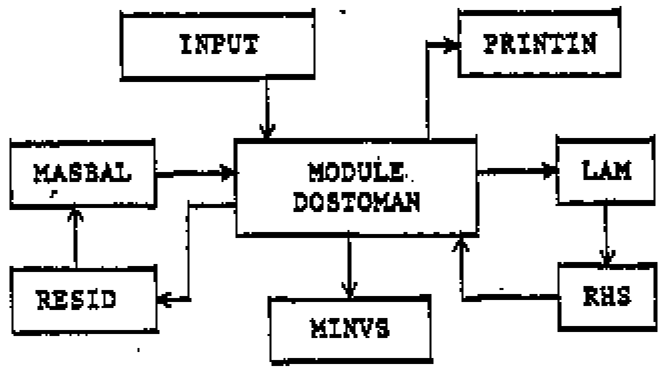

FIGURE 1. Flow Chart of DOSTOMAN

Module DOSTOMAN performs the main control function by coordinating the input and output of data and the calculations of compartment radionuclide inventories. The entire module is run for each time step specified and subroutines are called in clockwise in Figure 1, beginning with subroutine INPUT.

A.1.6 APPLICABILITY

The DOSTOMAN model as developed and coded is a compartmentalized simulation of environmental transport. As such it may be applied to any location - only the initial radionuclide inventories and the transfer coefficients input make it site-specific. However, the model was intended for application to humid locations - those with relatively high rates of precipitation and shallow water table. The Savannah River Plant can be classified as such a site. Therefore, the following discussion deals with conditions and practices only at SRP, with references to other sites where appropriate.

A.1.6.1 Disposal Alternatives

The major objective of the program to determine dose to man is to develop criteria for preparing the burial grounds for minimal post-operational control. In the short-term this involves evaluating expected dose to man based on established burial and site maintenance procedures. The effects of modifications to these procedures can be evaluated and recommendations can be made. In the long-term, the modeling will guide management decisions on decommissioning alternatives, which may include abandonment or other course, and on establishing the length of institutional control.

A.1.6.2 Waste Characteristics

Solid low-level waste at SRL includes contaminated equipment, reactor and reactor fuel hardware, spent lithium-aluminum targets, incidental waste from laboratory and production operations, and occasional shipments from offsite.[2] Accurate records are kept of the contents, radiation level, and storage location of each load of waste. Trench burial is used for alpha waste only if it contains less than 10 nanocuries per gram alpha contamination and no measurable beta-gamma activity, and for beta-gamma waste containing less than 10 nanocuries per gram alpha contamination. An exception to this is for large bulky waste which is too contaminated with gamma emitters to feasibly monitor the alpha content; such waste is buried directly in soil on top of a 6-ft backfill to keep the equipment above water that might accumulate in the trench bottom.

A.1.6.3 Hydrogeological Environments

The solid waste burial grounds at SRP are underlain by several hundred feet of unconsolidated and semi-consolidated sandy clay and clayey sand sediments which rest on granitic and gneissic crystalline bedrock. The sediments are saturated to within 40 to 60 feet of the ground surface. Clay lenses and layers are scattered irregularly through the subsurface and retard downward water flow to varying degrees. Ground water beneath the burial grounds generally flows laterally toward neighboring surface streams, with some flow downward which ultimately discharges to these same streams. Ground-water velocities are on the order of 40 feet per year in the saturated zone and seven feet per year in the unsaturated zone. Approximately 1.3 feet of precipitation reach the water table annually.[3]

The DOSTOMAN model was designed for simulating environments where the water table is very shallow. Flow through the unsaturated zone is treated very simplistically (constant soil moisture content is assumed) and therefore does not realistically handle hydrogeological environments in which significant transport occurs in the unsaturated zone.

A.1.6.4 Climate

The climate in the Savannah River area is relatively temperate, with long summers and mild winters. The average winter temperature is 9°C, and the average summer temperature is 27°C. Average annual precipitation (mostly in the form of rainfall) is 47 inches and occurs mainly in the late winter and from spring to late summer. Approximately one-third of this precipitation goes to each of surface runoff, evapotranspiration, and ground-water recharge. Average wind velocity is 6 miles per hour and generally comes from the west or southwest. There is some possibility of hurricanes and tornadoes affecting the site.[3]

Similar conditions occur at moist humid eastern sites, with some local variations. Arid regions, on the other hand, would have very little precipitation and therefore little ground-water recharge and vegetation.

A.1.6.5 Initiating Incidents

Initiating incidents for radionuclide movement at SRP are primarily a consequence of the humid environment of the site. Water percolating down from the surface mobilizes radionuclides from buried waste and transports them through the soil to ground water and ultimately to surface water or to man's immediate environment. Much of this movement, however, is so slow as to allow radioactive decay to reduce concentrations of many radionuclides to relatively low levels. Ion exchange acting in clayey sediments assists in retarding radionuclide transport.

Another consequence of the relatively humid environment is the growth of vegetation, both deep-rooted and shallow-rooted varieties, that may pick up some contamination. Other means of initiating radionuclide movement are intrusion by man and animals, and by exposure of the waste by surface erosion.

A.1.6.6 Pathways

The pathways for radionuclide movement in the environment consist of all processes and transport mediums which will move either dissolved ions or particulates. Figure 2 shows a generalized pathways conceptual model for SRP.[4] It was developed to simulate a specific land-use scenario involving four persons living on a home farm occupying the entire 200 acres of the burial ground. All food (meat, milk, and vegetables) are grown on the site and all water is obtained from a well drilled into the ground water underlying the site. The people occasionally intrude into the buried waste and contaminated soil and routinely breathe the air above the site. Also, the people occasionally swim in surface water which may be receiving contaminants from the burial grounds.

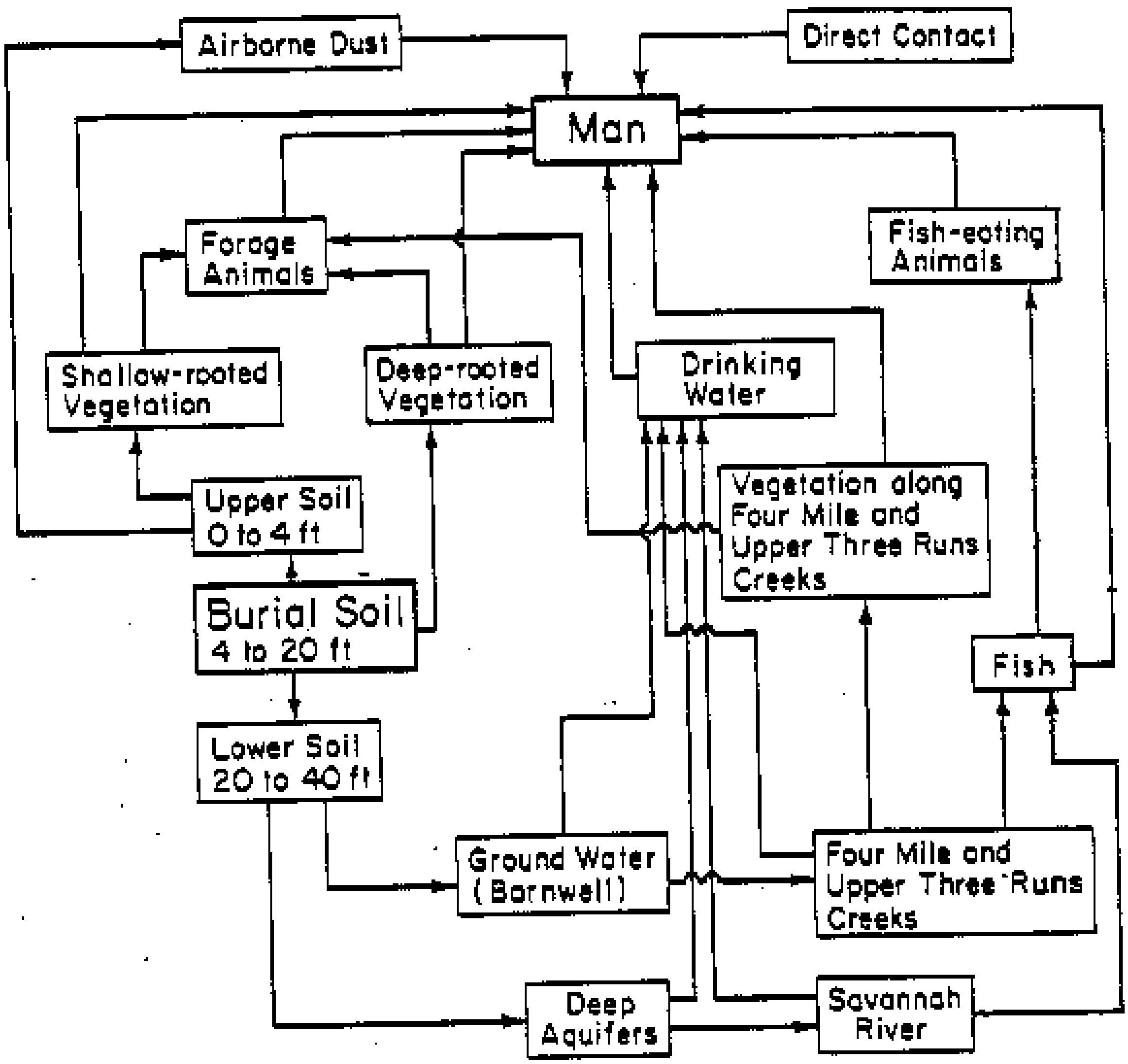

Figure 2. Radionuclide Transport Model

Although this conceptual pathways model was developed for a specific land-use scenario, its application is much broader. Other proposed land-use scenarios (see "Future and Potential Applications" - Section A.1.10) may add to or delete from the compartments and transfers shown, or modify their relative significance. The same is true for the use of the DOSTOMAN model at other geographic locations and under other climatic influences.

In most situations not all of the pathways shown in Figure 2 are significant contributors to the transport of radionuclides to man. These "critical" pathways will depend very much on the characteristics of the land-use scenario being simulated and on the particular radionuclide. In the home farm scenario for SRP described earlier, two critical pathways stand out:

1) The penetration of deep-rooted vegetation into the waste and contaminated soil brings radionuclides to the surface where they may be ingested directly by man or may enter livestock. This pathway can be critical for both short- and long-lived nuclides.

2) Radionuclides are carried down through the soil into the saturated zone and can be ingested directly by man in his water supply. Soil generally retards movement by this pathway so that it may be critical only for long-lived radionuclides. An exception to this is for tritium which is not significantly retarded by the soil. However, the projected length of institutional, post-operational control over the burial ground (on the order of 100 years) will allow for the radioactive decay of most of the tritium.

A.1.6.7 Receptors

Man is the ultimate receptor of concern of the dose from radionuclides moving through the environment. The model can be set up to account for the effects on all critical body organs. Internal and external dose can be considered. Both individual and population dose can be determined, depending on the proposed land use. Additional receptors can be livestock and other animal foods which may be affected adversely by radiation. The main concern with respect to animals is, however, where they fit into the pathways for contributing dose to man.

A.1.6.8 Biological Uptake/Transfer

In the home farm scenario, biological uptake and transfer occurs through vegetative pathways (deep-rooted vegetation, shallow-rooted grass, and vegetable crops) and through herbivore (cow and deer) and fish pathways. Other animal vectors such as birds and wild animals other than deer can be considered also.

Vegetative uptake occurs both through the roots by their contact with buried waste and contaminated soil and through the leaves due to fallout. Concentration factors control the distribution of radionuclides between plant and soil and are specific for the type of plant, type of radionuclide, and geochemical parameters such as the ratio of radionuclide to other nuclides in the soil. Transfer occurs as ions move up through the vegetation at the rate of plant internal processes. Determining transfer coefficients for vegetative uptake and transfer depends on knowing:

1) Soil-to-plant concentration factors
2) Plant root and surface vegetation growth rates
3) Root distributions
4) Root death rates

The effects of fallout require knowing:

1) Total vegetation surface area liable to catch fallout
2) Depositional velocity of particles carrying radionuclides

Animal uptake occurs when they consume contaminated food and water, breathe contaminated air, and ingest contaminated soil. Transfer will then occur from the gastrointestinal and respiratory tracts to critical body organs and to body parts consumed by man (especially muscle). Calculating animal uptake requires knowing:

1) Ingestion rates of soil, water, and vegetation
2) Inhalation rates
3) Animal mass

Internal transfer to critical body organs and to consumable body parts has been measured for many animal species. For uptake of radionuclides by fish, the following are needed:

1) Water-to-fish concentration factors
2) Fish mass

The transfer of accumulated radionuclides from vegetation and animals to man depends on his ingestion rate of these species as foodstuffs. Therefore, the following are required:

1) Consumption rate of animals and plants and their products (e.g., milk)
2) Animal and plant mass

A.1.6.9 Dose

At the present time only the dose from Pu-238 and Pu-239 has been determined for the home farm scenario. Initial inventory of each radionuclide for the simulations was 2600 and 500 curies, respectively. Pu-238 gave a peak dose of 4 millirem/person/year at about 300 years after burial ground operations ceased. The critical pathway for this radionuclide was uptake by deep-rooted vegetation, which provides dose directly to man by his consumption of fruit and nuts, and indirectly through consumption of the leaves by deer. Direct intrusion by man also contributed to the dose from Pu-238.

The dose from Pu-239 had two peaks due to the existence of two critical pathways for this radionuclide. A peak dose of 2 millirem/person/year is received at 400 years after burial ground operations ceased due to the deep-rooted vegetation pathway. Eventually, long-lived Pu-239 is transported into the ground water and is ingested by man via his domestic water supply. This provides a peak dose of 130 millirem/person/year at 38,000 years. For both radionuclides, the critical organ in man is the skeleton.

Continued literature review and ongoing field and laboratory studies may provide input data that will update and refine these dose calculations. Simulation runs are being made for Cs-137 and Sr-90; dose will be calculated for these, also. Simulations may be run for other radionuclides, if appropriate.

A.1.7 DATA INPUT REQUIREMENTS

The data required to run the model include all those factors which influence the rate of movement of radionuclides in the environment. Such hydrologic, geochemical, and lithologic information as water table disposition, ion distribution coefficients, bulk density, and porosity must be known. The radionuclide inventory must be defined as an initial condition for a simulation. Data must also be available on plant and animal concentration factors. Site-specific data are desirable; however, considerable information may be obtained from the literature.

Specifically, these items must be provided:

1) Initial radionuclide inventory of each compartment. If the run is a continuation of a previous simulation, the initial inventories will be the inventories existing in the compartments at the end of the previous run. For first runs, the inventories should be best-estimates of the quantity of radionuclide in the compartment, based on records or measurements. Only one radionuclide can be considered in each simulation run.

2) Transfer coefficients between compartments. Transfer coefficients must be read into the model in the form

$$A \cdot Y^X$$

This allows the numerator and denominator of a calculated transfer coefficient to be kept separate. For example, if

$$\lambda_{a,b} = (\text{growth rate})/(\text{total mass})$$

then the transfer coefficient is read in as

$$\lambda_{a,b} = (\text{growth rate}) \times (\text{total mass})^{-1}$$

Transfer coefficients may consist of several components, which can vary in sign. Therefore, factors influencing the movement of radionuclides between two compartments in either direction can be combined into one transfer coefficient, assuming that all factors are operating over the same time period.

The nature or makeup of the transfer coefficients will depend greatly on the particular interaction considered. Coefficients accounting for radionuclide movement in ground water will depend upon the flow velocity, radionuclide distribution coefficient, soil bulk density, and soil porosity. Coefficients simulating vegetative uptake require data on soil-to-plant concentration factors, mass growth rate, and root distribution. Some coefficients may be relatively simple in specification, such as a leach rate.

The following is a list of specific data required by the model. Additions to or deletions from this list may be required depending on the land-use scenario under consideration.

General Data Required

Length of institutional control period
Area of the land of interest

Geologic Data Required

Radionuclide distribution coefficient
Ground-water flow rates (saturated and unsaturated)
Soil bulk density
Soil porosity
Saturated aquifer thickness
Depth to mean water table
Surface erosion rates

Particle transport rate
Fraction of soil in respirable range
Rate of sediment deposition
Surface water body volumes and flow rates
Stream sediment loads

Waste Data Required

Leach rates
Radionuclide inventory
Depth of burial
Particle transport rate

Atmospheric Data Required

Airborne concentration of dust
Rate of surface soil loss due to erosion
Atmospheric mixing depth

Human Factor Data Required

Man's inhalation rate
Duration of intrusion into waste or contaminated soil
Soil ingestion rate during intrusion
Number of persons involved
Meat, milk, and vegetable consumption rates
Particle depositional velocities
Duration of exposure to contaminated surface water
Fraction of radionuclides absorbed by gastrointestinal and respiratory tracts
Water consumption rate
Probability of intrusion into waste or contaminated soil

Animal Factor Data Required

Inhalation rates
Soil ingestion rates
Number of animals involved
Food ingestion rates
Milk production rate
Mass of each animal type
Water consumption rates
Concentration factors
Fraction of radionuclides absorbed by different parts of each animal
Death rates

Vegetative Factor Data Required

Leaf surface areas
Area of land applied to each type of vegetation
Number of plants involved
Rate of decay of surface litter
Concentration factors between plant and soil
Plant growth rates
Root distributions with depth
Mass of each vegetation type
Death rates

The input for transfer coefficients occurs widely in the literature. For site-specific data, however, laboratory and field tests may be necessary.

3) Compartment interactions. In order for the DOSTOMAN model to set up the transfer coefficient matrix, it must know all of the simulation run. For each compartment, it must therefore be specified which compartments receive radionuclides from and send radionuclides to the compartment in question. Therefore, each possible interaction is listed as part of the input.

4) Radioactive decay constant. Simulation runs of the DOSTOMAN model can handle only one radionuclide at a time; therefore, one decay constant needs to be specified prior to the run. It should be in units consistent with those of the transfer coefficients (e.g., 1/year).

5) Time step size. Specification of the time step should be consistent with the expected rate of movement of the radionuclide and the anticipated length of time to be simulated. As discussed under "Model Operating Characteristics" (Section A.1.4), periods of time in which radionuclide inventories in compartments are rapidly changing should be simulated with small time steps (on the order of one year). However, if long periods of time are to be simulated, it is advisable to increase the time step size later in the simulation. Time step size increases should be made at a rate of no greater than 1.5X for each increase (i.e., t_{i+1} is equal to or less than 1.5 x t_i) in order to reduce computational errors.

6) Time functions. In certain situations, a transfer coefficient may not be applicable for a certain period of time. For example, if deep-rooted vegetation is excluded from a waste disposal site for a period of years after operations have ceased, transfer of radionuclides from buried waste or contaminated

soil to the surface via this pathway will not begin immediately. For this situation, a time lag should be specified for application of the transfer coefficient. If a time lag is not specified, the transfer is assumed to be occurring from the beginning of the simulation run.

7) Sources or sinks. In certain situations, other sources or sinks for radionuclides may develop in parts of the modeled system other than the original location (e.g., a buried waste site). For example, radionuclides may be introduced as fallout to surface soil, or exhumation of buried waste may occur after radionuclide movement in the environment has begun. Such sources or sinks (with their locations, strengths, and times of application) should be specified.

A.1.8 COMPUTER AND LANGUAGE USED

The DOSTOMAN model may be used on any modern computer facility. Core requirements will vary with the number of compartments and time steps being simulated, but average requirements will be on the order of 500 K bytes for 69 compartments, 200 transfer coefficients, and 200 time steps. At the Savannah River Laboratory, the IBM 360/195 and the IBM 370/158 provide more than adequate capabilities. Hardware for plotting is desirable. The model is written in the FORTRAN computer language.

A.1.9 CURRENT STATUS

Development work on the DOSTOMAN model is presently complete and simulating several simple test cases has demonstrated the model's validity. The model is being used to simulate hypothetical land-use scenarios.

A.1.10 FUTURE AND POTENTIAL APPLICATIONS

Several land uses are possible for the burial ground area at the Savannah River Plant after operations and institutional control have ended. It is the purpose of the present dose-to-man modeling effort to simulate as realistically as possible the more likely of these land-use scenarios. As discussed under "Applicability" (Section A.1.6), the scenario considered to date involves a small home farm utilizing the entire 200 acres of burial ground area and completely supporting and sustaining a small family. This particular land use is considered plausible based on historical uses of the land in this region.

Proposed land-use scenarios expand on the generally agricultural nature of the region. A commercial forest will be simulated which has limited recreation use and widespread distribution of products. The tree type will be several species of pine, typically grown in large plantations in the area. Dose to workers and leisure forest users will be determined and the effects of the widespread distribution of lumber, sawdust, and radionuclides mobilized during forest management practices will be evaluated. Also to be simulated will be a commercial farm, with typical regional crops such as corn and soybeans. Dose to farm workers and to the population handling and consuming the produce will be evaluated.

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APPENDIX C

EXAMPLES OF USE OF THE COMPARTMENTAL MODEL IN TRANSPORT AND PATHWAY ANALYSES FOR THE MANAGEMENT OF NUCLEAR WASTE

OSR 24-A114
(REV 10-81)

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CC: J. T. Granaghan, SRP
J. T. Lowe, SRL

September 24, 1984

Mr. C. G. Halsted, Director
Process & Weapons Division
Savannah River Operations Office
U.S. Department of Energy
Aiken, SC 29801

Dear Mr. Halsted:

TECHNICAL BASIS FOR LIMITS FOR THE DISPOSAL OF TRANSURANIC (TRU) WASTE

Based on discussions with Harold Saucier and Mike O'Rear of your staff, we have enclosed DPST-84-226, "Technical Basis for Limits for the Disposal of Transuranic (TRU) Waste," which provides a summary of SRP experience with TRU waste management, monitoring and transport modeling with regard to the TRU disposal limit of 100 nCi/g. Our site-specific results are consistent with analyses by other organizations and support 100 nCi/g as an environmentally acceptable TRU disposal limit for shallow land burial.

As an operational practice at the Savannah River Plant, we recommend that transuranic waste between 10 nCi/g and 100 nCi/g be handled as Greater Confinement Disposal (GCD) waste. The GCD is currently being demonstrated at the SRP burial ground for the higher activity fraction of low level waste. Approximately one hundred thousand cubic feet of waste containing approximately 95% of the radioactivity (50,000 curies per year) in solid LLW will be emplaced in GCD boreholes or in engineered trenches in which the waste is encapsulated in concrete and buried with a 15 ft. overburden. The GCD disposal mode is equivalent to that described in 10CFR61 for Class C waste. Disposal of alpha waste is entirely consistent with the NRC regulation (10CFR61.55). Implementation of disposal of TRU waste between 10 and 100 nCi/g will require that a change be made in SROO Order SR 5820.1, which states that 10 to 100 nCi/g waste be stored retrievably and will require preparation of a subsidiary Test Authorization under the GCD Test Authorization 2-1045 and supporting NEPA documentation.

The volume of suspect alpha waste buried annually in shallow trenches is approximately 1×10^5 ft^3. If all of that volume were at the 10 nCi/g concentration limit, the amount of Pu disposal per year is approximately two curies. The estimated volume of waste in the 10 to 100 nCi/g concentration range is less than 5×10^3 ft^3/year. If all of that volume were at the recommended upper limit of 100 nCi/g, the additional input to the burial ground inventory is less than two curies per year. Even without the added environmental protection provided by the stabilized waste form of the GCD cement grout, and the deeper burial, the addition represents a minor incremental dose-to-man in the long term projection. Considering the added environmental protection provided by the GCD technique, and the fact that ^{238}Pu (86 year half life) is the dominant radioactivity in SRP transuranic waste, the long term dose-to-man is a negligible increment.

Questions your staff may have should be directed to O. A. Towler (extension 2285) of the Waste Disposal Technology Division staff or C. M. King (extension 5206) of my staff.

Sincerely,

T. V. Crawford, Director
Environmental & Analytical Technology

ELA:jn
Enc

Chuck fyi

BCC Distribution, Letter T. V. Crawford to C. G. Halsted, September 24, 1984, Re: Technical Basis for Limits for the Disposal of Transuranic (TRU) Waste

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September 24, 1984

M E M O R A N D U M

TO: M. M. ANDERSON, JR

FROM: C. M. KING CMK

TECHNICAL BASIS FOR
LIMITS FOR THE DISPOSAL OF TRANSURANIC (TRU) WASTE

CONTENTS

TECHNICAL BASIS FOR LIMITS FOR DISPOSAL OF TRANSURANIC (TRU) WASTE:

1.1 INTRODUCTION

Since 1973, the definition of transuranic (TRU) waste[1-2] is that waste which contains more than 10 nCi/g of alpha activity from transuranium elements or U-233. These wastes are materials or equipment that have been contaminated in processing of plutonium or other transuranium elements. Those wastes that exceed this 10 nCi/g limit are placed in retrievable storage for later transfer to a repository. Those wastes that are lower than the limit have been sent to shallow land burial. The 10 nCi/g limit was derived[1,2] by considering the highest levels of Ra-226 that occur in natural geologic deposits. The rationale for the radium analogy[2] was that if people had lived with these levels of radium (and other alpha emitters) in discrete locations with no apparent harm, the same would be true for deposits of transuranium elements in shallow land burial.

The present limits defining the level at which wastes containing transuranium elements are to be placed into retrievable storage for eventual shipment to a repository are several years old. It is recognized that the cost of possible treatment of the wastes, transportation, and emplacement in a repository may be high. Since the original definition, several studies of the impact of these wastes in land burial have been made. As a result, a re-examination of the entire question was proposed to see if a method of classification of TRU wastes exists that will result in significantly lower costs and still protect the health and safety of workers and the public. A ten-fold increase of the current limit to 100 nCi/g has been promulgated by DOE.

Based upon actual experience at the Savannah River Plant with shallow land disposal of transuranic elements, an analysis of disposal limits for TRU burial has been conducted with emphasis upon observed TRU element migration over the 28 year period of TRU disposal in earthen trenches, as well as projection's - based upon transport modeling - of future TRU element migration potential. Disposal limits have been projected based upon analysis of potential dose-to-man for a maximally exposed individual.

1.2 CONCLUSIONS

Historical TRU disposal at SRP has occurred at levels greater than 100 nCi/g. TRU migration to the water table below the burial site, over the 28 year operating history, has been minimal and would result in human exposure well below Federal regulatory guidelines (DOE 5480.1A Chapter XI: Requirements for Radiation Protection).[34]

Potential plutonium transport from land buried waste to the Savannah River at the SRP plant boundary was analyzed via transport modeling calculations. Projected Savannah River contamination levels and dose-to-man were shown to be considerably less than DOE requirements on water contamination outside the bounds of DOE installations (DOE 5480.1A) as well as DOE limits on permissible exposure (500 mrem/person/year, bone) at the boundary of DOE installations.[34] Assuming a 100 nCi/g TRU disposal limit was implemented at SRP, site-boundary analysis was shown to be well within DOE Guidelines.

Transport modeling projections on land disposal of plutonium isotopes based on the assumption of land occupation of the disposal site after closure imply plutonium isotopes - particularly long-lived Pu-239 - will continue to migrate. Pathway analyses, under conservative assumptions of exposure to a maximally exposed individual directly occupying the site, indicate the significant pathways leading to human exposure are uptake by vegetation and groundwater contamination. Calculated maximum individual exposures are less than the Federal regulatory guideline of 500 mrem/person/year for the maximally exposed individual.

Analysis of dose results in perspective to historical disposal levels indicate that a 100 nCi/g disposal limit would be reasonable, with a safe margin, based upon the historical performance of the burial ground as a containment system and transport modeling results on potential radionuclide migration in the future. Conservative assumptions in transport modeling make it likely that even if dose regulations were changed to lower values, environmental impact of TRU transport would not exceed any potential new standard. In any case, consistent with ALARA, Savannah River Plant should use 100 nCi/g for Greater Confinement Disposal.

The transport results and an operational TRU disposal limit of 100 nCi/g are consistent with independent analyses conducted by several other organizations.[18-24,29,32]

An operational TRU disposal limit of 100 nCi/g, derived by site-specific transport and pathway analysis, is consistent with the recommendations of the National Council on Radiation Protection and Measurements (NCRP)[2], the Program Committee of the Workshop on Alpha-Contaminated Waste Management[21,22], and the assessment of Defense Transuranic Waste by J. J. Cohen of Science Applications, Inc.[29]

1.3 DISCUSSION

1.3.1 Limits Based Upon SRP Experience With Shallow Land Disposal of Transuranics

Waste management operations[3] began at the Savannah River Plant in 1954. Until 1965, waste was placed into plastic bags and cardboard boxes, and approximately 4,000 curies of TRU waste contained in 25,000 M^3 of waste were buried in earthen trenches.[3] Use began in 1965 of prefabricated concrete containers placed in trenches for TRU waste above 0.1 Ci/package. In 1974, the 10 nCi/g limit for retrievable storage was implemented. Since 1965, 98% of the TRU activity - corresponding to approximately 10% of the TRU volume-is judged to be recoverable from the burial trenches or above ground storage pads. Design is underway for facilities to retrieve this waste and process some of it for deep geologic storage.

A summary of TRU land disposal history at SRP, and operating performance of the burial ground as a containment system for TRU nuclides is provided in Table I, along with exposure results based upon observed TRU groundwater contamination. The results can also be put into perspective with historical TRU disposal levels from the operating history of the SRP burial facility.

The bulk of the TRU activity disposed of in earthen trenches consists of plutonium isotopes. As of December 31, 1982,[4] 3,400 decayed Ci of Pu-238 and 600 decayed Ci of Pu-239 constitute the remaining activity in solid radioactive waste buried in backfilled trenches at the SRP burial ground. The estimated volume[4] of Pu waste is 12,000 m^3 of Pu-238 and 20,300 m^3 of Pu-239.

Based on the curie inventory and waste volume of plutonium isotopes in shallow land burial, the estimate of the nCi/g concentration in actual SRP buried waste is:

Pu-238: 2,900 nCi/g
Pu-239: 300 nCi/g.

for an average waste bulk density[3] of 6 lbs/cu ft. Hence, the actual historical disposal of transuranic waste at SRP during the period 1955 to 1965 had been in excess of the 10 nCi/g limit imposed in 1974. This fact can now be placed into perspective with actual TRU migration data.

The historical performance of the SRP burial ground as a radionuclide containment system has been recently analysed by several workers.[5] The performance of the burial ground for retention of TRU contaminated materials can be described by defining a "containment factor."[5] This is simply the ratio of radioactivity buried to that which has reached the water table, as estimated from groundwater monitoring. The "containment factor" for alpha emitting radionuclides has been estimated[5] to be 1×10^6 - a very large value implying high retention of these isotopes. This is based upon the observation from grid well monitoring that Pu-238 and Pu-239 are observed in the water table[4,5] at 3 to 5 pCi/L. In part, the measurement of Pu isotopes in groundwater at these levels is believed to be associated with "anomalous" mobility[4,5] of plutonium due to localized organic complex formation, competitive cation exchange, or abnormal pH conditions - all factors which enhance localized movement from buried waste to the water table.[4,5] Work on establishing a correlation between wells with anomalous chemistry and wells containing measurable low-level radioactivity is still in progress.[4,5]

If one assumes the groundwater could serve as a drinking water supply to a maximally exposed individual who sampled the water table at a rate of 2 liters/day (the maximum individual water consumption rate),[6,7] the maximum individual bone dose received would be 2.1 mrem/person/year.[7] This is well below the maximum individual exposure limit of 500 mrem/person/year to bone.[8-10] It must also be emphasized that the calculated annual individual dose of 2.1 mrem would be to an individual who had access to the burial site and sampled and consumed the alpha contaminated groundwater on a daily basis over a period of one year - a highly improbable event.

Hence, actual SRP transuranic disposal rates well in excess of 100 nCi/g have resulted in minimal observed migration of TRU nuclides to the water table due to high soil adhesion properties for TRU nuclides.[5,30,31] Doses calculated from assumed water consumption are well below maximum individual limits.

It can be implied from actual TRU movement to the water table over the 28 year period of TRU disposal to earthen trenches, that a 100 nCi/g limit would be reasonable - with a safe margin - based upon actual burial ground performance and historical TRU disposal practice at the Savannah River Plant.

1.3.2 Limits Based Upon Transport Modeling Projections

1.3.2.1 SRL DOSTOMAN Results/SRP TRU Disposal

A mathematical model - so called DOSTOMAN - was developed and has been in use since 1978 to simulate the potential migration of radionuclides from unencapsulated waste in the burial ground. The conceptual model simulates the various hydrologic, animal, vegetative, atmospheric, and terrestrial pathways in calculating a potential dose-to-man versus time for hypothetical post-closure land occupation scenarios. Dose projections have been used to provide guidance in planning for the eventual decommissioning of the burial ground. Model methodology and examples of its use have been published in numerous technical publications.[11-17,27,36]

The DOSTOMAN code[11-17] solves a mass balance equation based on a set of simultaneous linear differential equations that simulate radionuclide transport. The code extends the calculations to a number of pathways by scenario analysis. Realistic scenarios such as hydrologic transport and hypothetical scenarios such as future land occupation are used to estimate environmental impacts, usually stated as dose commitments. These in turn are used to evaluate site performance, radionuclide disposal limits, improved concepts for land disposal of waste, and decommissioning alternatives. The code relies on site-specific input data such as radionuclide inventory, chemical form, release rate, K_d's, and geohydrologic parameters.

Calculations on radionuclide transport from buried waste forms to the hydrologic system contiguous to the SRP burial ground are based upon the HTRANSPORT (hydrological transport) subprogram of the SRL DOSTOMAN Code. HTRANSPORT mathematically describes transport in one dimension by a set of linear differential equations[12,13,37] which account for mass transport by advection[38] and chemisorption[39] of the contaminant by soil particles. The basic equations assume Darcy's Law[38-42] is applicable in the unsaturated and saturated zones.

Attenuation of contaminant transport by soil sorption assumes that the linear Freundlich adsorption isotherm[39] is applicable (Freundlich proportionality constant is the soil/water partition coefficient, K_d, for the solute of interest) and the solute Retardation Factor (RF) equation[38-40,42] is applicable. HTRANSPORT has been validated mathematically[37] against an exact analytical solution and empirically for the tritium plume[4,5] below the 643-G burial ground. Based on the literature[38,43] advective transport will provide a conservative upper limit estimate for solute contamination of the hydrological system. More details are provided in Appendix II. Pathways analyzed have been described in detail in prior publications.[11-17]

1.3.2.1.1 Pu Transport: SRP Site Boundary Analysis

Model projections of plutonium transport[11,15] have been re-analyzed to estimate the extent of migration of plutonium isotopes to the hydrological system contiguous to the SRP low-level waste burial ground. In principle, percolating rainwater will leach radionuclides from land-buried radioactive waste, causing movement through the unsaturated zone to the water table. The groundwater will outcrop to the surface stream - Four Mile Creek - which flows to the Savannah River. Hence, potential contamination of the Savannah River at the SRP site boundary can be estimated and projected for plutonium transport from information on

- the annual rate of plutonium release from buried waste to burial soil
- the soil adhesion properties of plutonium in the unsaturated and saturated zones
- soil bulk density and porosity of the saturated and unsaturated zones
- percolating rainwater rates and minimum flowrates of tributary and Savannah River
- dimensions of the unsaturated zone and distance of the flow path to the outcrop
- radionuclide half-lives (to account for time-dependent radioactive decay)
- unsaturated and saturated zone water flow rates (to account for time-dependent equilibration of soil-absorbable plutonium isotopes with the flowing water columns)
- chemical speciation of plutonium[30,31]
- water quality information from groundwater monitoring

The mass transport equation for simulating solute movement in the hydrological system - MOBILNUC subprogram of DOSTOMAN[12] - provides time-dependent projections of radionuclide flux (pCi/yr) to the hydrological system and estimates of tributary and Savannah River contamination for movement of radionuclides from land buried low-level waste. Results for the plutonium analysis are summarized in Table II for each isotope for two cases:

- soil absorption[13] of plutonium to reflect a soil/water distribution coefficient (K_d) of 150 (a conservative value which will tend to overproject the rate of plutonium movement to the water table)[30,31]

- minimal soil absorption of plutonium isotopes (K_d = 5 to illustrate an extreme, worst-case, situation)[30,31]

Summarized in Table II are the projected maximum concentrations of plutonium in the Savannah River at the SRP boundary, along with the resulting dose for consumption of Savannah River water. The exposure analysis is also extended to a human foodchain sequence (water, fish, vegetation, milk, and meat) based upon USNRC 1.109 Regulatory Guide methodology.[6] The total foodchain results (Appendix I) illustrate the maximum risk to an individual consuming river water and using river water for irrigation purposes at the SRP site boundary and have been described, in detail, in prior publications.[6]

The estimated Savannah River concentration (6×10^{-5} pCi/L) is less than the DOE 5480.1A Uncontrolled Area Limit for plutonium[34] (5×10^{3} pCi/L) by at least a factor of 1,000,000.

The maximum projected annual bone dose (4×10^{-6} mrem/person/year) is less than the EPA Public Drinking Water Supply Limit[7] of 4 mrem/person/year for the water pathway. In addition, the conservative food chain calculation (4×10^{-5} mrem/person/year) is significantly less than the boundary dose limit of 25/75/25 mrem/person/year (whole body/ thyroid/other organs) recently proposed by the EPA (40 CFR 191).[26]

The boundary dose calculations reflect an historical TRU disposal rate of $\geq$300 nCi of TRU/g of waste (as described in Section 1.3.1), corresponding to TRU decayed inventories of 3400 Ci of Pu-238 and 600 Ci of Pu-239 through 1982.[4] An incremental increase in TRU disposal at the rate of 100 nCi/g would add an additional 2.0 Ci/year (upper limit) to the TRU inventory designated for shallow land burial. This is based upon the current annual TRU volume of 15,000 - 20,000 cuft/yr (6 lbs/cuft) now sent to above-ground stored TRU pads. Approximately 30% of the annual TRU pad volume could be diverted to land burial since the TRU concentration is estimated to be < 100 nCi/g. The projected ten-year increment to shallow land burial is a total of 20 Ci (upper limit)- small relative to the historic disposal quantities. The environmental consequence of this additional incremental inventory is summarized in Table III. The maximum projected SRP boundary dose to bone (6×10^{-5} mrem/person/year) - based on the conservative food chain calculation - is at least a factor of 100,000 below the boundary dose limit of 40 CFR 191 (25/75/25).

The time scale in the calculation of projected Savannah River contamination dose not exceed 10,000 years. This practice is consistent with the U.S. Environmental Protection Agency computational procedures now in use with the U.S. E.P.A. PRESTO (Predictions of Radiological Effects of Shallow Trench Operation) transport simulation Code.[35]

Based upon SRP boundary dose analysis, a 100 nCi/g disposal rate would not impose a significant additional dose to individuals outside of the SRP site boundary.

1.3.2.1.2 Pu Transport: Hypothetical Land Occupation

The details of the transport modeling analyses for land disposal of plutonium isotopes were first examined by Wilhite with a re-analysis by Fauth. Fauth and Wilhite presented their analyses of Pu disposal and transport publically at the symposium on Environmental Transport Mechanisms: Control of Radionuclides in Soil (Las Vegas, Nevada; June 8-13, 1980).[15] A presentation of the results of these prior studies with emphasis on placing the maximum individual dose analyses into perspective with actual nCi/g plutonium disposal rates based on historical SRP burial ground operation was presented by King and Wilhite and published in the Proceedings of Alpha Contaminated Waste Management Workshop (August 10-13, 1982) in Gaithersburg, Md.[16]

The Fauth/Wilhite results are shown graphically in Figure I for the transport of plutonium isotopes from buried waste into the burial ground biosphere for the hypothetical post-closure use of the 200 acre burial site as a small family farm - 100 years after burial operations cease. The family (4 adults) live continuously on the site and obtain their annual food and water supply from

- Site fruit trees and vegetables
- Grazing animals
- A well in the Barnwell formation.

Plant uptake of radionuclides occurs due to assumed vegetative root penetration of buried waste - leading to upward movement of activity and soil contamination via root and crop decay. The individuals are potentially exposed to contamination due to consumption of vegetation, herbivore's milk and meat, water, and occasional intrusion into contaminated soil resulting in skin contamination and inhalation of dust. Movement of TRU nuclides downward to the Barnwell water supply is controlled by rainwater percolation rates and water/soil equilibrium constants (distribution coefficients). Site specific data were used as much as possible in the transport calculations.

The interpretation of the results on plutonium transport, per the hypothetical land occupation scenario, is as follows (Figure I):

- Pu-238 exhibits a transport maximum at about 400 years - corresponding to a maximum individual dose of 4 mrem/person/year to bone (critical organ). The dose results from radionuclide migration upward by vegetative uptake, leading to soil contamination. The primary transport vector is vegetation consumption with minor contributions via ingestion and inhalation due to soil resuspension and occasional human intrusion. The maximum exposure is well below maximum individual standards.[8-10,34] For Pu-238, radioactive decay causes the dose to decrease to infinitesimal levels over longer periods of time.

- Pu-239 shows a somewhat longer transport tendency with time due to the long radionuclide half-life of that isotope. The transport maxima is comparable in magnitude with that of Pu-238 and corresponds to a bone dose of 2 mrem/person/year at 800-1000 years. The bone dose gradually drops to 0.2 mrem/person/year over extended periods of time (10^4 years). The primary transport pathway is uptake by vegetation and individual consumption of vegetation under the premise of the hypothetical land occupation scenario.

The time-scale for transport analysis can be quite variable but could reflect the half-lives of the nuclides of interest. The Environmental Protection Agency in their development of codes for the EPA 40CFR193 proposed rulemaking on standards for low level waste disposal (EPA 520/5-83-004 PRESTO-EPA: A Low-Level Radioactive Waste Environmental Transport and Risk Assessment Code Methodology)[35] recommend analyses not to exceed 10,000 years. In our TRU transport analysis for hypothetical land occupation scenarios, we follow the Environmental Protection Agency computational procedures.

The small-farm scenario used by Fauth and Wilhite is a worst-case situation[20] since it assumes loss of institutional control and public occupation of the burial ground site with annual individual food requirements derived entirely from agricultural land-use of the site. In addition, basic input data used to generate the transfer coefficients[11-17] were chosen to be conservative and, hence, tend to overestimate the dose. In any case, the individual dose estimates - by any pathway - are less than the DOE guideline of 500 mrem/person/year for the maximum exposed individual.[8-10,34]

The hypothetical land occupation results on TRU waste transport can now be placed into perspective with actual plutonium disposal rates - as previously described. This summary is presented in Table IV. Actual TRU disposal has historically occurred at levels in excess of 300 nCi/g. The projected maximum individual bone dose - corrected for updated 1982 inventories[4] of buried Pu isotopes - is a total of of 7.7 mrem/person/year and does not exceed the DOE guideline of 500 mrem/person/year for maximum individual exposure to bone.[34]

The environmental consequence of future TRU disposal at a 100 nCi/g annual disposal level is summarized in Table V. Assuming 100 nCi/g were implemented as a land disposal limit over the next ten years, an additional 20 Ci of plutonium could conceivably be added to earthen trenches. Based on the Fauth/Wilhite analysis[15] (Case 1), the upper limit of bone dose would approach 8 mrem/person/year, due to increased plutonium inventory. This is a highly conservative result (factor of 10) based upon hypothetical land occupation, vegetative root penetration of land disposed nuclear waste, maximum Pu release rates to the environment, and an upper limit of future Pu disposal (2.0 Ci/year). Basing the calculated transport analysis upon field measured (lysimeter) radionuclide release rates[27] (Case II) results in a maximum individual bone dose of 0.8 mrem/person/year. Elimination of the plant uptake pathway (Case III) by the addition of a burial ground overburden above the waste (decommissioning option) or Greater Confinement Disposal[28] of the incremental plutonium inventory would further reduce the maximum bone dose estimate to 0.4 mrem/person/year (to an individual assumed to have access to the disposal site in the future).

1.3.2.2 Compendium of SRP Site Specific Pathway Analyses

1.3.2.2.1 Calculated Environmental Impact as a Function of Scenario

A summary of SRP site specific pathway analyses for assumed TRU shallow land disposal to earthen trenchs at the assumed limit of 100 nCi/g is given in Table VI. For the realistic and hypothetical scenarios for which calculations were performed:

- burial ground groundwater as a drinking water supply
- Savannah River water as a drinking water supply
- Savannah River water as a source for crop irrigation and marine life leading to a human foodchain analysis

- the use of the Savannah River for recreational purposes[6] (boating, fishing, swimming, shoreline recreation)

- hypothetical land occupation of the burial ground site, after institutional control ceased, with use of the land for agricultural and recreational purposes,

the environmental impact - based on the current inventory of plutonium isotopes supplemented by the 100 nCi/g increment (2 Ci/year for the next ten years) - is slight and well below DOE guidelines[34] for maximum permissible human exposure.

1.3.2.2.1 Incremental Environmental Impact as a Function of Scenario

An incremental dose has also been calculated to illustrate the environmental impact associated with the assumed change in the TRU SLB disposal limit from 10 nCi/g to 100 nCi/g. The incremental effect is summarized in Table VII for each of the realistic and hypothetical scenarios used in the SRP site specific pathway analyses. The incremental dose associated with the change is calculated to be insignificant (10^{-11} to 10^{-1} mrem/person/year bone dose).

1.3.2.3 TRU Demarcation Valves based upon SRP Site Specific Transport Modeling, Pathway Analyses, and Scenarios

Using the analysis procedures documented by other organizations,[20,24,29] TRU demarcation or interface valves can be calculated from the transport modeling calculations for each SRP site specific scenario examined. Results are illustrated in Figure II. The demarcation or interface valves are determined on the assumption that the 500 mrem/person/year bone dose guideline[34] is an acceptable upper limit of exposure for a "few isolated individuals".[29] By extrapolation of the calculated dose for each scenario to the 500 mrem/person/year limit, a TRU demarcation or interface valve can be derived.

The results of this exercise (Figure II) indicate that for each SRP site specific scenario examined, the TRU disposal limit could be at least 1000 nCi/g.

Based upon the conservative Case 1 DOSTOMAN transport analysis of Fauth and Wilhite,[15] an environmentally acceptable TRU disposal limit (Table VIII) could be at least

- 1000 nCi/g for Pu-239 and

- 2000 nCi/g for Pu-238.

At these model projected TRU disposal levels, the 500 mrem/person/year exposure guideline would not be exceeded for TRU shallow land disposal well into the future, since the TRU incremental volume is small. In perspective, the 100 nCi/g proposed limit is conservative with a large margin of safety.

1.3.2.4 Other Studies on Transport Modeling/TRU Disposal

A comparison can now be made of the SRL DOSTOMAN TRU disposal limit with limits based upon independent transport modeling analyses by other organizations.[18-26] This summary is presented in Table IX. Limits for the shallow land burial of transuranic elements were derived by pathway analysis to man. Pathways examined included transport to the groundwater and surface streams, intrusion, and exposure to individuals living on the burial ground - pathways similar to our own but analyses conducted independent of the SRL work. Limits were derived for each pathway and TRU disposal operational limits evolved based upon a dose to the critical organ of 500 mrem/year for the maximum exposed individual. The operational limits for pathway/transport analysis by Healy and Rodgers (LASL);[1] Rogers (Ford/Bacon/Davis);[18] Idaho Operations Office;[19] Cohen and King (LLNL)[20] and others are comparable in magnitude with the SRL model projected disposal limit. Most results favor 100 nCi/g as a conservative limit, with a safe margin. In many cases, the limits derived by technical analysis of environmental transport are greater than 100 nCi/g.

The most pessimistic value is the range of 2-50 nCi/g based on the original work by Healy and Rodgers of Los Alamos. Their principle pathway for exposure was based upon direct human intrusion into the waste - the so-called "archeological intruder." Exposure is based upon direct human ingestion and inhalation of contaminated soil. A realistic point of view for SRP TRU disposal, is that the Healy/Rodgers intrusion scenario is a highly improbable event for a greater confinement mode of disposal or for a properly decommissioned burial ground.

1.3.3 Conclusions on TRU Disposal by the National Council on Radiation Protection and Measurements (NCRP) and the Program Committee of the Alpha-Contaminated Waste Management Workshop

The National Council on Radiation Protection and Measurement (NCRP), in work by their Scientific Committee 38 (SC 38) and the SC 38 Task Group on Criteria for the Disposal of Transuranic (TRU) Contaminated Waste recommended[2] that the 10 nCi/g limit for TRU waste be abolished and replaced by site-specific controls based on permissible doses to people. These dose limits can be converted to waste concentration limits by the application of <u>site-specific</u> pathway models. In most of the scenarios studied, the limiting dose will result from human intrusion. Human intrusion scenarios can be ameliorated by greater confinement disposal methods.[28] The SRL transport modeling/pathway analysis has been utilized in this fashion for a site-specific assessment of TRU disposal consequence and is consistent with the NCRP recommendations. Greater Confinement Disposal[28] of TRU waste exists as a management option for consideration if additional environmental barriers are deemed necessary for continued safe TRU disposal to earthen trenches.

The Program Committee for the Workshop on Management of Alpha-Contaminated Waste concluded[21,22] that a level of 100 nCi of long lived alpha contamination per gram of waste, averaged over the contents of a waste package, can be designated as a concentration in low-level waste for near-surface disposal. Based upon technical input and discussions at the Workshop, such a concentration is unlikely to result in exposure exceeding present dose limits. The Committee also concluded that site-specific or case-by-case analyses may be required that take into account the particular attributes and circumstances of the waste and the disposal systems or facility. The SRL transport analysis was conducted with major emphasis on utilizing site-specific facility and radionuclide basic data for a complete accounting of the exposure potential associated with TRU transport. The approach and conclusions of our analysis are consistent with the recommendations of the DOE-sponsored Workshop on Alpha-Contaminated Waste Management.[21,22]

TABLE I

TRU Disposal and Operating Performance of the SRP Burial Ground

	TRU Nuclide				
	Pu-238	Pu-239	Cm-244	Other	Reference
Decayed Curie Inventory (12/31/82)	3400	600	3500	56	4
Calculated Burial nCi/g of Waste*	2900	300	1550	25	-
Containment Factor	1×10^6	1×10^6	-	-	5
Observed Average Burial Ground Groundwater concentration pCi/L	5	3	ND**	ND**	4
Drinking Water Dose, mrem/person/yr***	1.3	0.8	-	-	-

* Average bulk density 6 lbs/cu. ft. (Reference 3)

** ND (Not Detected); No Gamma emmitters other than Co-60 and Cs-137 were observed;[4] Less than nominal lower limit of detection[4] of 7 pCi/L.

*** Annual Bone Dose[33] to Maximum Exposed Individual assumed to consume 2 L/day (730 L/yr)[7] of Contaminated Burial Ground Groundwater.

TABLE II

Pu Transport: SRP Site Boundary Analysis

Calculated Values	Pu-238 Soil Adhesion*	Pu-238 Soil Adhesion**	Pu-239 Soil Adhesion*	Pu-239 Soil Adhesion**
Maximum Flux to the Outcrop, pCi/yr	5×10^{4}	3×10^{8}	8×10^{3}	5×10^{7}
4 Mile Creek Concentration, pCi/L	3×10^{-6}	2×10^{-2}	4×10^{-7}	3×10^{-3}
Savannah River Concentration, pCi/L	8×10^{-9}	5×10^{-5}	1×10^{-9}	8×10^{-6}
Foodchain Dose, mrem/person/year***				
- Water	4×10^{-10}	3×10^{-6}	6×10^{-11}	5×10^{-7}
- Total	3×10^{-9}	3×10^{-5}	5×10^{-10}	6×10^{-6}

* Equilibrium Distribution Coefficient of 150.[30,31]

** Equilibrium Distribution Coefficient of 5 (minimum soil adhesion)[30,31]

*** Foodchain Example, Appendix I

Annual Dose to Bone[33] for chronic one year intake of plutonium from contaminated water and foodstuffs (fish, vegetation, herbivore's milk and meat) at maximum exposed individual consumption rates.[6]

The time scale in the calculation of the projected Savannah River contamination does not exceed 10,000 years in accordance with computational procedures in use with the EPA PRESTO Code.[35]

TABLE III

Environmental Consequence of Future TRU Disposal at 100 nCi/g: SRP Site Boundary Analysis

Assumed TRU Disposal Limit, nCi/g	100	
Calculated 10-Year Increment to Shallow Land Burial, Ci	15*	20**
Total Plutonium Inventory in 10 Years, Ci		
Pu-238	3415	3420
Pu-239	615	620
Maximum Boundary Dose, mrem/person/year***		
Pu-238	4×10^{-5}	5×10^{-5}
Pu-239	7×10^{-6}	8×10^{-6}

* 15,000 cubic feet of TRU pad waste/year at average bulk density[3] of 6 lb/cu ft (typical SRP TRU pad); 30% Diverted to Shallow Land Burial

** 20,000 cubic feet of TRU pad waste/year at a bulk density[3] of 6 lb/cu ft; 30% diverted to Shallow Land Burial

*** Critical organ bone, minimum soil adhesion, human foodchain analysis;

Annual dose to bone[33] for chronic one year intake of plutonium from contaminated water and foodstuffs (fish, vegetation, herbivore's milk and meat) at maximum exposed individual consumption rates.[6]

The time scale in the calculation of the projected Savannah River contamination - leading to a water and foodchain dose - does not exceed 10,000 years in accordance with computational procedures in use with the EPA PRESTO Code.

FIGURE I.

Dose-to-Man from Unencapsulated Pu Waste

Pu Transport
Hypothetical Land Occupation
(2800 Ci Pu-238/800 Ci Pu-239)

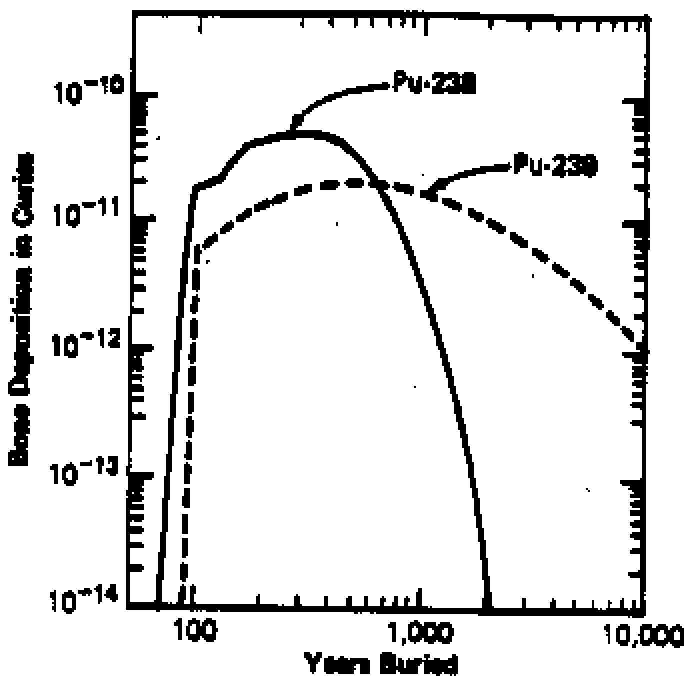

TABLE IV

TRU Disposal Based Upon DOSTOMAN Transport Analysis: Hypothetical Land Occupation

	Pu-239	Pu-238
Calculated TRU Disposal Level	300 nCi/g	2900 nCi/g
Projected DOSTOMAN Individual Dose*	2.0 mrem/person/yr	4.0 mrem/person/yr
Dose Based on 1982 Pu Inventory**	2.4 mrem/person/yr	5.3 mrem/person/yr

* Original analysis based upon 2600 Ci of Pu-238 and 500 Ci of Pu-239 (Reference 15)

** 1982 Pu Inventory:

Reference 4: DPST-83-829, Vol. II, Edited by J. A. Stone and E. J. Christensen
3400 Ci of Pu-238 (Decayed)
600 Ci of Pu-239 (Decayed)

NOTE

Exposure is based upon an annual dose to bone[33] in mrem/person/year to be consistent with Wilhite - Fauth original calculations.[15] Annual Bone Dose[33] for chronic one year intake of plutonium at the model projected year of maximum intake by a maximum exposed individual (adult) assumed to receive all of his annual foodstuffs from agricultural land use of the SRP Shallow Land Disposal Site[13,15,16]

TABLE V

Environmental Consequence of Future TRU Disposal at 100 nCi/g Levels: Hypothetical Land Occupation

Assumed TRU Disposal Limit, nCi/g	100		
	Case 1	Case 2	Case 3
Calculated 10-Year Increment to Shallow Land Burial, Ci*	20	20	20
Total Plutonium Inventory in 10 Years, Ci			
Pu-238	3420	3420	3420
Pu-239	620	620	620
Projected Dose, mrem/person/year**			
Pu-238	5.4	0.54	0.27
Pu-239	2.5	0.25	0.13
Total	7.9	0.79	0.40

* 20,000 cubic feet of TRU pad waste/year at a bulk density[3] of 6 lb/cu ft.; 30% Diversion to Shallow Land Burial

Case 1: Wilhite/Fauth results[15] projected for increased Pu inventory; 1% per year Release Rate

Case 2: Lysimeter Based Radionuclide Release Rates (10^{-3}/year)

Case 3: Elimination of the Plant Uptake Pathway by Burial Ground Overburden or Greater Confinement Disposal of the Incremental TRU Volume.

** Annual Bone Dose[33] in mrem/person/year for consistency with original Wilhite - Fauth published work[15]

Annual Bone Dose[33] for chronic one year intake of plutonium at the model projected year of maximum intake by a maximally exposed individual (adult) assumed to receive all of his annual foodstuffs from agricultural land use of the SRP Shallow Land Disposal site[13,15,16]

TABLE VI

Calculated Environmental Impact for TRU Disposal at 100 nCi/g as a Function of Scenario*

Scenario	Bone Dose Mrem/Person/Year Pu-238	Bone Dose Mrem/Person/Year Pu-239
Groundwater as drinking water[4]	1.3	0.8
Site boundary analysis -		
Savannah River as drinking water[7]	3×10^{-6}	5×10^{-7}
Human foodchain scenario[6]	5×10^{-5}	8×10^{-6}
Recreational uses of river water[6]	2×10^{-8}	5×10^{-9}
Hypothetical land occupation scenarios -		
Base case: 100 years in future[15]	5.4	2.5
Lower leach rate based on lysimeter data[27]	0.5	0.3
No vegetative uptake (GCD or overburden)[28]	0.3	0.1

* The total source term includes the historic disposal of Pu Isotopes[4] (4000 decayed Ci) supplimented by 2 Ci/year of each Pu Isotope using an assumed 100 nCi/g SLB disposal limit.

TABLE VII

Incremental Environmental Impact for TRU Disposal at 100 nCi/g as a Function of Scenario*

Scenario	Incremental Bone Dose Mrem/Person/Year	
	Pu-238	Pu-239
Groundwater as drinking water[4]	10^{-3}	10^{-4}
Site boundary analysis -		
Savannah River as drinking water[7]	10^{-8}	10^{-9}
Human foodchain scenario[6]	10^{-5}	10^{-6}
Recreational uses of river water[6]	10^{-10}	10^{-11}
Hypothetical land occupation scenarios -		
Base case: 100 years in future[15]	10^{-1}	10^{-2}
Lower leach rate based on lysimeter data[27]	10^{-2}	10^{-3}
No vegetative uptake (GCD or overburden)[28]	10^{-3}	10^{-4}

* Incremental Bone Dose associated with the change in TRU disposal from 10 nCi/g to an assumed 100 nCi/g.

FIGURE II.

Annual Bone Dose versus Pu-239 Interface Values for SRP Site Specific Scenarios

Annual Bone Dose
Versus
Pu-239 Interface Values
for SRP Site Specific Scenarios

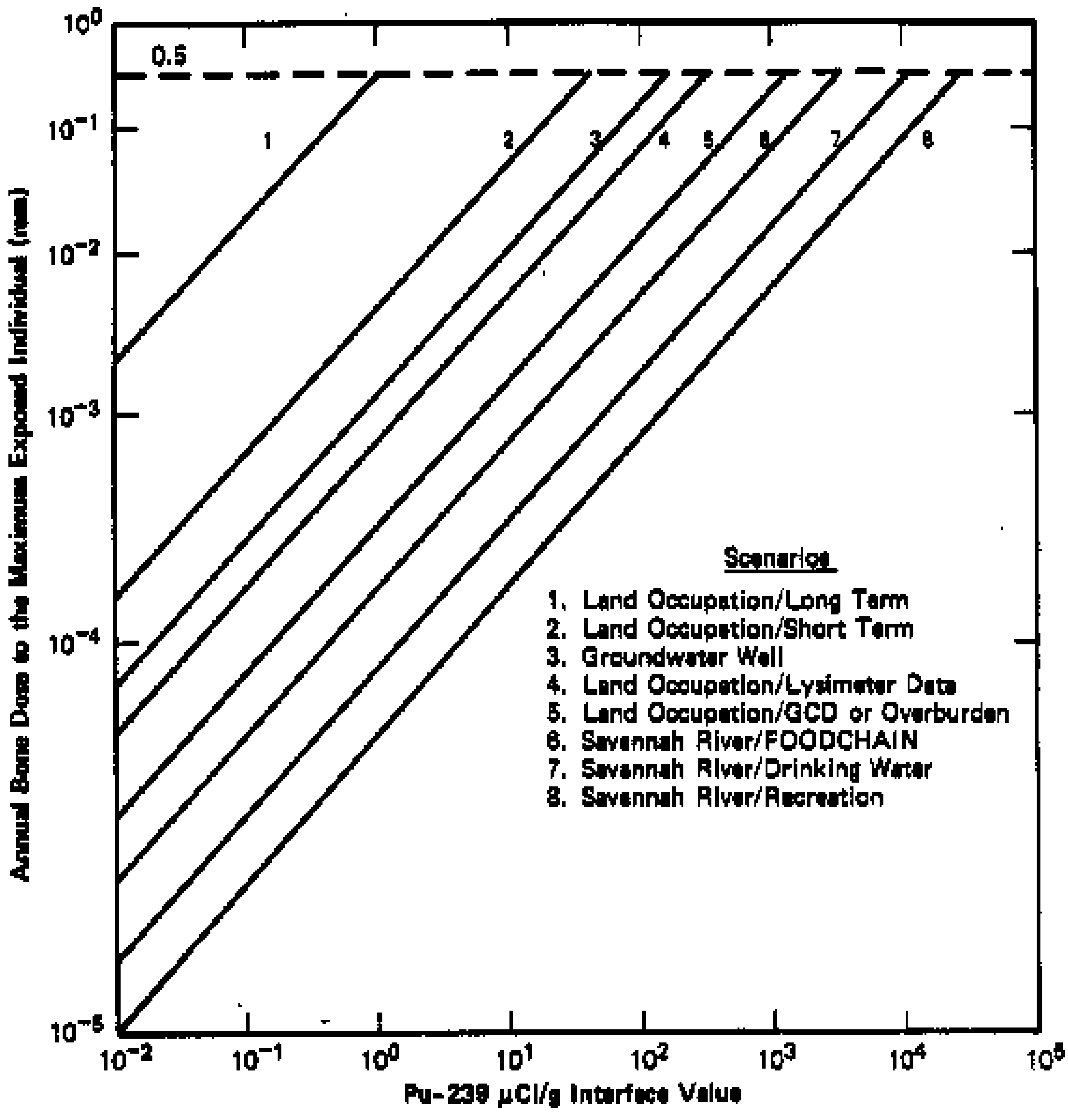

TABLE VIII

SRL Model Projected TRU Disposal Limits (based upon Hypothetical Land Occupation Scenarios)

	Pu-239	Pu-238
Annual TRU Disposal Limit, nCi/g	1000	2000
Calculated Annual Increment to Land Burial, Ci*	20	40
Increment to Land Burial over 10 years, Ci	200	400
Model Projected Dose, mrem/person/year**	3.3	6.0

* 6000 cubic feet/yr at average bulk density[3] of 6 lbs/cu ft

** Based upon Fauth/Wilhite results[15] for Hypothetical Land Occupation of the Shallow Land Burial Site; Annual Bone Dose[33] for chronic one year intake at the model projected year of maximum exposure to an individual (adult) assumed to receive all of his annual foodstuffs from agricultural land use of the SRP Shallow Land Disposal Site[13,15,16]; assumed period of institutional control is 100 years; principle pathway for exposure is vegetative uptake due to assumed root penetration of buried radioactive waste.[13,15,16]

TABLE IX

Summary of Previous Studies Providing Concentration Guidelines for Transuranic (TRU) Disposal

Author	Citation	Date	Pu-239 Guidelines (nCi/g)*
Cohen, King	UCRL-52535[20]	1978	1,000
Ledicotte, Tarnuzzer, Rodger, Frendberg, & Morton	Waste Management-78[23]	1978	500
Adam & Rogers	NUREG-0456[24]	1978	1,000
Rogers	NUREG/CR 1005[18]	1979	100
Healy & Rodgers	LA-UR-79-100 (draft)[1]	1979	2-50
DOE	INEL-DEIS, Vol. 1[19]	1981	2,000
NRC	NUREG-0782[25]	1981	100**
EPA	40 CFR 191 (draft)[26]	1981	100
Kennedy	ORNL CONF 820845[32]	1982	2200

* Based on various exposure scenarios and assumptions concerning burial depth, nuclide mix, and other factors with Pu-239 as the major nuclide. Guidelines correspond to Bone Dose Limit of 500 mrem/person/year.

** The value of 100 nCi/g for Category C wastes has been included by NRC in the Final Environmental Impact Statement on 10 CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste" (NUREG 0782).

NOTE

Scenario Calculations for these studies are based upon Hydrologic/Land Occupation Pathway Analyses similar to the SRL analyses described herein.

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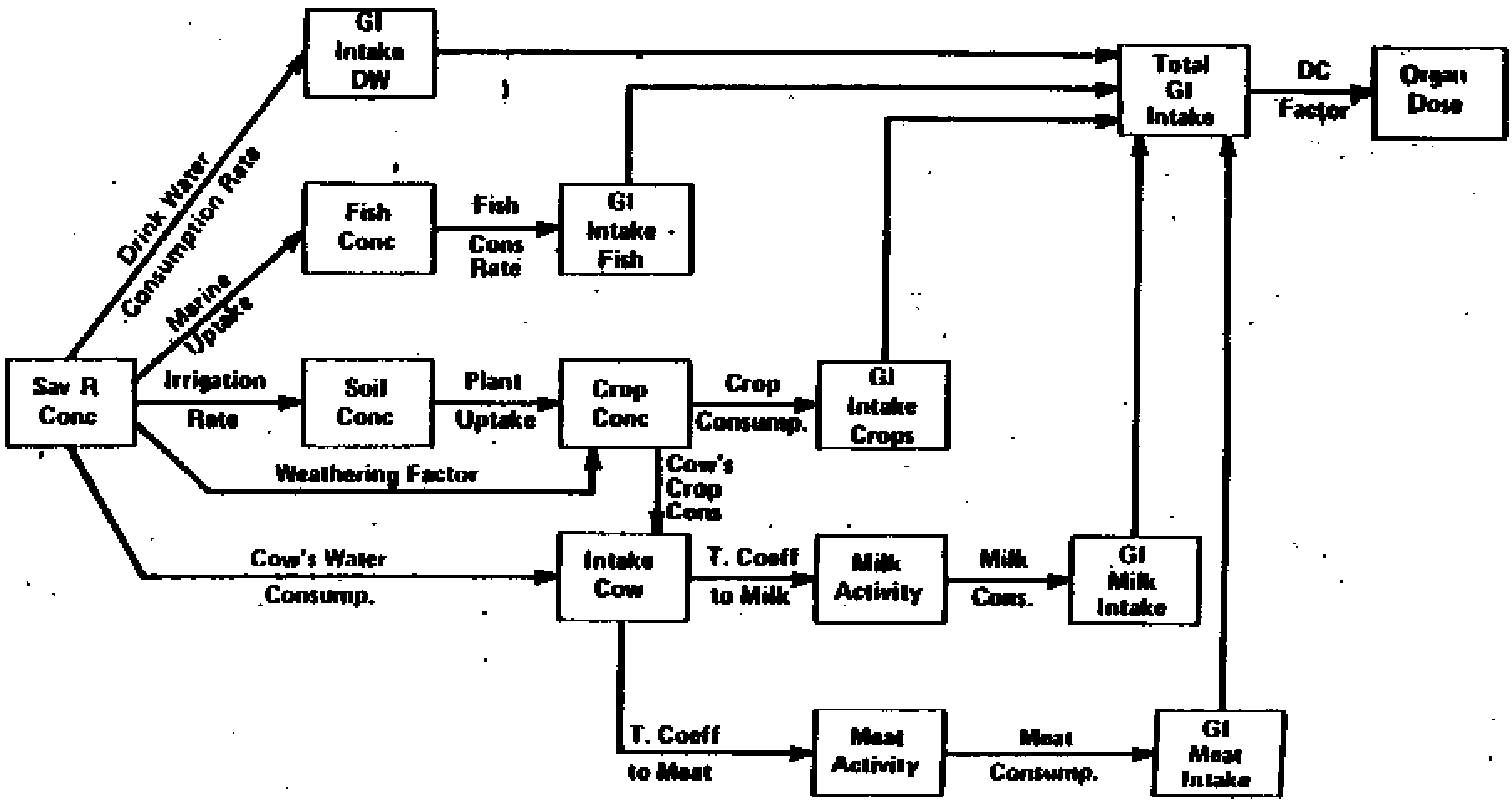
APPENDIX I

Example of Foodchain Calculations for Plutonium Isotopes

THE "FOODCHAIN" MATRIX*



*NRC Reg Guide 1.109 Methodology

Use of Contaminated Water for Crop Irrigation

Foodchain Vectors: Drink Water, Fish, Crops, Animal's Milk, and Meat

PLUTONIUM - 239

```
1RUN
MOBILNUC/FOODCHAIN CALCULATION

--------------------------------------------------

ANNUAL INDIVIDUAL EXPOSURES FROM FOODCHAIN PATHWAYS(MREM/YR)

ANNUAL EXPOSURE(TOTAL BODY) FROM WATER CONSUMPTION=8.4064E-06.
ANNUAL EXPOSURE(BONE) FROM WATER CONSUMPTION=9.99E-05.
ANNUAL EXPOSURE(LIVER) FROM WATER CONSUMPTION=3.64734E-05.
ANNUAL EXPOSURE(THYROID) FROM WATER CONSUMPTION=0
ANNUAL EXPOSURE(KIDNEY) FROM WATER CONSUMPTION=3.60084E-05.
ANNUAL EXPOSURE(LUNG) FROM WATER CONSUMPTION=0
ANNUAL EXPOSURE(GI-LLI) FROM WATER CONSUMPTION=2.98704E-05

ANNUAL EXPOSURE(TOTAL BODY) FROM FISH CONSUMPTION=2.72740E-06.
ANNUAL EXPOSURE(BONE) FROM FISH CONSUMPTION=3.213E-05.
ANNUAL EXPOSURE(LIVER) FROM FISH CONSUMPTION=1.343700E-05
ANNUAL EXPOSURE(THYROID) FROM FISH CONSUMPTION=0
ANNUAL EXPOSURE(KIDNEY) FROM FISH CONSUMPTION=1.150100E-05
ANNUAL EXPOSURE(LUNG) FROM FISH CONSUMPTION=0
ANNUAL EXPOSURE(GI-LLI) FROM FISH CONSUMPTION=9.51040E-06

ANNUAL EXPOSURE(TOTAL BODY) FROM CROP CONSUMPTION=2.05758085E-04
ANNUAL EXPOSURE(BONE) FROM CROP CONSUMPTION=2.4237872E-03
ANNUAL EXPOSURE(LIVER) FROM CROP CONSUMPTION=9.36243342E-04
ANNUAL EXPOSURE(THYROID) FROM CROP CONSUMPTION=0
ANNUAL EXPOSURE(KIDNEY) FROM CROP CONSUMPTION=8.73627817E-04
ANNUAL EXPOSURE(LUNG) FROM CROP CONSUMPTION=0
ANNUAL EXPOSURE(GI-LLI) FROM CROP CONSUMPTION=7.1743213E-04

ANNUAL EXPOSURE(TOTAL BODY) FROM MILK CONSUMPTION=3.64334432E-08
ANNUAL EXPOSURE(BONE) FROM MILK CONSUMPTION=4.29874331E-07
ANNUAL EXPOSURE(LIVER) FROM MILK CONSUMPTION=1.46099441E-07
ANNUAL EXPOSURE(THYROID) FROM MILK CONSUMPTION=0
ANNUAL EXPOSURE(KIDNEY) FROM MILK CONSUMPTION=1.54687489E-07
ANNUAL EXPOSURE(LUNG) FROM MILK CONSUMPTION=0
ANNUAL EXPOSURE(GI-LLI) FROM MILK CONSUMPTION=1.27806882E-07

ANNUAL EXPOSURE(TOTAL BODY) FROM MEAT CONSUMPTION=9.04716299E-08
ANNUAL EXPOSURE(BONE) FROM MEAT CONSUMPTION=1.0687452E-06
ANNUAL EXPOSURE(LIVER) FROM MEAT CONSUMPTION=4.12569579E-07
ANNUAL EXPOSURE(THYROID) FROM MEAT CONSUMPTION=0
ANNUAL EXPOSURE(KIDNEY) FROM MEAT CONSUMPTION=3.04149172E-07
ANNUAL EXPOSURE(LUNG) FROM MEAT CONSUMPTION=0
ANNUAL EXPOSURE(GI-LLI) FROM MEAT CONSUMPTION=3.15446521E-07

SUM OF EXPOSURES(TOTAL BODY)=          2.17804031E-04
SUM OF EXPOSURES(BONE)=                2.55728284E-03
SUM OF EXPOSURES(LIVER)=               9.89922291E-04
SUM OF EXPOSURES(THYROID)=             0
SUM OF EXPOSURES(KIDNEY)=              9.21750103E-04
```

```
SUM OF EXPOSURES(LUNG)=                          0
SUM OF EXPOSURES(GI-LLI)=                        [illegible].56955483E-04

------------------------------------------------

PERCENT CONTRIBUTION FROM H2O  PATHWAY=
2.90649129       %
PERCENT CONTRIBUTION FROM FISH PATHWAY=
1.25641206       %
PERCENT CONTRIBUTION FROM CROP PATHWAY=
94.7706424       %
PERCENT CONTRIBUTION FROM MILK PATHWAY=
.0167705299      %
PERCENT CONTRIBUTION FROM MEAT PATHWAY=
.0416757033      %

------------------------------------------------

ANNUAL POPULATION DOSES FROM DRINKING WATER(MAN-REM/YR)

POPULATION DOSE TO WHOLE BODY=
5.936200E-04
POPULATION DOSE TO BONE=
4.993E-03
POPULATION DOSE TO LIVER=
2.797060E-03
POPULATION DOSE TO THYROID=
0
POPULATION DOSE TO KIDNEY=
2.529900E-03
POPULATION DOSE TO LUNG=
0
POPULATION DOSE TO GI-LLI=
3.069920E-03

ANNUAL POPULATION DOSES FROM TOTAL FOODCHAIN(MAN-REM/YR)

POPULATION DOSE TO WHOLE BODY=
.0151957301
POPULATION DOSE TO BONE=
.179009742
POPULATION DOSE TO LIVER=
.0692966003
POPULATION DOSE TO THYROID=
0
POPULATION DOSE TO KIDNEY=
.0645230672
POPULATION DOSE TO LUNG=
0
POPULATION DOSE TO GI-LLI=
.0529060830

------------------------------------------------

ADDITIONAL FATAL CANCERS FOR PRESENT POPULATION(DRINKING WATER):

ADDITIONAL FATAL CANCERS(W.BODY) FROM DRINKING WATER/YR=1.994696E-10
ADDITIONAL FATAL CANCERS(BONE) FROM DRINKING WATER/YR=7.367444E-11
ADDITIONAL FATAL CANCERS(LIVER) FROM DRINKING WATER/YR=2.138537[illegible]E-08
```

ADDITIONAL FATAL CANCERS(THYROID) FROM DRINKING WATER/YR=0
ADDITIONAL FATAL CANCERS(KIDNEY) FROM DRINKING WATER/YR=1.0002352E-08
ADDITIONAL FATAL CANCERS(LUNG) FROM DRINKING WATER/YR=0
ADDITIONAL FATAL CANCERS(GI-LLI) FROM DRINKING WATER/YR=1.22475392E-08

ADDITIONAL FATAL CANCERS FOR FUTURE POPULATION(DRINKING WATER):

ADDITIONAL FATAL CANCERS(W.BODY) FROM DRINKING WATER/YR=9.4980479E-10
ADDITIONAL FATAL CANCERS(BONE) FROM DRINKING WATER/YR=3.0184713E-10
ADDITIONAL FATAL CANCERS(LIVER) FROM DRINKING WATER/YR=1.06929186E-07
ADDITIONAL FATAL CANCERS(THYROID) FROM DRINKING WATER/YR=0
ADDITIONAL FATAL CANCERS(KIDNEY) FROM DRINKING WATER/YR=5.0411760E-09
ADDITIONAL FATAL CANCERS(LUNG) FROM DRINKING WATER/YR=0
ADDITIONAL FATAL CANCERS(GI-LLI) FROM DRINKING WATER/YR=6.2376941E-08

ADDITIONAL FATAL CANCERS FOR PRESENT POPULATION(FOODCHAIN):

ADDITIONAL FATAL CANCERS(W. BODY) FROM TOTAL FOODCHAIN/YR=4.8627092E-09
ADDITIONAL FATAL CANCERS(BONE) FROM TOTAL FOODCHAIN/YR=7.1683897E-08
ADDITIONAL FATAL CANCERS(LIVER) FROM TOTAL FOODCHAIN/YR=5.47443617E-07
ADDITIONAL FATAL CANCERS(THYROID) FROM TOTAL FOODCHAIN/YR=0
ADDITIONAL FATAL CANCERS(KIDNEY) FROM TOTAL FOODCHAIN/YR=2.58092269E-07
ADDITIONAL FATAL CANCERS(LUNG) FROM TOTAL FOODCHAIN/YR=0
ADDITIONAL FATAL CANCERS(GI-LLI) FROM TOTAL FOODCHAIN/YR=3.39114056E-07

ADDITIONAL FATAL CANCERS FOR FUTURE POPULATION(FOODCHAIN):

ADDITIONAL FATAL CANCERS(W. BODY) FROM TOTAL FOODCHAIN/YR=2.4313501E-08
ADDITIONAL FATAL CANCERS(BONE) FROM TOTAL FOODCHAIN/YR=3.58019485E-07
ADDITIONAL FATAL CANCERS(LIVER) FROM TOTAL FOODCHAIN/YR=2.73721899E-06
ADDITIONAL FATAL CANCERS(THYROID) FROM TOTAL FOODCHAIN/YR=0
ADDITIONAL FATAL CANCERS(KIDNEY) FROM TOTAL FOODCHAIN/YR=1.29846135E-06
ADDITIONAL FATAL CANCERS(LUNG) FROM TOTAL FOODCHAIN/YR=0
ADDITIONAL FATAL CANCERS(GI-LLI) FROM TOTAL FOODCHAIN/YR=1.49558828E-06

PARAMETERS USED IN FOODCHAIN CALCULATION:

NUCLIDE CONCENTRATION(PCI/L):	1.2E-03
ORGAN DOSE FACTORS(MREM/PCI)	
WHOLE BODY:	1.91E-05
BONE:	2.25E-04
LIVER:	5.71E-05
THYROID:	0
KIDNEY:	8.11E-05
LUNG:	0
GI-LLI:	6.66E-05
MAN'S WATER CONSUMPTION(L/YR):	370
MAN'S FISH CONSUMPTION(KG/YR):	34
FISH UPTAKE FACTOR(CI/G/CI/ML):	3.5
CROP TRANSFER COEFF.(G/G):	2.5E-04
MAN'S CROP CONSUMPTION(KG/YR):	520
NUCLIDE BUILDUP TIME(YRS):	1
MILK TRANSFER COEFF.(MIC.CI/L/MIC.CI/DAY):	2E-04
MAN'S MILK CONSUMPTION(L/YR):	310
MEAT TRANSFER COEFF.(MIC.CI/KG/MIC./DAY):	1.4E-03
MAN'S MEAT CONSUMPTION(KG/YR):	110

HEALTH EFFECTS RISK FACTORS FROM BEIR III (REFERENCE: ENVIRONMENTAL IMPLICATIONS OF TC-99; DPST-82-600; TABLE D1.)

APPENDIX II

Methodology for Radionuclide Environmental Transport Calculations

APPENDIX II

Methodology for Radionuclide Environmental Transport Calculations

Calculations on radionuclide transport from buried waste forms to the hydrologic system contiguous to the SRP burial ground are based upon the HTRANSPORT (hydrological transport) subprogram of the SRL DOSTOMAN Code. HTRANSPORT mathematically describes transport in one dimension by a set of linear differential equations[12,13,37] which account for mass transport by advection[38] and chemisorption[39] of the contaminant by soil particles. The basic equations assume Darcy's Law[38-42] is applicable in the unsaturated and saturated zones:

$V_w = k_p \frac{i}{e}$, where

V_w = average velocity of water in cm/sec in the zone of interest;

k_p is the hydraulic conductivity[42] or soil permeability[42] in cm/sec in the zone of interest;

i is the hydrostatic gradient[42] [dimensionless] and

e is the soil porosity or void volume in the zone of interest [dimensionless].

Attenuation of contaminant transport by soil sorption assumes that the linear Freundlich adsorption isotherm[39] is applicable (Freundlich proportionality constant is the soil/water partition coefficient, K_d, for the solute of interest) and the solute Retardation Factor (RF) equation[38-40,42] is applicable:

$$V_{solute} = V_w \cdot RF$$

$$RF = (1 + K_d \frac{b}{e})^{-1}$$

where b is the soil bulk density for the zone of interest.

HTRANSPORT has been validated mathematically[37] against an exact analytical solution and empirically for the tritium plume[4,5] below the 643-G burial ground. Based on the literature,[38,43] advective transport will provide a conservative upper limit estimate for solute contamination of the hydrological system.

The transport component that is _not_ included in HTRANSPORT is dispersion[38,43] based on Fick's Second Law of Diffusion.[39] This is probably important for low soil adhesion contaminants (organics, tritium), but is most frequently interpreted in the literature[38,40] as a _dilution_ or _spreading_ effect. Therefore, advective transport is believed sufficient for a conservative estimate of the extent of contamination. The second order partial differential equations for dispersion/diffusion in one dimension[39,42] will be incorporated into the HTRANSPORT subprogram over the next year based on cooperative work now in progress with the Clemson University Department of Environmental Systems Engineering. In addition, through work on the SRL Groundwater Modeling Working Group, other codes[38,40,42] for multidimensional contaminant transport analysis by advection/dispersion/adsorption will be available to SRL through subcontractors if a more complex, multidimensional analysis is deemed necessary for estimating future contaminant transport at SRP hazardous waste/mixed waste/radioactive waste sites. More complex modeling will also require a more extensive site-specific empirical data base on geohydrology and contaminant environmental properties (soil partition coefficients, biodegradation rate, dispersivities) than is, at present, available.

DP-MS-82-83

ALPHA CONTAMINATED WASTE MANAGEMENT AND ENVIRONMENTAL IMPACT AT THE SAVANNAH RIVER PLANT

by

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Impromptu Talk Given by C. M. King, Savannah River Laboratory as Taped at August 12, 1982 Session of the Alpha Contaminated Waste Management Workshop, Gaithersburg, Maryland

The next speaker is not listed on your program. He is Charles M. King from the Savannah River Laboratory. Charles studied at Drexel, Yale, the University of Pennylvania, and at the Max Plank Institute (Muhlheim, W. Germany). He has worked in actinide technology, and recently, he has had the responsibility for environmental transport modeling of shallow land and greater confinement disposal of buried waste at the Savannah River Plant. The title of his presentation will be Alpha Contaminated Waste Management and Environmental Impact at the Savannah River Plant. Chuck.

As Gerry mentioned, I'm new to your business, having been in the waste management game about one year. Fortunately, I was assigned to Ed Albenesius and John Wiley at SRL on a very interesting and challenging program. I've been working in the nuclear business for 3 years after 10 years with Du Pont Commercial. So this is a very interesting week to me because I'm learning. The learning curve is going straight up in the air. I'm asking many questions because I'm trying to understand what your business is about. There have been numerous highlights to me this week.

SLIDE 1

This is the first in a series of talks about actual alpha contaminated waste management at different sites in the DOE complex. I'll concentrate on our situation at Savannah River Plant. We've been burying waste since 1953 when production started. Alpha waste burial actually occurred starting in 1955 and continued through about 1965 when retrievable storage of most of the TRU activity began.

SLIDE 2

Here is a depiction of the burial ground as it resides at the Savannah River Plant. This is a 195-acre site. The original site, 75 acres, went into use in 1953 and was filled with waste by 1972. It is a shallow land burial facility.

The new site is about 125 acres. The burial ground resides between the F- and H-Area chemical processing plants from which much of the waste is generated. F Area is a Purex process for plutonium processing. H Area is a modified Purex process in which neptunium, enriched uranium, and Pu-238 processing occurs. The burial ground was chosen to be placed between the 200-Area facilities because of its proximity to the chemical processing plants from whence most of the waste is derived. The burial ground is about 1700 feet from a tributary stream called Four Mile Creek, which eventually flows into the Savannah River. The river, of course, eventually dumps into the Atlantic Ocean.

SLIDE 3

Part of the input into environmental transport modeling involves knowledge about the topography and hydrology of the site. Here is a simple diagram of the topography around the burial ground. The 200-acre burial ground resides on the so-called Barnwell formation of the Coastal Plain Geologic Province in South Carolina. The Barnwell formation consists of clayey sands and sandy clays that have some ion exchange capacity. Of course, in the eastern part of the United States, the water table is shallow. At the burial ground, the average depth to the water table from the surface is about 45 feet. We are right now in the midst of looking for potential new burial sites and finding places where the average depth to the water table may be as great as 75 feet.

SLIDE 4

Here is a summary of the extent to which we have disposed of nuclides in earthen trench burial through 1975. For the plutonium isotopes, about 3000 curies have actually gone into the ground, based upon DP-1537, the Environmental Impact Statement on SRP Waste Management Operations. Fission products are also disposed of, as well as a variety of other isotopes, particularly tritium. Since 1974, the bulk of the transuranic type (TRU) waste has gone to retrievable storage in drums and culverts on concrete pads, primarily based upon the 10 nanocurie per gram limit. On the average since 1974, we estimate about one curie of TRU waste going to earthen trench burial per year.

SLIDE 5

Data from DOE/NE-0017* helps to put earthen trench buried at the Savannah River Plant into perspective to the rest of the DOE complex. We have about 360,000 cubic meters of low-level waste at SRP which is a somewhat larger volume than at most of the other sites.

SLIDE 6

We have specific standards which we use for burial limits as a function of nuclide. Transuranics are currently at 10 nanocuries per gram. The purpose of transport modeling is to arrive at a scientific analytical approach to justifying these burial limits and to validate burial ground operational methods. It is the burial limits on TRU waste, plutonium isotopes in particular, that I'm going to address today.

SLIDE 7

The 500-curie inventory estimate on ^{239}Pu and 2500-curie estimate on Pu-238 in trenches actually translates to levels of plutonium isotopes exceeding 100 nanocuries per gram. We've made an estimate that the Pu-239 inventory would be equivalent to an average concentration of 200 to 300 nanocuries per gram of waste actually in the ground; similarly, Pu-238 is about five-fold higher.

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* "Spent Fuel and Radioactive Waste Inventories and Projections as of December 31, 1980." U.S. Dept. of Energy, Assistant Secretary for Nuclear Energy, Nuclear Waste Management Program, Sept. 1981.

SLIDE 8

Since 1978, we have evolved a transport equation to model the situation of buried waste. It is a site-specific risk assessment of burial ground operation — the burial ground that is now in operation as well as any greater confinement disposal alternatives that are proposed for potential use at our site. So it is quite a useful tool. As you have heard from some of the previous speakers, nuclide specific information is needed for transport modeling. Some of that information includes soil ion exchange properties, commonly referred to as distribution coefficients. This is the ion exchange capacity parameter of the nuclide in soil. Plant and animal concentration factors, and waste to soil migration rates are also a key part of the input, along with dosimetry data. As I mentioned previously, it is necessary to have an understanding of hydrology and topography of the site you are trying to model. This includes unsaturated zone and groundwater flow rates.

SLIDE 9

Our approach has been to compartmentalize the environment, and to express the rate of movement of a nuclide from one environmental compartment to another in the form of differential equations. Terms for the rate of movement into a compartment, out of a compartment, source and sink terms, and radioactive decay are included in a simple differential equation. The modeling complexity arises due to a need for one equation for each pathway in the scenario being modeled. The key input to these equations are the transfer

Slide 9 (continued)

coefficients (the λ's). They are an estimate of the fraction of a nuclide that will move in time from one environmental compartment to another. The transfer coefficients, of course, have some physical meaning. They are a function of the distribution coefficients, plant uptake factors, etc.

SLIDE 10

Here is a simple illustration of the compartmentalization procedure in which we describe the transfer coefficient from buried waste to burial soil as a reflection of leach rate or release rate. It is useful to have experimental information on this particular transfer coefficient. Dr. Rogers showed information about release rates in his talk yesterday. Based on his data, our release rates are conservative. We generally use 10^{-2}, or 1% per year. This rate is based upon exhumation in 1975 of a single piece of equipment that had actually been buried. We retrieved the equipment and measured the nuclide content of the soil relative to the surface contamination to make an estimate of the release rate and rate of movement in that short period of time. Movement from buried soil, through the unsaturated zone, to the groundwater table will be a function of the retardation equations which have parameters of distribution coefficient, soil porosity, and bulk density. Movement to other parts of the environment (i.e., animal and vegetative pathways) is generally described by concentration factors,

Slide 10 (continued)

documented by a variety of groups. USNRC Regulatory Guide 1.109, and updates on that document, provide information on herbivore and plant vectors.

SLIDE 11

This schematic is a complete flow diagram for description of buried waste transport into the environment. We have attempted to incorporate numerous pathways in describing nuclide environmental transport, consistent with a scenario being modeled.

SLIDE 12

Some of the specific pathways that we have incorporated into the model include waste to soil migration, particle and hydrological transport, vegetative uptake, herbivore and fish assimilation, erosion, resuspension, recreation, intrusion, human ingestion, inhalation, and nuclide physiology in man.

SLIDE 13

This is a representation of the full matrix that has evolved in our description of the environment, a 70 x 70 matrix. The arithmetic is a typical eigenvalue problem like some of you may be familiar with in quantum mechanics or problems in physical chemistry for solution of chemical bond energies in a polyatomic molecule. The arithmetic is quite analogous to other problems that

Slide 13 (continued)

have been dealt with in physical science. Hence, a 70 x 70 matrix with about 200 transfer coefficients and quite a bit of input data required to get a solution, is solved by finite difference, matrix inversion methods. The output is the decayed nuclide level in each compartment with time.

SLIDE 14

The land occupation scenario, which is one of several that we have evolved, is a small population land use example consistent with the historical use of the Savannah River Plant prior to occupancy by the Atomic Energy Commission. We have had a study conducted by the University of South Carolina, Institute for Southern Studies in which property deeds back to 1800 were examined to trace the historical land use of the site. This scenario is consistent with that historical land use.

SLIDE 15

Some of the basic input data for analysis of migration of the plutonium isotopes — Pu inventory, release rate, distribution coefficient, soil adhesion properties — are well documented. In the absence of solubilizing complexing agents, Pu has a large holdup factor in cation exchangeable soils, which generally means extremely slow downward movement. The question is how slow is slow? We are trying to make a quantitative statement about rate of

Slide 15 (continued)

movement relative to radioactive decay. Plant uptake factors are generally small for Pu relative to the other elements. Pu-238 has a fairly short half-life; Pu-239, quite long. In both cases, based upon ICRP-2 and ICRP-30 dose commitment factors, Pu isotopes tend to concentrate in bone and bone marrow.

SLIDE 16

Here is a comparison of some of the physical property data that are input to the model, relative to such data for other radionuclides. The distribution coefficient of plutonium is much higher than, for example, that of strontium. Plant uptake factors are much lower relative to other fission byproducts. Release rates, based upon our exhumation work, are the same for most of the radionuclides.

SLIDE 17

Some of the projections that we have made from this modeling effort are shown next. This represents model-projected bone deposition of Pu as a function of time. Please bear with us on the time axis, as we've heard frequently stated. From the philosophy of Jack Healy at LANL, we don't pretend to be able to have predictive powers out into these kinds of time spans but it is easy to let the computer run. The important point here is that for Pu-239, there is an interesting bimodal pathway that comes out of our model

Slide 17 (continued)

which is a consequence of the long Pu-239 half-life. Pu-239 initially goes through a maximum bone deposition in something less than 1000 years, which translates to about 2 millirem-per-person annual dose commitment. The primary or critical pathway in this time period is vegetative uptake and ingestion of that vegetation as dictated by the scenario. As time goes on, because of the long half-life, Pu-239 will tend to move downward and the dose becomes more significant way out in the future as a consequence of hydrological transport, contamination of the groundwater, and the assumption that wellwater is a source of drinking water. Pu-238 eventually decays. The critical pathway to dose is primarily vegetative uptake. The dose consequence is comparable.

Hence, actual inventories buried at Savannah River Plant, 500 curies of Pu-239 and 2500 of Pu-238, translate to nanocurie-per-gram levels significantly greater than 100. Our impact analysis implies in reasonable periods of time (less than 1000 years) that the dose consequence of this burial is very low and much less than 10 CFR 61 criteria. So this gives us a margin that we can look at and put into perspective to 100 nanocuries per gram.

SLIDE 18

Here is a summary, similar to Dr Smith's presentation, of some of the projections that we and others have made via the modeling approach. We would estimate, with a safe margin, 500 nanocuries per gram is not unreasonable. Pu-238 values could be somewhat higher. Healy/Rogers, Ford/Bacon/Davis, INEL and Cohen results from Lawrence Livermore, are also shown to be comparable with SRL estimates.

Slide 19

It is necessary in every environmental impact and pathway analysis to do parameter sensitivity work and we do it routinely. The most important factors that enter into this analysis include soil/water distribution coefficients, institutional control period, waste soil leach rates, plant and animal concentration factors and the ability to pin down Pu inventory, the source term itself.

Slide 20

Keep in mind that every model is only as good as the data that goes into it, and is only as good as the substantiation of the physical basis of the approach. As was mentioned yesterday, the value of the results are relative, not absolute. Complexity does not necessarily mean credibility. Results are very scenario dependent.

Slide 20 (continued)

Validation is a key to any model analysis so we are working very hard right now in using our model to confirm by calculation the actual migration of nuclides that has occurred from buried wastes at Savannah River. Dr. Albenesius mentioned yesterday that tritium, for example, has been monitored for many years in groundwater below the disposal site. We're attempting to model tritium migration to compare with actual measurements on tritium plumes and tritium concentrations in the groundwater. Validation is a key aspect of any modeling analysis.

SLIDE 21

We can say now, from actual experience at Savannah River Plant, TRU wastes have been disposed of by shallow land burial at greater than 100 nanocourie per gram levels.. Pathway analysis indicates that critical routes are vegetative uptake due to root penetraction of waste and in the very, very long-term hydrological transport for the long-lived nuclides. The individual exposure consequence of this burial is very small. 100 nanocurie per gram seems reasonable with a safe margin based upon our analysis and results of other modeling efforts. The impact of 100 nanocurie per gram change in regulation at SRP would be a 10-30% diversion of waste from TRU pads to shallow land burial. The economic significance of this cannot be ignored. If you assume that the TRU pad/above-ground stored waste is eventually designated for WIPP, you can add another economic increment to that cost incentive analysis.

The SRL DOSTOMAN methodology, User's Guide, and published examples of its use are available upon request.

Thank you very much.

(Applause)

Thank you Chuck. We have a few minutes for questions. Bill.

(Bill Kennedy, Battel-Northwest.) You've probably heard me make this comment before on the model validation steps and I simply make the statement that I don't know that you ever really validate a model. You can calibrate it against a known situation and set of circumstances but whenever you attempt to extend the analysis beyond that calibration point, which by necessity has to be done in order to predict results for more complicated conditions, you're leaving that zone of calibration somewhat. You may be confident that you've calibrated it for a known set of conditions, but I doubt that you've ever really validated the results.

(Chuck.) Yes. That's a good point. Of course, attempt at validation can only be validation of actual data in real-world time: the recent past or the present. Whether that validation reflects the ability to project into the future is the major part of the uncertainty in the analysis. Let me just give an example about some meaningful validation of our equations that we just went through and we hope to report about in detail in the not-to-distant future. One fission byproduct that we have buried to a very small extent in shallow land burial is technicium-99, which has a fission yield comparable to that of strontium-90 on a weight basis. On a curie basis, Tc-99 fission yield is much less because of its extremely long-half life. We have calculated that, at the most, 100 curies of technicium are buried in shallow trenches at SRP. Technicium mostly exists in the chemical pertechnetate anionic form. SRP clay soils have very low anion-exchange capacity so technicium, in most environments, will tend to move, like tritium. We have projected, with our fission-yield inventory and soil retention properties as input it to our model, very small amounts (50 to 100 femto curies-per-milliliter) of Tc-99 in the water underneath the burial ground (a factor of 50 to 100 less than the EPA drinking water standard for Tc-99). We then did an actual experimental measurement on TC-99 in the water underneath the burial ground (work by S. Oblath at SRL) and found the predicted levels of technicium. So, it's the first step in the right direction to having some confidence in these somewhat complex equations that we're dealing with.

Preston? any other questions?

(Preston Hunter, Ford/Bacon/Davis.) Chuck, just to make a comment on, again, your comparison table similar to the comment

Tom Smith made in use of the 100 to 400 nanocurie-per-gram Ford/Bacon/Davis figure. I think I'd just like to indicate — in fact I was going to make this comment when Tom was giving his talk — a lot of these comparison tables are very interesting and very nice to look at in terms of values that are derived. I think we should recognize that it depends upon a variety of assumptions and preconditions that are put into those tables. Now, I don't know; maybe you know? I think a study that would be valuable is to really look at comparing the different assumptions that went into deriving those numbers. For example, you have in a table that Ford/Bacon/Davis came up with a 100 nanocurie-per-gram limit with one set of conditions for transuranic waste disposal. On the other hand, I could show you some other input conditions, including the intrusion scenario where we would support the NRC's position on Class A waste at 10 nanocuries per gram. When you take all these things into account, particularly when you're dealing with models that have a 70 x 70 matrix — although I haven't dealt with that model — it's very important to recognize that the input data that's used, and the scenario assumptions that are used, be very explicitly clarified in any discussion.

(Chuck.) That's a very good point, Preston, and I think we really have a perfect opportunity here if analytical transport modeling is going to be one of the approaches that is to be used as input to DOE to establish criteria. The people who are doing some of this transport modeling have a perfect opportunity to sit down and document the input data and the nature of the model in detail to help justify and establish this criteria that we're debating. SRL has such documentation. We really have a great opportunity here.

(Preston.) I would agree.

(Joe Lieberman, NSA.) It was a very nice presentation, Chuck. Very informative. In line with the question that Bill Kennedy asked. I agree that we're talking really calibration rather than validation. You mention technicium. Have you done any work on any other nuclide or if you haven't, can you, based on what you've done, speculate at all as to how the transfer factors for other nuclides might develop?

(Chuck.) We've done quite a bit of work on the analysis of the predominant fission byproducts, cesium and strontium. A lot of what I talked about today, including some information on cesium and strontium, is published in the Tucson Waste Management '82 Proceedings which are available to the public. The fission byproducts present an interesting problem, particularly strontium, because of its somewhat different physical properties. Ion exchange holdup by the soil is somewhat less, although it is cationic, and relative to plutonium, distribution coefficients are generally lower. Sr-90 is more subject to movement. Certainly, Sr-90 dose commitment factors (DCF's) are greater than DCF's for nuclides like cesium. Strontium and cesium are being looked at very hard right now to ascertain whether these burial limits, are in fact valid ones. In the future, we talk about potential greater confinement disposal of byproducts from the Defense Waste Processing Facility. One of these is technicium. We are modeling greater confinement disposal and the disposal concepts that are a spinoff of the Defense Waste Processing Facility programs. Technicium is one nuclide. There are others like iodine and ruthenium. I think in light of ICRP30 statements, perhaps neptunium-237 as a TRU waste nuclide should be considered. Np-237 needs another look because the ICRP30 dose factors for Np-237 increase by a factor of 200-300 relative to the ICRP2. Is this a concern, particularly to those of us who are dealing with neptunium processing and waste disposal?

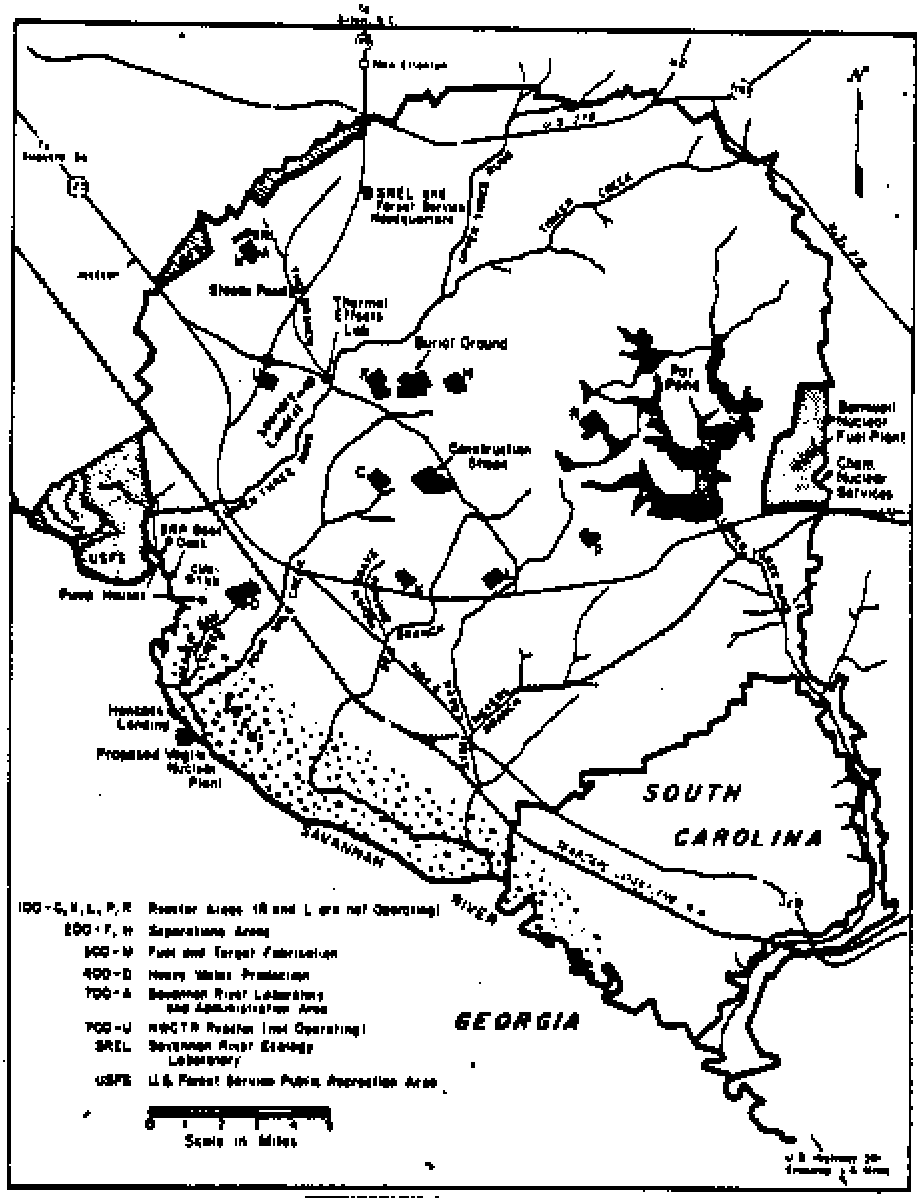
(Bill Lawless, Savannah River.) Chuck, good talk on short notice. Because of the simplifying assumptions used in the model, have you had a chance to calculate your range of uncertainties?

(Chuck.) I have to add here that Bill is our most immediate DOE contact at Savannah River and he helps me make this a healty exercise because he is constantly skeptical, and rightfully so. A perfect Devil's Advocate! I would guesstimate Bill, a 100% uncertainty in these numbers, primarily due to uncertainty in the source term. So if you talk about 2 millirem per person, that may be 4 mrem/person. If you talk about 500 nanocurie per gram as being a reasonable Pu-239 model projected limit, there's uncertainty; it may well be 250 nCi/g. But still a model projected limit of greater than 100 nanocurie per gram.

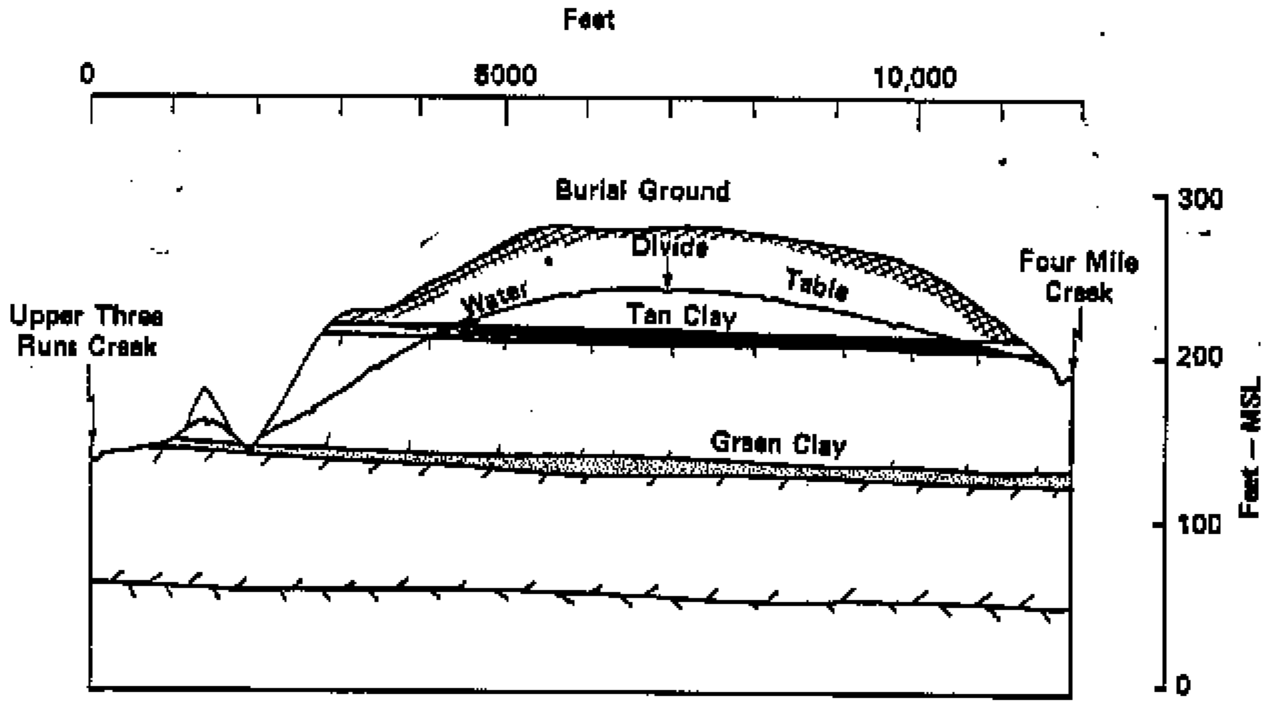
Other questions? Thank you, Chuck.

ALPHA CONTAMINATED WASTE MANAGEMENT and ENVIRONMENTAL IMPACT at the SAVANNAH RIVER PLANT

C.M.King
E.L.Wilhite



SLIDE 2. The Savannah River Plant Site



Feet
0
5000
10,000
Burial Ground
Divide
Water
Table
Tan Clay
Upper Three
Runs Creek
Four Mile
Creek
Green Clay
300
200
100
0
Feet — MSL

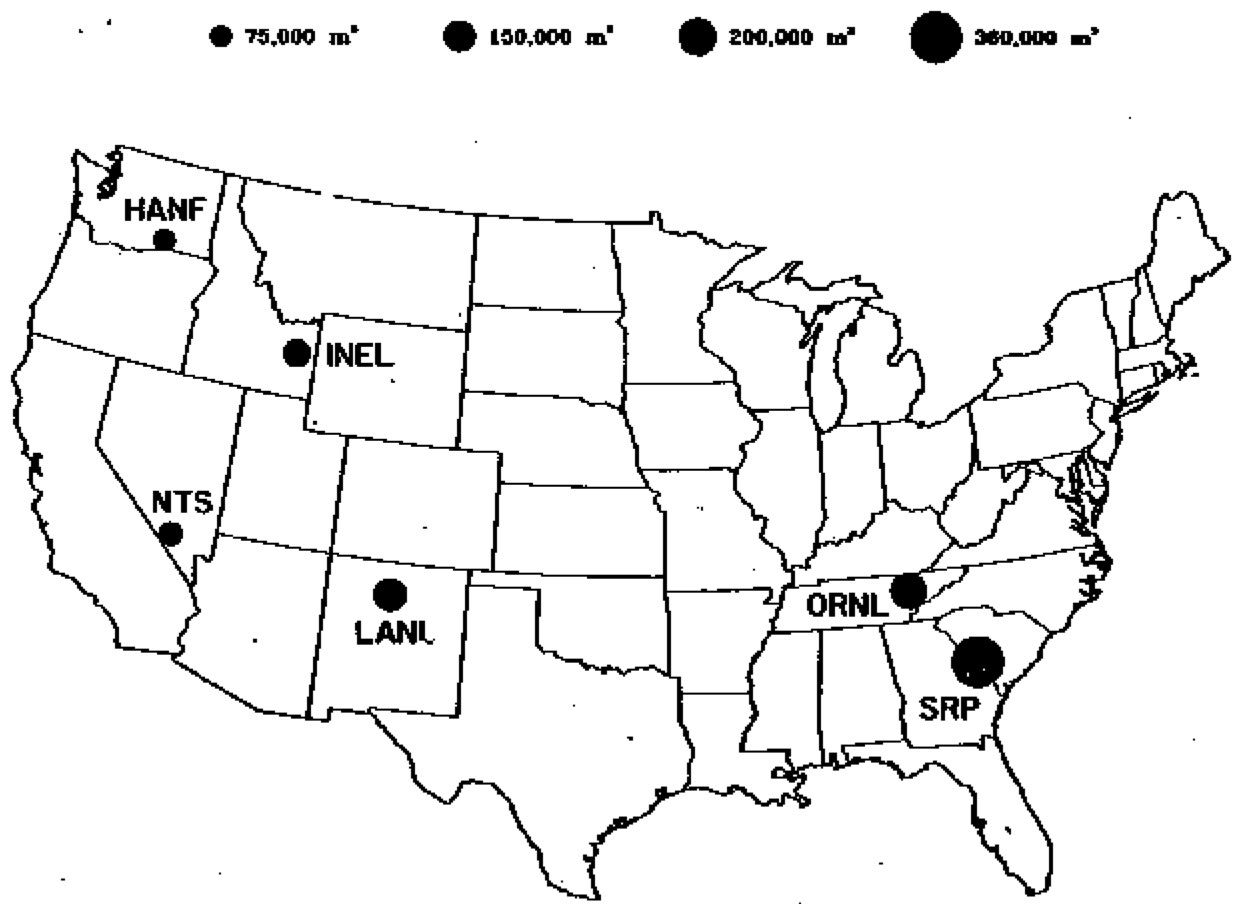
SLIDE 3.

BURIAL GROUND SOLID WASTE

(THROUGH 1975)

RADIONUCLIDE	EARTHEN TRENCHES*	RETRIEVABLE STORAGE*
Pu^{238}	2,500	245,000
Pu^{239}	490	1,700
Cs^{137}	23,300	2,000
Sr^{90}	23,300	2,000
H^{3}	2,450,000	100,000
Co^{60}	970,000	–
Cm^{244}	1,300	32,000

*Curies, corrected for decay
Source: DP 1537-EIS on SRP Waste Management Operations



SLIDE 5. Location and Accumulated Volume of LLW at Principal DOE Sites Through 1980

BURIAL GROUND ANNUAL TECHNICAL STANDARDS

BETA/GAMMA FISSION AND ACTIVATION PRODUCTS

Cs^{137}	500 Ci.
Sr^{90}	500 Ci.
Co^{60}	3×10^{3} Ci.
He^{3}	4×10^{3} Ci.
Other nuclides ($T_{1/2}$ >10 yr.)	1×10^{3} Ci.
Other nuclides ($T_{1/2}$ <10 yr.)	5×10^{5} Ci.

TRANSURANICS

< 10 nCi/g of Waste

ALPHA CONTAMINATED WASTE DISPOSAL at SRP

ISOTOPE	ASSUMPTIONS
Pu^{239}	500 Ci 1953 – 1968 50,000 CUBIC FT./Yr 6 LBS./CUBIC FT.

AVERAGE CONCENTRATION = 200 – 300 nCi/g

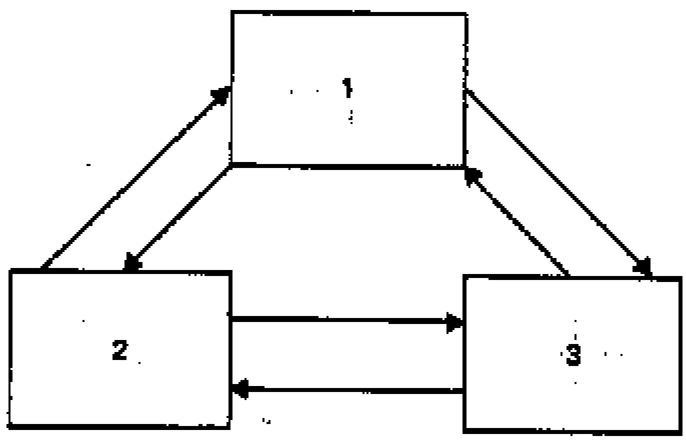
Pu^{238}	2500 Ci 1953 – 1968 50,000 CUBIC FT./Yr 6 LBS./CUBIC FT.

AVERAGE CONCENTRATION = 1000 – 1500 nCi/g

DOSE–TO–MAN MODEL

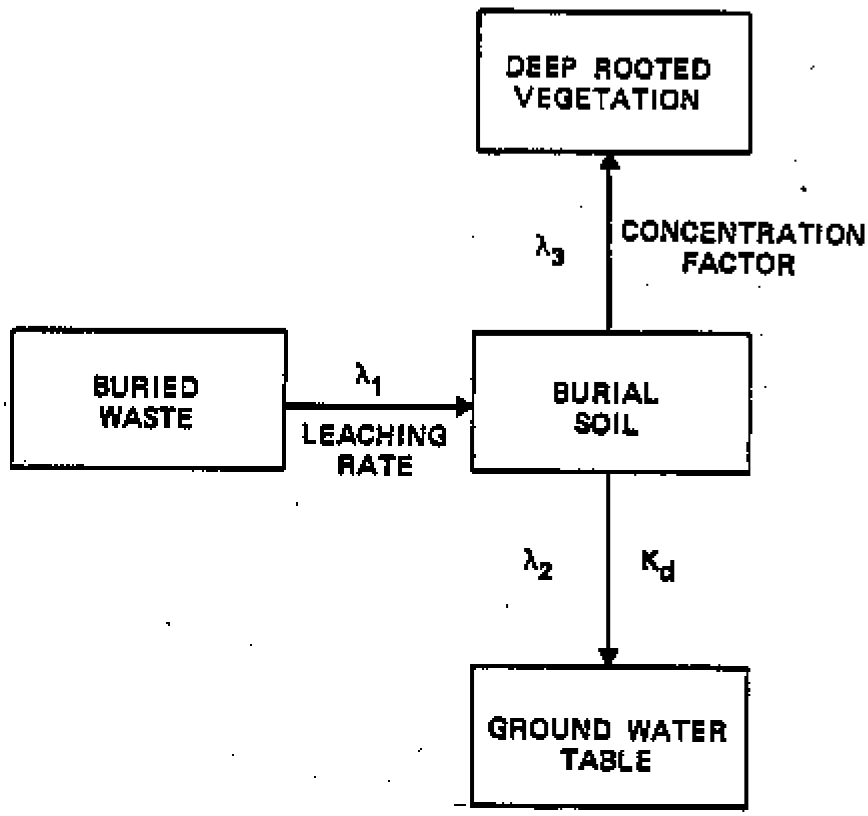
- SITE SPECIFIC RISK ASSESSMENT OF BURIAL GROUND OPERATIONS
- KEY INPUT
  NUCLIDE SPECIFIC
  - K_D, DISTRIBUTION COEFFICIENT
  - C_F, PLANT AND ANIMAL CONCENTRATION FACTORS
  - λ_S, WASTE TO SOIL RELEASE RATE

  BURIAL GROUND TOPOGRAPHY/GEOLOGY

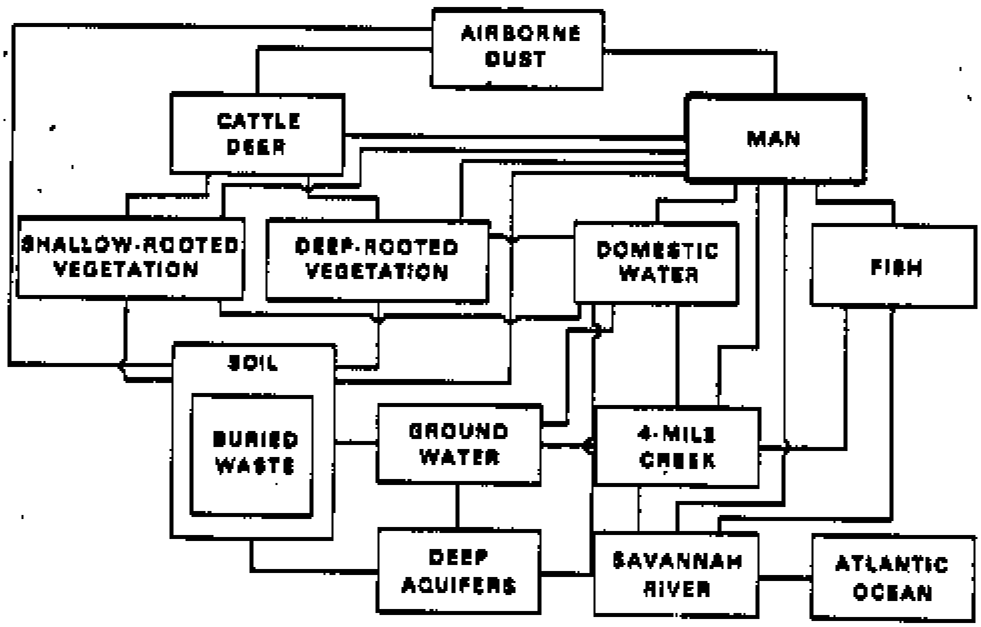


$$\frac{dQ_n}{dt} = \sum_{m=1}^{n} \lambda_{n,m} Q_m - \sum_{m=1}^{n} \lambda_{m,n} Q_n \pm S_n - \lambda_r Q_n$$

SLIDE 9. Compartmentalized Concept


DEEP ROOTED VEGETATION
λ_3
CONCENTRATION FACTOR
BURIED WASTE
λ_1
LEACHING RATE
BURIAL SOIL
λ_2
K_d
GROUND WATER TABLE

SLIDE 10.

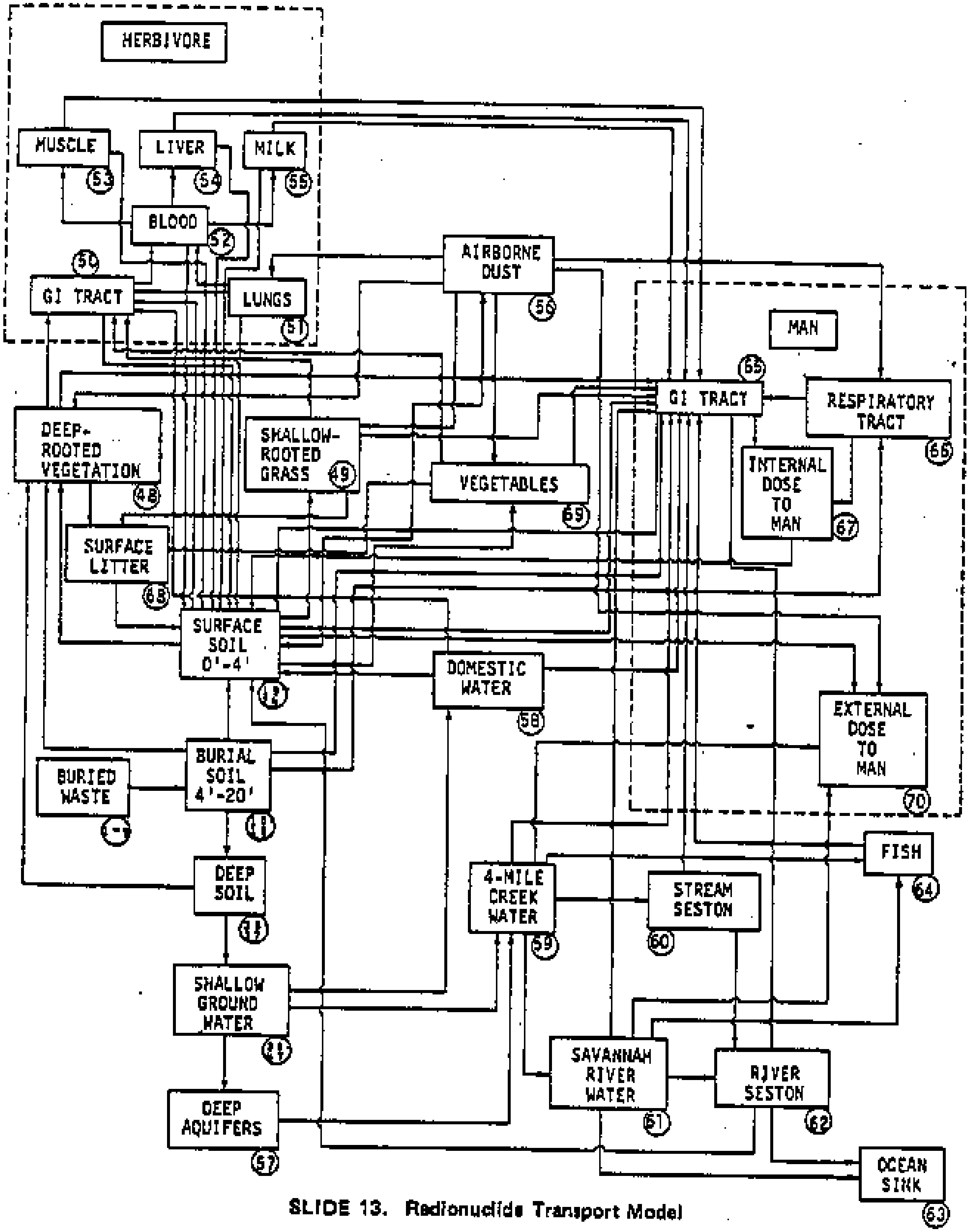


SLIDE 11. DOSTOMAN Diagram

BURIAL GROUND NUCLIDE MIGRATION MODEL

PATHWAYS

- WASTE TO SOIL
- PARTICLE TRANSPORT
- HYDROLOGICAL TRANSPORT
  - SOIL, GROUNDWATER, STREAMS
- VEGETATIVE UPTAKE
  - GRASS, VEGETABLES, TREES
- HERBIVORE INGESTION & PHYSIOLOGY
- FISH ASSIMILATION
- EROSION/RESUSPENSION
- INTRUSION
- HUMAN INGESTION, INHALATION & PHYSIOLOGY
- RECREATION



SLIDE 13. Radionuclide Transport Model

HOME FARM SCENARIO

EXTREME CASE

- INHABITANTS: FOUR PERSONS, 40 CATTLE, 60 DEER (INTRUSION)
- LAND USE
  - VEGATABLE GARDEN (2 ACRES)
  - PASTURE GRASS FOR GRAZING (150 ACRES)
  - FRUIT AND MISCELLANEOUS TREES (48 ACRES)
- ALL SUSTENANCE FOR PERSONS AND CATTLE PRODUCED ON FARM
- WATER COMES FROM WELL SUNKEN INTO THE GROUNDS
- SWIMMING IN SAVANNAH RIVER AND ITS TRIBUTARIES

RADIONUCLIDE MIGRATION MODEL
Pu CASES

$I_0^{238} = 2500$ Ci

$I_0^{239} = 500$ Ci

$\lambda_s = 1\%/yr$

$K_D = 1600$
- LARGE SOIL RETENTION
- SLOW DOWNWARD MOVEMENT

C_r PLANTS $= 10^{-4}$
- LOW PLANT UPTAKE

$T_{1/2}^{238} = 87.8$ yrs.

$T_{1/2}^{239} \simeq 2.44 \times 10^4$ yrs.

HUMAN PHYSIOLOGY
- BONE

RADIONUCLIDE MIGRATION MODEL
Pu CASES

$I_o^{238} = 2500$ Ci

$I_o^{239} = 500$ Ci

$\lambda_s = 1\%/yr$

$K_D = 1600$
- LARGE SOIL RETENTION
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C_r PLANTS $= 10^{-4}$
- LOW PLANT UPTAKE

$T_{1/2}^{238} = 87.8$ yrs.

$T_{1/2}^{239} = 2.44 \times 10^4$ yrs.

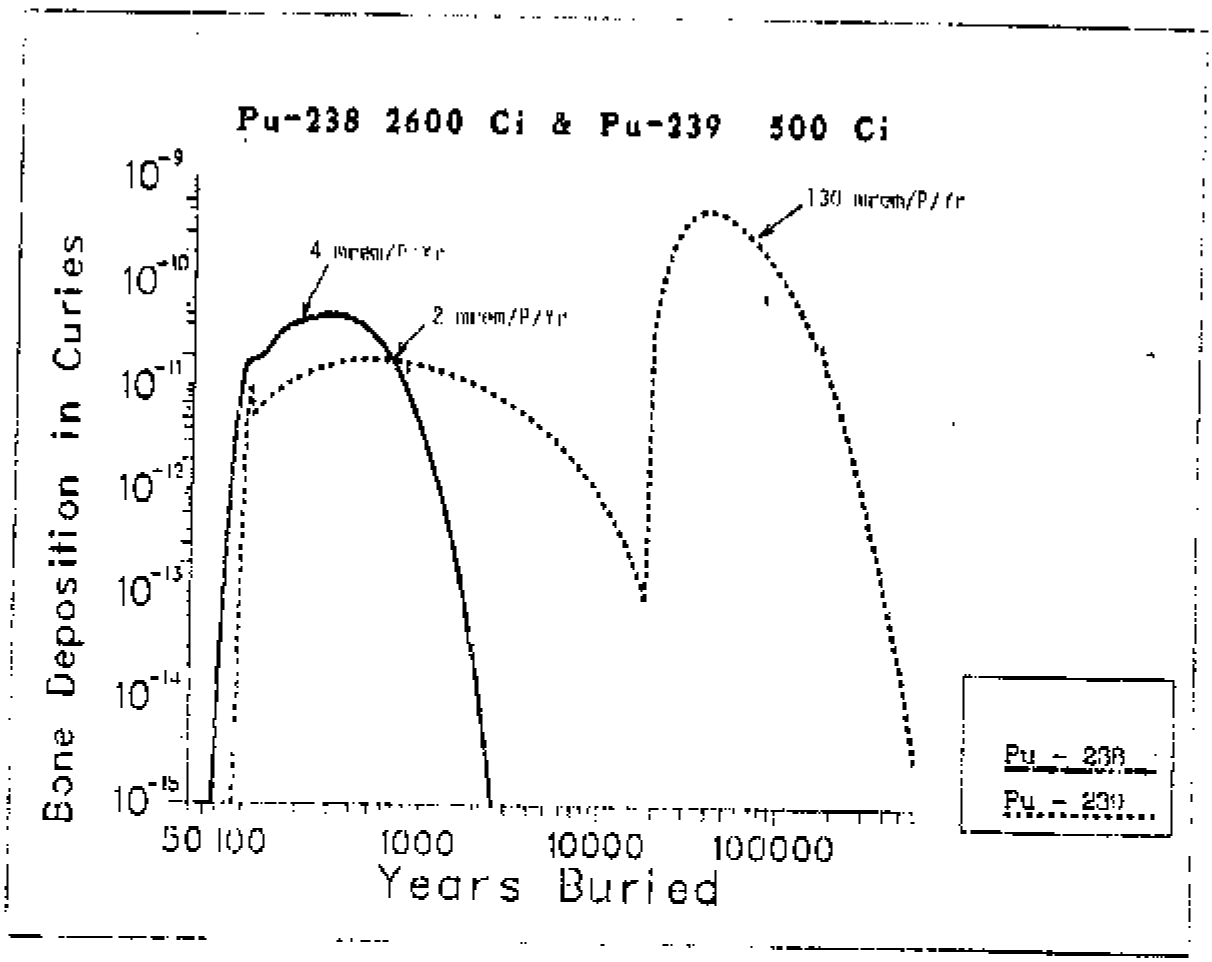
HUMAN PHYSIOLOGY
- BONE

DOSE-TO-MAN

NUCLIDE-SPECIFIC PARAMETERS

	K_D [1]	C_F [2]	λ_S [3]
Pu	1600	10^{-6}	10^{-2}
Cs	500	0.10	10^{-2}
Sr	160	0.35	10^{-2}

1. K_D, DISTRIBUTION COEFFICIENT – SOIL/WATER
2. C_F, PLANT/SOIL CONCENTRATION FACTORS
3. λ_S, WASTE TO SOIL RELEASE RATE



SLIDE 17. Dose-to-Man from Unencapsulated Pu Waste

TRU WASTE

MODEL PROJECTIONS vs 10nCi/g

SOURCE	PATHWAY	Pu^{239} in WASTE(nCi/g)
– SRL DOSTOMAN DP-MS-81-24 DP-MS-81-98Rev	FARMING/ WELL WATER	200-500
– HEALY-RODGERS(LANL) LA-UR-79-100	INTRUSION/ EROSION	$\leqslant$ 360 (SLB) $\leqslant$ 800 (GCD)
– FORD/BACON/DAVIS NUREG/CR-1005 Vol1	INTRUDER	100 – 400
– INEL (Draft EIS, Management of Defense TRU Waste at INEL, Vol 1, 1981)	EXCAVATION/ FARMING	2000
– J.COHEN/W.C.KING UCRL-52535(1978)	RECLAMATION/ AIRBORNE	1000 nCi/cc.

PLACKETT – BURMAN SENSITIVITY ANALYSIS

MOST IMPORTANT

- CONTROL PERIOD AFTER SHUTDOWN
- SOIL/WATER K_D'
- WASTE TO SOIL LEACH RATE
- PLANT/SOIL C_f
- GI TO ORGAN TRANSFER RATE
- INVENTORY

MODEL LIMITATIONS

- VALUE OF RESULTS: RELATIVE NOT ABSOLUTE
- COMPLEXITY $\neq$ CREDIBILITY
- SCENARIO
- VALIDATION
- ALTERNATIVE/OPTION ANALYSIS

CONCLUSIONS

- ACTUAL EXPERIENCE AT SRP WITH SLB OF TRU AT > 100 nCi/g
- CRITICAL PATHWAYS (FARMING SCENARIO)
  - SHORT TERM : VEGETATIVE UPTAKE
  - LONG TERM : HYDROLOGICAL TRANSPORT
- 100 nCi/g ?
  - REASONABLE WITH SAFE MARGIN
- IMPACT OF 100 nCi/g AT SRP
  - 10 – 30 % DIVERSION FROM TRU PADS TO SLB

RADIONUCLIDE MIGRATION MODEL FOR BURIED WASTE AT THE SAVANNAH RIVER PLANT

by

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Paper Proposed for Presentation
at "Waste Management '82"
Tucson, Arizona,
March 8-11, 1982

RADIONUCLIDE MIGRATION MODEL FOR BURIED WASTE AT THE SAVANNAH RIVER PLANT*

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ABSTRACT

Solid waste has been buried at the Savannah River Plant burial ground since 1953. The solid waste is contaminated with alpha-emitting transuranium (TRU) nuclides, with beta-gamma-emitting activation and fission products, and with tritium. To provide guidance for the current use and eventual permanent retirement of the burial site from active service, a radionuclide environmental transport model has been used to project the potential influence on man if the burial site were occupied after decommissioning.

The model used to simulate nuclide migration includes the various hydrological, animal, vegetative, atmospheric, and terrestrial pathways in estimating dose to man as a function of time. Specific scenarios include a four-person home farm on the 195-acre burial ground. Key input to the model includes site-specific nuclide migration rates through soil, nuclide distribution coefficients, and site topography. Coupled with literature data on plant and animal concentration factors, transfer coefficients reflecting migration routes are input to a set of linear differential equations for subsequent matrix solution. Output from the model is the nuclide-specific decayed curie intake by man. To discern principal migration routes, model-compartment inventories with time can also be displayed. Dose projections subsequently account for organ concentrations in man for the nuclide of interest.

Radionuclide migration has been examined in depth with the dose-to-man model. Movement by vegetative pathways is the primary route for potential dose to man for short-lived isotopes. Hydrological routes provide a secondary scheme for long-lived nuclides. Details of model methodology are reviewed.

*The information contained in this article was developed during the course of work under Contract No. DE-AC09-76SR00001 with the U.S. Department of Energy.

INTRODUCTION

One centrally located solid waste storage site is used to store all radioactive solid waste produced at the Savannah River Plant (SRP) and occasional special Department of Energy (DOE) shipments from offsite. This storage site occupies 195 acres between the two chemical separations areas at SRP, approximately 6 miles from the nearest plant boundary. The original area of 76 acres, which began to receive waste in 1953, was filled in 1972, and operations were shifted to a 119-acre site contiguous to the original area.

The purpose of our ongoing study of radionuclides in buried waste is to address the validity of the current limits for burial of all radionuclides and to provide guidance in developing criteria for future management, surveillance, and control of the burial site in the years following the end of plant operation.

As part of our approach to providing guidance, a mathematical model to simulate the potential movement of radionuclides from buried solid waste, through the environment, to man has been formulated. Model results specify critical pathways for nuclide transport and also estimate projected dose to man from buried solid waste. The radionuclide transport model is formulated to be specific to the Savannah River Site, as governed by the input data. However, the formulation is generic and applicable to the migration analysis of nuclear wastes at other sites, as well as toxic chemical wastes.

DESCRIPTION OF THE BURIAL GROUND

The 195-acre burial ground[1] resides on the Barnwell formation of the Coastal Plain geologic province, about 30 miles southeast of the Piedmont Plateau (the other principal geologic province in South Carolina). The principal surface and near-surface soils are clayey sands or sandy clays, averaging about one-third clay, with some cation exchange capacity (1-5 meq/100 g soil). The mean water table is at a depth of 45 feet, with a fluctuation of about 2 ft/yr. The rate of downward migration of percolate water is 7 ft/yr, and the lateral flow of water in the saturated zone at the water table is 40 ft/yr. The nearest perimeter of the burial site is 0.5 miles from the closest onsite stream (Four Mile Creek). The predominant storage mode is earthen trench burial.

Radioactive waste disposed of by shallow land, earthen trench burial is truly a heterogeneous mixture. Examples of materials in storage include: (1) contaminated equipment (obsolete tanks, pipes, jumpers, and other process equipment from the fuel separation plants), (2) reactor and reactor fuel hardware (fuel components and housing; spent Li-Al targets), (3) incidental lab and production wastes (cellulosic and plastic materials, analytical and decontamination residues, spent equipment), (4) chemicals (oil in drums containing absorbents; mercury in one-liter polyethylene bottles; ion exchange resins), (5) off-site materials (tritiated waste from Mound; LANL and Mound ^{238}Pu process waste; debris from two U.S. Military airplane accidents in foreign countries), (6) miscellaneous materials (animal carcasses, building rubble).

For modeling purposes, inventories of key nuclides buried in earthen trenches have been retrieved from computer records.[1] Nuclides of half-life greater than 20 years (^{238}Pu, ^{239}Pu, ^{137}Cs, ^{90}Sr) are of greatest interest for projecting potential environmental transport since they will persist well into the future and are of greatest potential concern. Coupled with recent history of burial ground operations and projections on future waste generation rates, model inventories for these four nuclides have been estimated through the year 2000.

DESCRIPTION OF THE SRL DOSTOMAN MODEL TO PROJECT ENVIRONMENTAL TRANSPORT

The DOSTOMAN model, as developed and coded, makes a compartmentalized simulation of the transport of radionuclides in the environment. The compartments, which represent different portions of the environment, include the nuclide source, soil, vegetation, herbivores, atmosphere, groundwater, surface water, and man (Fig. 1). Movement of radionuclides between compartments is controlled by transfer coefficients, which specify the fraction of radionuclides entering or leaving a compartment during a specified period of time. Time functions account for factors such as institutional control prior to public use. Sources and sinks independent of the natural movement of radionuclides are provided.

The general form of the model equation was developed by ORNL personnel for a study to predict the uptake of selected radionuclide species by cows.[2] Refinements were made to expand the description of the numerous pathways for potential transport and to project radiation doses to man. The DOSTOMAN model employs a single equation that considers only the movement of radionuclides through the system. Such factors as water and wind velocity, erosion, intrusion, resuspension, vegetative decay, etc., are accounted for in the transfer coefficients. This equation accounts for the four factors determining the radionuclide inventory in a compartment: (1) transfer in from other compartments, (2) transfer out to other compartments, (3) source or sink terms, and (4) radioactive decay.

The DOSTOMAN model calculates the radionuclide inventory in each compartment at the end of every time step specified. Because a finite difference technique is used to solve the simultaneous equations, some possibility exists for error to accumulate during a simulation run. This error can be minimized by controlling the specification of the time steps. Subroutines for evaluating the numerical stability are provided in the program: (1) RESID determines the difference (residual) between the calculated values for the right- and left-hand sides of the set of simultaneous equations and (2) MASBAL calculates the state of mass balance of the nuclide inventory at a particular time and compares the total to the sum of initial nuclide inventory values. These data are output with each incremental time-step calculation.

DOSTOMAN may be applied to other disposal facilities at other locations - only the initial radionuclide inventories and the transfer coefficients make it site specific. However, the model was intended for application to humid locations - those with relatively high rates of precipitation and shallow water table. The Savannah River Plant has these characteristics.

The data required to run the model include all those factors which influence the rate of movement of radionuclides in the environment. Topographical, hydrogeologic, and geochemical information such as depth to water table, distance to streams, aquifers and rivers, ion exchange coefficients, and bulk density and porosity of the disposal media must be known. The initial radionuclide inventory must be defined. Plant and animal concentration factors must be specified. Physiology of radionuclides in animals and man must be included. Although site-specific data are desirable, considerable information may be obtained from the literature.

DOSTOMAN has seven general data files: (1) initial radionuclide inventory of each compartment, (2) transfer coefficients between compartments, (3) compartment interactions, (4) radioactive decay constant, (5) time-step size, (6) time functions (to account for the delayed presence of man), and (7) sources and sinks.

DOSTOMAN is written in FORTRAN and may be used on any modern computer facility. Core requirements will vary with the number of compartments and time steps being simulated. For example, on the IBM 360/195 at SRL, a simulation involving 200 time steps, 200 transfer coefficients, and 69 separate compartments (a 69 x 69 matrix) requires about six minutes of central processing unit time. About 500 K bytes are requird for such a simulation. Hardware for plotting is desirable. Only one radionuclide can be considered in each run because the decay constant and many of the compartment inventories and transfer coefficients are specific to that radionuclide.

Development work on DOSTOMAN is complete and simulations of several simple test cases have demonstrated the validity of the model. It is currently being used to simulate hypothetical postclosure land use scenarios. Reference 3 contains a more detailed description of the model.

SITE SPECIFIC PATHWAY PARAMETERS

The Significance of K_d: The Nuclide Soil/Water Distribution Coefficient

The underground disposal of radioactive wastes is a method to deplete the radiation by storing the wastes for a sufficiently long period of time, in relation to the half-life of the radionuclides, utilizing the capacity of soil to exchange and absorb nuclides. Hence, it is necessary to gain clear understanding of soil dynamics since hydrological transport in soil is the initial pathway by which radioactive substances released from disposed waste migrate. Proper predictions of the migration of radioactive substances underground are mandatory to secure the validity of underground disposal. The distribution coefficient (K_d) of a radionuclide between water and soil is often used as a parameter to reflect the rate of migration of radioactive substances in soils.[4] Using distribution coefficients and the assumption that exchange equilibrium exists and is maintained between the concentration of nuclides in groundwater and that in soil, predictions of the underground migration of nuclides can be achieved. Hence, the distribution coefficient may affect very significantly the safety evaluation of the underground disposal method.

The distribution coefficient will vary[5] depending on such factors as the method of measurement, oxidation state and physical form of the nuclides, coexisting ions in underground water, the chemical stability of coexisting ions, the pH of percolating water and soil properties (clay and organic content, ion exchange capacity, pH). Generally, two methods of measurement are used to experimentally determine distribution coefficients.[6] The "batch" (static method) and "column" (dynamic measurement) procedures will generally provide a range in the value of K_d to reflect equilibrium or pseudo-equilibrium conditions which exist in the heterogeneous system of nuclides in contact with soil.

Prior studies [4,7] have shown that the distribution coefficient can be related to the time required for the nuclide to move through a soil column, if soil properties such as bulk density, porosity, and linear rate of percolation are known. Hence, for our site specific case of SRP burial ground migration, time requirements for nuclide movement to the groundwater and Four-Mile Creek can be estimated and are, in fact, the basis for some of the time function input to the model. Put in perspective to nuclide decay patterns, this information is useful for a qualitative assessment of the significance of K_d. Figure 2 illustrates such a comparison for the long half-life nuclides of interest to the transport model (^{239}Pu, ^{238}Pu, ^{137}Cs, ^{90}Sr).

If K_d is large (>100: Pu isotopes, ^{137}Cs), movement to the primary bodies of water takes a long time relative to ^{238}Pu or ^{137}Cs half-lives, and radioactive decay will be nearly quantitative before hydrological transport to the groundwater occurs. Qualitatively, groundwater/drinking water pathways for dose to man should be modest and other transport mechanisms have to be operative for significant dose to a population. For nuclides of long half-life (^{239}Pu), hydrological transport to drinking water supplies, as well as other routes, may be competitive with the rate of radioactive decay, leading to multiple pathways for potential dose to individuals. This will be dictated by the value of the distribution coefficient.

If K_d is low (<50), downward movement to underlying groundwater systems may occur at significant rates, and be competitive with the spontaneous decay of nuclides of half-lives >20 years. Under this circumstance, deep soil and groundwater compartments should accumulate radionuclides, and drinking water pathways for dose to man may dominate.

K_d values for Cs and Pu isotopes are consistently >500, from a variety of measurements.[4,7] Values for ^{90}Sr are somewhat more uncertain. For example, measurements of ^{90}Sr K_d for SRP soil[7] vary by a factor of 10^2 (5 to 500) depending upon pH, cation content of percolate and soil, the clay content of a given layer of soil, and Sr concentration. More recent measurements[6] for well-characterized SRP soil and well water suggest K_d values for ^{90}Sr at ≤ 50. Japanese workers[4] show an interesting correlation of ^{90}Sr K_d with the cation exchange capacity of the soil. Coupled with data on SRP burial soil exchange capacity,[7] ^{90}Sr K_d values ≤ 50 are implied.

In any case, it should be clear that, in the assessment of risk of potential movement of buried radionuclides, results will be very sensitive to the soil/water exchange equilibria as reflected by the values of the distribution coefficient. For the purposes of this paper, to illustrate model projections, K_d values of 1600 for Pu isotopes, 1000 for ^{137}Cs, and 50 for ^{90}Sr have been used.

LAND USE SCENARIO

The model has been used to project the dose to man from buried inventories of nuclides for the postulated future use of the burial ground as a small home-farm 100 years after burial ground decommissioning. Localized utilization of farm produce (vegetables, fruit trees), cattle (milk, meat), and wild deer (meat) to provide the total sustenance for a family of four residing continuously on the 195-acre burial site is assumed. The family obtains its water supply from a well drilled in the Barnwell formation, which is also used for irrigation. Land utilization is partitioned to a vegetable plot (2 acres), fruit trees (48 acres), and pasture (145 acres), with the pasture supporting 40 cattle. Deer (60) intrude on the farm to forage. The population will occasionally intrude into the buried waste and contaminated soil and routinely breathe the air above the site. Recreation such as fishing or swimming in surface waters, which may be receiving contaminants from the burial ground, is also included. Although this is a limited population scenario, this land use is entirely consistent with historical documents which trace the agricultural community which once existed on the site of the Savannah River Plant.[8]

MODEL PROJECTIONS FOR LONG-LIVED RADIONUCLIDES

Pu Isotopes

Model results for Pu isotopes have been reported previously[9] and are illustrated in Fig. 3 for ^{238}Pu (2600 Ci) and ^{239}Pu (500 Ci) for population curie intake to the bone skeleton (critical organ for Pu) as a function of time. Multiple transport pathways are illustrated here.

^{238}Pu shows a peak intake to bone of 60 pCi, corresponding to a maximum dose of 4 mrem/person/year, at approximately 300 years after cessation of burial ground operations. Analysis of model compartment inventories indicates the primary mode of movement is uptake by deep-rooted vegetation with primary dose from fruit consumption and a smaller dose from ingestion of animal stock. Direct intrusion into waste by man makes a minor contribution to dose via ingestion and inhalation of soil containing Pu from waste-to-soil migration and vegetative decay. ^{238}Pu is retained in soil, due to a high distribution coefficient, but decays before hydrological transport becomes significant. Prior studies[10] have shown that, with time, the major risk of ^{238}Pu in the environment is associated with daughter products (i.e., ^{226}Ra) due to decay:

$$^{238}_{94}Pu \xrightarrow{\alpha} {}^{234}_{92}U \xrightarrow{\alpha} {}^{230}_{90}Th \xrightarrow{\alpha} {}^{226}_{88}Ra,$$

since the radiological hazard of ^{226}Ra is significantly greater.[11] By use of the Bateman equation for successive decay,[12] a ^{226}Ra waste inventory of no more than 30 Ci would accumulate with time. Worst-case assumptions on movement through the environment to man result in a dose estimate of <0.1 mRem/person/yr.

^{239}Pu shows a bimodal distribution for bone deposition with time, illustrative of two critical pathways for migration of this radionuclide. A maximum intake of 20 pCi (2 mRem/person/yr) is observed at 400 years after burial operations ceased, due to the deep-rooted vegetation pathway. Eventually, long-lived ^{239}Pu is transported downward into the groundwater and is ingested via the well water supply. This contributes to a peak intake of 600 pCi (130 mRem/person/yr) at 38,000 years.

Fission Byproducts

Model projections for annual intake to the gastrointestinal tract via ingestion, as a function of period of residence, are shown in Fig. 4 for ^{137}Cs and ^{90}Sr. Results are shown graphically for individual intake. Fission byproducts are transported from buried waste primarily by four pathways: hydrologic transport to deep soil, uptake by vegetation, human intrusion, and erosion of the ground surface. Of these, only vegetative uptake leads to a significant dose. Movement by hydrologic transport is slow (particularly for Cs) due to the soil ion exchange characteristics and the low flow velocities in the subsurface. The short half-lives of both nuclides (≤30 years) result in near-quantitative decay in the time frame of reaching domestic water supplies. Erosion is so slow and human intrusion so infrequent that neither contribute significantly to dose.

^{137}Cs is relatively soluble and essentially 100% is absorbed through the gastrointestinal tract[11] and widely distributed by the blood - leading to a whole-body dose from assimilation. Annual dose rises from 18 mRem per person for the first year of residence (101 years since cessation of burial operations) to a peak of 190 mRem per person in the 33rd year of residence. The maximum dose is comparable with average annual dose due to background radiation.[13]

Although the curie intake projections for ^{90}Sr (Fig. 4) are about an order of magnitude less than ^{137}Cs, the dose results are similar. Only a small portion of ^{90}Sr enters the body by absorption through the gastrointestinal tract (2.25%)[11]. That which is absorbed concentrates in bone, the critical organ for ^{90}Sr. Model projections for annual bone dose increase from 13 mRem per person (1st year of residence) to 170 mRem per person (year of maximum intake), again comparable to annual background radiation dose.

Plackett-Burman statistical analysis[14] has indicated the key model parameters, (1) period of institutional control and (2) soil/water distribution coefficients, are two of the more sensitive variables dictating results. For ^{90}Sr, this parametric sensitivity is illustrated in Fig. 5, using a 50-year dose commitment calculation. The model projects that control over the site (i.e., excluding public use) may be mandatory, for perhaps as long as 200 years after burial has ceased, to keep the risk of exposure below public standards. The model has also been used to project that viable options to such long surveillance periods include an earthen overburden to the existing site or deeper burial in a new disposal facility. For critical pathways such as vegetative uptake, greater distance between the root zone and waste will diminish the radiological hazard as long as the waste inventory relationship to groundwater is maintained ($\geq$20 ft).

The importance of distribution coefficient is well illustrated in Fig. 5. Low values of K_d also provide an interesting result. For K_d's <10, rate of downward movement is rapid with ^{90}Sr potentially reaching the groundwater in <100 years. The net effect is accumulation of ^{90}Sr in deep soil (>20 ft) and groundwater. Four Mile Creek would not be subject to ^{90}Sr flows in <400 years, during which time decay is near-quantitative. Burial soil retains less Sr, exposing much less inventory to the vegetative pathway of migration. The dose pathway is the same - vegetative uptake and ingestion - but the available upper soil inventories are reduced.

ANALYSIS OF THE RADIOLOGICAL HAZARD

The lifetime effect of chronic one-year intake of a nuclide, expressed as a 50-year dose commitment, is a more valid assessment of the radiological hazard. In this form, the influence of biological retention in the critical organ and radioactive decay are expressed over the average lifetime of an adult. DOSTOMAN model projections are summarized in Table I with dose commitment results presented in relation to useful standards. For ^{239}Pu, the peak individual dose of 130 mRem/person/yr increases to a lifetime effect of 6 Rem/person due to the long bone retention (72,000 days)[11] and radioactive decay half-life (2.4×10^4 years)[11] of that isotope. The ^{137}Cs result (0.2 Rem/ person) is nearly equal to the annual dose since the isotope is rapidly excreted with a biological half-life of 115 days.[11] For ^{90}Sr, the maximum annual

TABLE I
DOSTOMAN Model Projections
for SRP Burial Ground Nuclides

Nuclide	Maximum Intake to GI Tract (μCi/Person/Year)	Maximum Annual Dose (mRem/Person/Year)	50 Year Dose Commitment (Rem/Person)
^{238}Pu	0.23	4	0.2
^{239}Pu	0.12	2	0.1
	7.6	130	6.0
^{137}Cs	3.0	190	0.2
^{90}Sr	0.50	170	3.8
Background Radiation			5-10
10 CFR 20 Public			25
DOE Occupational			250

dose of 0.17 Rem/person/yr increases to a 50-year dose commitment of 3.8 Rem/person due to the long biological half-life of ^{90}Sr in bone (18,000 days),[11] coupled with the influence of an energetic decay daughter (^{90}Y).[11] Although the projected maximum intake by ingestion is about an order of magnitude less for ^{90}Sr, relative to ^{137}Cs and ^{239}Pu, the radiological effect over a lifetime is more significant. The projected lifetime dose commitment results are still comparable to the cumulative effect of background radiation.

SUMMARY

Nuclide transport modeling can be useful as an analytical approach to addressing the question of the validity of burial ground practices. In fact, migration modeling continues to receive industry-wide attention as a method of evaluating currently active commercial sites[15] as well as future locations for institutional wastes,[16,17] to address the nationwide need for regional burial repositories.

The DOSTOMAN code, developed to treat the site specific case of SRP buried waste, will continue to be useful as one of the tools to provide guidance. Subject to choice of exposure scenario, critical pathways for nuclide movement can be defined. In cases where the results are more uncertain due to the nature of the input data, the model has been used to discern which alternatives to burial ground management should receive active consideration (i.e., intermediate depth burial, overburden). Continuing refinements of pathway descriptions, population scenarios, and input data will improve the validity of projections.

The predominance of deep-rooted vegetative uptake as a recurring critical pathway for dose to man clearly suggests immediate site management practices to control such species. This type of control has, in fact, been implemented into the low-level waste management operating procedures on a routine basis.

PROGRAM

The accuracy of DOSTOMAN migration projections receives constant scrutiny. Several programs will be pursued to test this uncertainty. The EPA PRESTO code, developed by ORNL,[15] will be used to project migration with SRP burial ground input data. In addition, DOSTOMAN will be used to project the transport trends for the forage-cow-milk-man scenario[2] for which experimental data are available.

The validity of site specific input data is being examined in field and lab studies. An extensive lysimeter program (mini-burial ground) has been active since 1978 to measure nuclide movement in burial ground soil as a function of waste form. This will provide updated data on waste-to-soil migration rates and distribution coefficients. Direct measurement of deep-rooted vegetative uptake by trees and vegetable crops growing in place on a small portion of the SRP burial ground has been in progress since 1978.

Along with refinements of the nuclides examined to date, future programs will address the risk of burying larger inventories of other fission products. For example, ^{99}Tc will be a saltcrete component from the proposed Defense Waste Processing Facility at SRP. DOSTOMAN projections will be used to address the question of the safe rate of disposal of ^{99}Tc.

Expanded population scenarios are needed to supplement the home-farm treatment. Cases now being planned include a commercial farm, with typical regional crops (corn, soybeans), and a commercial forest with widespread distribution of products.

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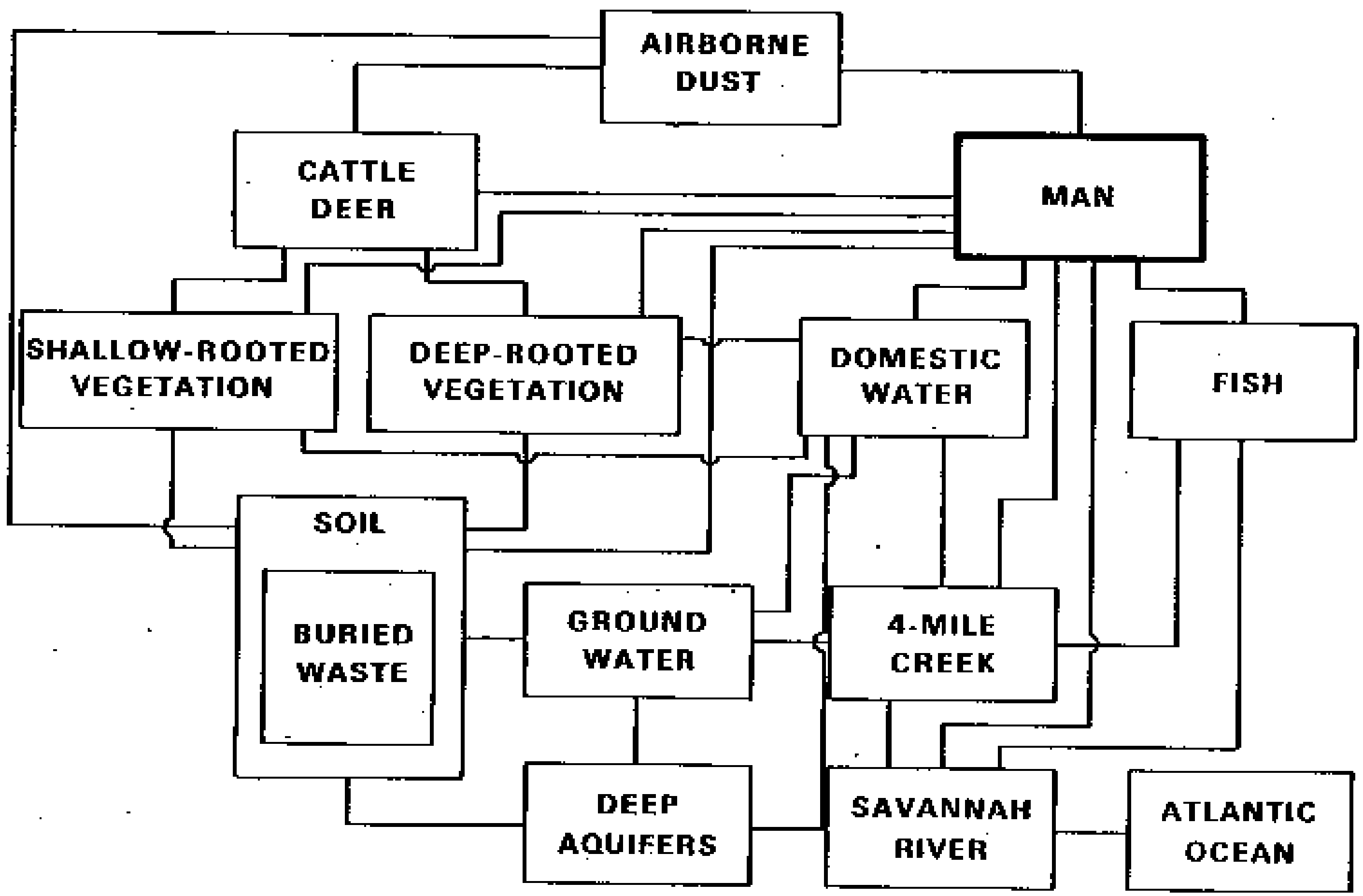

FIGURE 1. DOSTOMAN Diagram

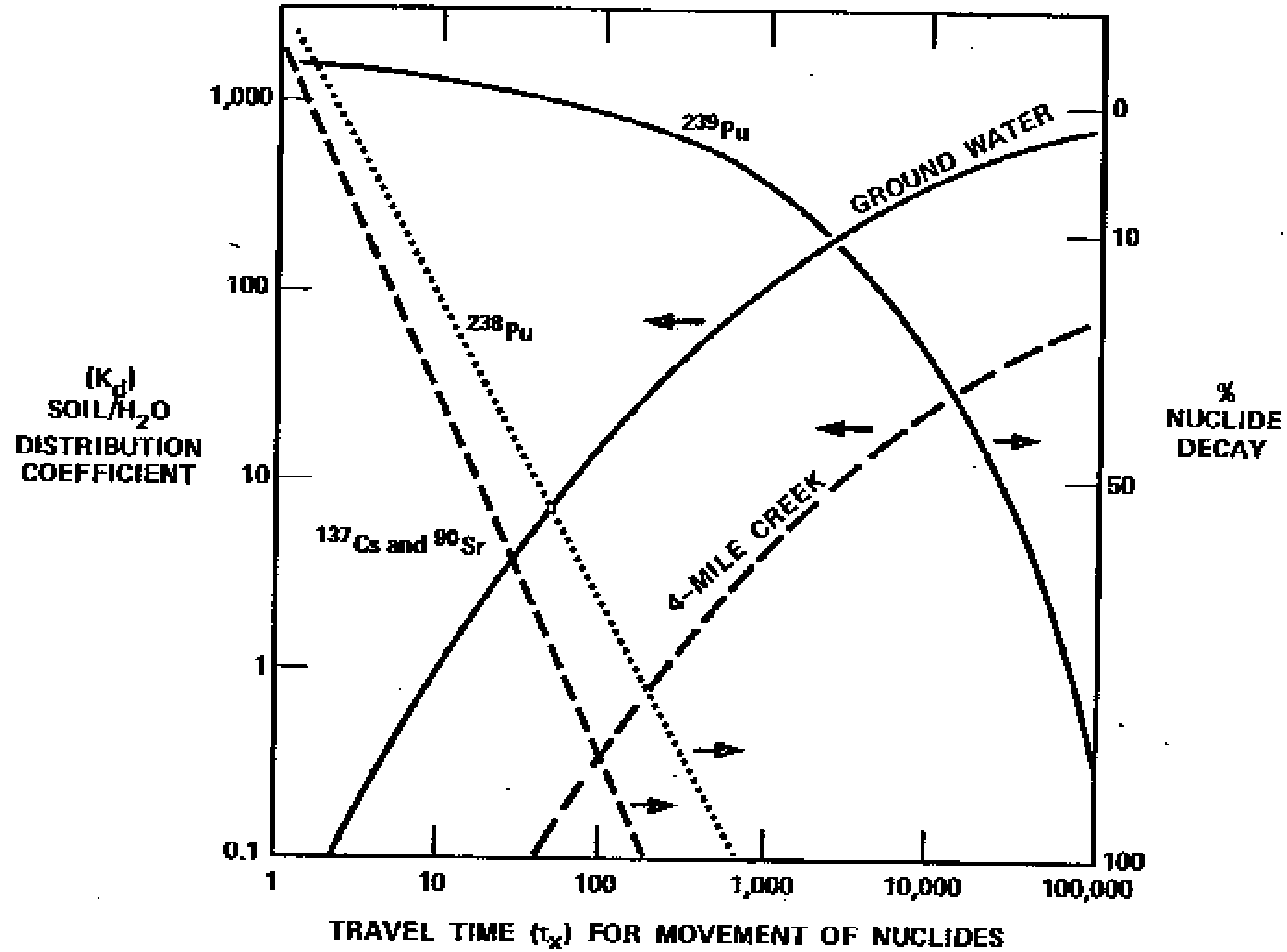

FIGURE 2. Nuclide Migration in SRP Soil

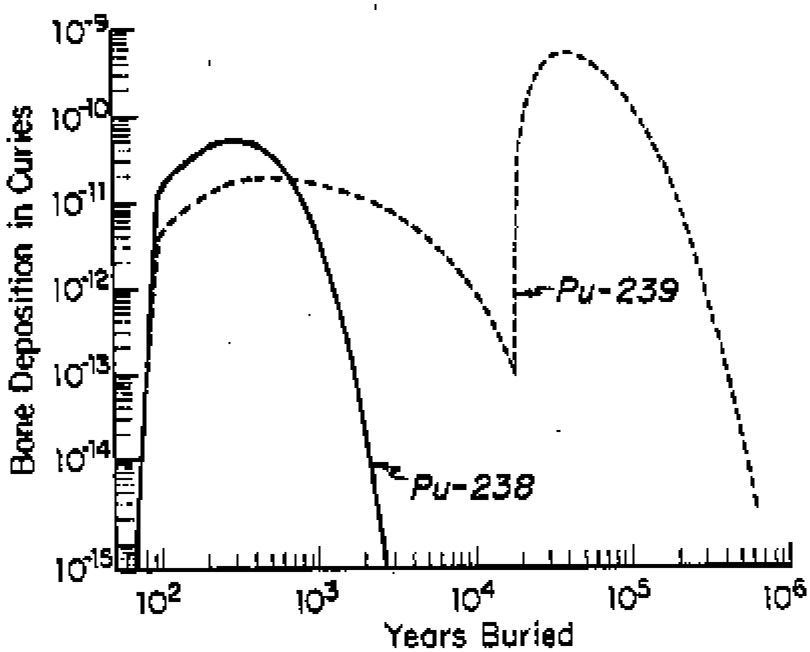

FIGURE 3. Model Projections for Pu Isotopes (Example)

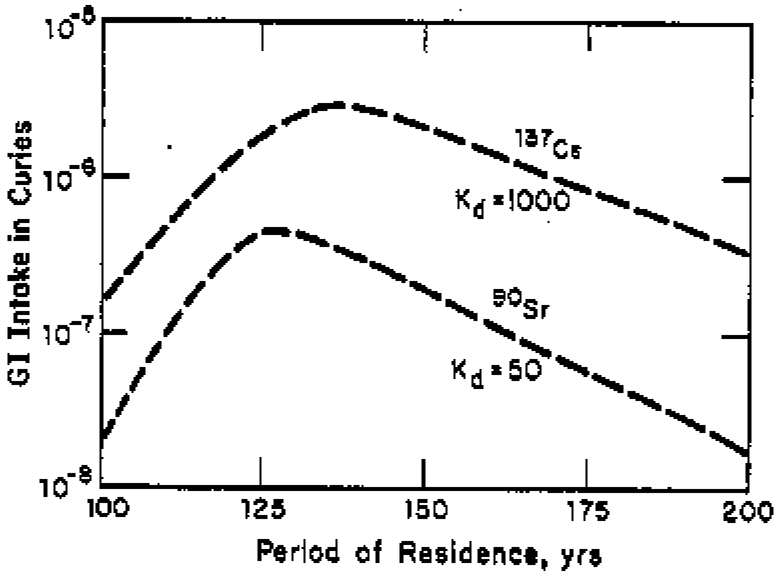

FIGURE 4. DOSTOMAN Projections for Cs/Sr (Example)

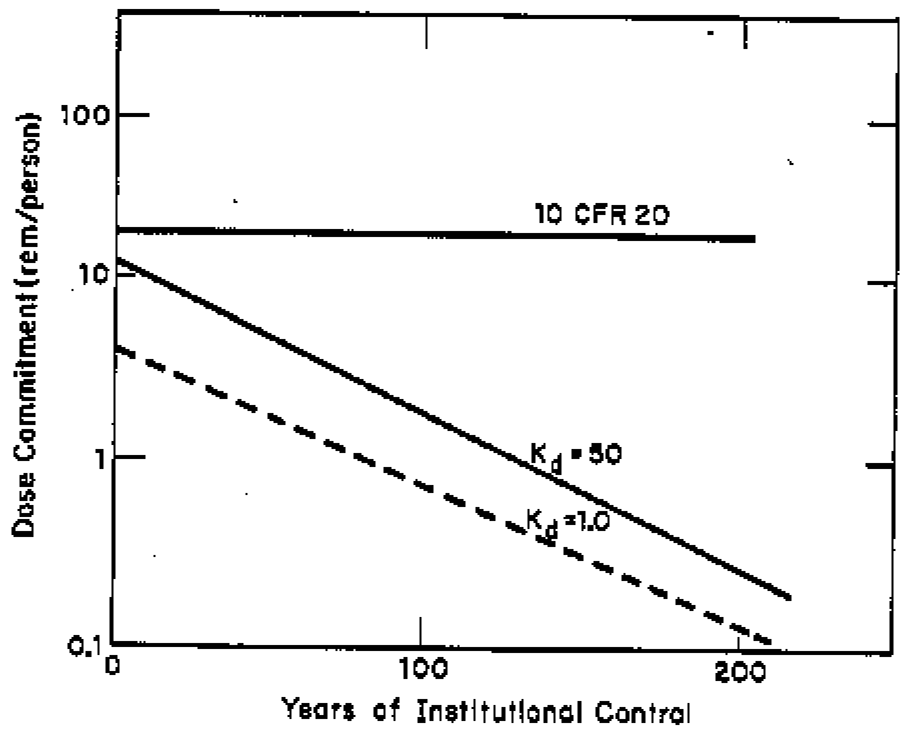

FIGURE 5. ^{90}Sr Results as a Function of Model Parameters (Example)

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May 31, 1983

TO: T. V. CRAWFORD AND E. L. ALBENESIUS

FROM: R. H. EMSLIE AND C. M. KING

SR-90 IN CURRENT BURIED WASTE:
ENVIRONMENTAL TRANSPORT PROJECTIONS VIA DOSTOMAN ANALYSIS

CONTENTS

Contents (Continued)

1.0 SR-90 IN CURRENT BURIED WASTE: ENVIRONMENTAL TRANSPORT PROJECTIONS VIA DOSTOMAN ANALYSIS

1.1 INTRODUCTION

Radioactive waste has been buried at the SRP burial ground since 1953. This waste includes alpha-emitting transuranium (TRU) nuclides, beta/gamma activation and fission products, and tritium. Of the beta emitting fission byproducts, Sr-90 inventories in burial ground earthen trenches are, along with Cs-137, reported to be among the largest of those nuclides with intermediate half-lives. Sr-90 possesses environmental physical properties which warrant a detailed examination of potential environmental transport and projection of dose to individuals and any plausible population groups. These properties include modest soil adhesion and high plant and animal uptake factors. In addition, dose factors for human ingestion pathways reflect long biological retention of Sr-90.

To provide guidance on the validity of current limits for burial of Sr-90 and in developing criteria for future management, surveillance, and control of the burial ground after site decommissioning, the DOSTOMAN environmental transport equations have been used to project Sr-90 transport and subsequent dose for a variety of plausible water use and land use scenarios.

1.2 SUMMARY

Sr-90 hydrological transport to the groundwater system below the burial site was projected to be insignificant relative to the NRC guidelines. Soil adhesion and radioactive decay couple synergistically to minimize groundwater contamination to well below Federal regulatory guidelines. Site boundary (Four Mile Creek) and Public (Savannah River) water contamination are orders of magnitude lower than groundwater due to high stream flowrates and subsequent dilution. For the extreme cases of maximum localized Sr-90 mobility due to change in soil properties or the presence of mobilizing chemicals, projected Sr-90 levels were also inconsequential to dose-to-man. For the population of 70,000 residing on the Savannah River (near Savannah, GA) which utilizes river water as a drinking water supply, the maximum population dose commitment would be 2.1×10^{-1} man-rem to the critical organ (bone). The average background radiation effect to the same population would be 7.0×10^{3} man-rem.

By use of NRC methodology, a low dose consequence (7×10^{-3} mrem/person) was projected for the use of Sr-90 contaminated water for crop irrigation. The NRC-based analysis extended to five foodchain pathways. The projected population dose commitment to water users downstream of SRP (70,000 people), assumed to use river water for irrigation purposes, is 0.5 man-rem (whole-body). The maximum total body population dose commitment of 0.5 man-rem per year, combined with a conservatively estimated relationship between low-level dose and population health effects (0.45×10^{-3} additional cancer cases per man-rem) implies a total expected number of additional health effects of 0.00023 per year. The interpretation of this result is that it would be very unlikely that even one person in the exposed population would be affected in any year in the distant future as a result of radiation exposure attributable to the land disposal of Sr-90. Consideration of the effects of various conservative assumptions used in this analysis suggest that the estimate of 0.00023 health effects per year is conservative by several factors of 10, since most of the radioactive Sr-90 eventually released to the disposal site would actually be expected to remain at the site, and most of the Sr-90 that would be transported away from the immediate area would be expected to be either absorbed within a short distance by soil particles or deposited in stream or river beds.

Direct land occupation, for the projected future use of the shallow land burial site for agricultural purposes, is the most conservative scenario for evaluation of burial site integrity. The principal migration pathway, direct vegetative root penetration into waste, is the most conservative pathway for high soil adhesion radionuclides.

Use of the limited population home farm scenario for the disposition of the burial ground after 100-year institutional control results in an estimate of the maximum radiation dose to an adult from Sr-90 to be 0.8 rem/person/year for the maximum year of exposure and 15.0 rem/person for year after year chronic exposure. The predominant exposure pathway for this land-use scenario is ingestion of fruit and vegetable crops contaminated by direct root penetration into the waste. Inhalation pathways as a consequence of soil resuspension and human intrusion are inconsequential.

Use of the extended population commercial farm scenario for the plausible land use of the 195-acre burial ground as a corn production farm with product distribution to a population of 3000 results in a population dose of 1800 man-rem. The average background radiation dose to the same population would be 300 man-rem per year or 15,000 man-rem over 50 years. The 10 CFR 20 maximum exposed individual limit to the same population would be 1500 man-rem per year or 75,000 man-rem over 50 years.

The calculated radiation doses for land occupation scenarios exceed the presently accepted maximum individual limit of 0.5 rem/person. However, the transport equation has been used to show that the dose can be reduced to acceptable levels by controlling the following parameters:

1. Limiting the annual rate of Sr-90 to <500 Ci/yr (the current SRP Technical Standard).

2. Disposal below the zone of vegetative root penetration.

3. Institutional control after site decommissioning prior to any land occupation.

1.3 RECOMMENDATIONS

1. After 600-Area burial ground decommissioning, a 10-15 foot overburden to the current site should be considered.

2. For new burial sites containing Sr-90, trench cap at 10-15 feet below ground surface and trench base >10 feet above groundwater levels should be maintained.

1.4 BACKGROUND

1.4.1 The Sr-90 Base Case

Historically, prior DOSTOMAN analyses[1-7] have been exclusively based upon the HOMEFARM scenario in which many pathways are in competition for transport of radionuclides. Root, et al.[7] extended this analysis to the situation of Sr-90 in shallow land burial with model dose projections based upon cumulative intake and dose for year after year site occupancy by a population of four. Those results illustrated the potential for high-dose consequence but strongly implied the results were very scenario dependent. The Root, et al.[7] work is herein referred to as the "Base Case" which will serve as the reference point for additional scenario and model parameter sensitivity analysis. The "Base Case" transfer coefficients are published in Root, et al.[7] from the methodology of Wilhite[4,8] for the 70 x 70 HOMEFARM matrix. It is the purpose of this document to extend the Sr-90 analysis to other scenarios, to illustrate the scenario dependence of transport modeling projections, and to examine the sensitivity of model parameters, burial ground management practices, and dosimetry data base to dose consequence for the shallow land burial of Sr-90.

The key "base case" model input parameters are summarized in Table 1, and are the reference point input data for further analysis.

1.4.2 The DOSTOMAN Transport Equations

1.4.2.1 Transport to the Groundwater System (No Site Occupancy; Influence on Drinking Water Supplies)

A key aspect of any analysis of the impact of the potential movement of radionuclides into the environment should initially be an analysis of any influence on the existing conditions at the shallow land burial site. The SRP 195-acre burial ground has a groundwater system approximately 25 feet below the base of the earthen trenches which reaches the nearest outcrop at Four Mile Creek, ~1700 feet from the perimeter of the burial ground.[12] Once reaching the tributary, movement of any soluble radionuclide would be rapid and at the rate of the tributary stream (~20 ft^3/sec)[12 15] finally moving to the Savannah River and the Ocean sink. The minimum flowrate of the Savannah River is 7500 ft^3/sec.[15]

As specified in 10 CFR 61,[16] the NRC land disposal Federal regulatory guide, the most important consequence of earthen trench burial of nuclear waste would be contamination of the groundwater below the burial site which eventually reaches a public drinking water supply. The criteria for protection of the groundwater, as specified in 10 CFR 61,[16] is dose to the critical organ, as a consequence of ingestion of water, of no greater than 25 mrem/person/yr (75 mrem, thyroid). Any hydrological transport analysis which projects Sr-90 concentration in contaminated water systems must be viewed in perspective to the NRC standard.

The environmental transport model for movement from buried waste, through the soil via percolating rain water, to the water system (groundwater, tributary, Savannah River and Ocean) is depicted graphically in Figure 1 with key input and output parameters for the hydrological transport equation also shown. A more generalized depiction — the "MOBILNUC" matrix — is presented in Appendix A as Figure A. A summary of input data for the calculation of hydrological transport of Sr-90 below the 195 acre burial ground which is necessary to project Sr-90 concentrations in contaminated water, and subsequent individual dose, is also presented in Appendix A, as Table A.

For calculation of groundwater contamination SRP meteorological data is utilized. The average annual rainfall rate at SRP between 1952 — 1978 was 120 cm/yr.[12 15] Average rainfall loss by runoff and evapotranspiration is a total of 80 cm/yr.[12] By difference, the average amount of rainwater penetrating the Barnwell formation by infiltration is 40 cm/yr. For the 195-acre burial ground, this corresponds to an infiltrating rainwater volume of 3.2×10^{11} mL/yr reaching the groundwater. This volume approximates the volume of water subject to contamination by leaching of radionuclides from buried waste and is used to calculate the contamination of groundwater by hydrological transport of Sr-90. Flow rates of a typical tributary stream (i.e., Four Mile Creek) and the Savannah River are 1.8×10^{13} mL/yr and 6.7×10^{15} mL/yr, respectively, and are used to calculate the potential contamination of those bodies of water.

For Sr-90 movement to the water table, the rate limiting step will be controlled by a combination of radioactive decay ($t_{1/2}$ = 29 years),[18] soil retention properties and leach rate from the waste form (the fraction of Sr-90 moving into the external environment from the waste source per unit time). Even though Sr-90 has an intermediate half-life, 1 Ci of Sr-90 would decay to 8400 µCi in 200 years and 10 µCi in 500 years, potentially significant levels from the viewpoint of contamination particularly in light of the buried waste inventory for Sr-90 of ~13,000 Ci. Soil retention, as reflected by Base Case distribution coefficient, is moderately high (average K_d = 160 corresponding to a transport rate relative to percolating rainwater of 0.1%). Leach rate, based upon earlier exhumation studies,[13] is 10^{-2} per year; probably the most tenuous data input to the transport equation. However, the same leach rate assumption has been used in all prior DOSTOMAN analyses.[1-7] Recent data from lysimeter studies indicate a leach rate of 10^{-3} to 10^{-4} is more likely.

The hydrological transport equation is in computer storage as JOSHUA DOSTOMAN MOBILNUC.

1.4.2.2 Contaminated Water/FOODCHAIN Analysis (NRC Methodology for Use of Contaminated Water for Crop Irrigation)

Assuming groundwater and outlying stream contamination does occur, is drinking water dose the most significant pathway to express the potential environmental and maximum exposed individual impact? Recent Environmental Impact Statements[15] have used only drinking water, recreation and fish consumption as pathways to exposure and well illustrate the relative importance of water consumption among those potential dose vectors.

The United States Nuclear Regulatory Commission has provided guidance on this subject. To evaluate the dose from ingestion of terrestrial foods potentially contaminated by radionuclides released to the hydrosphere, NRC Regulatory Guide 1.109[19] was evolved. Ingestion of contaminated foods is one of the potentially important modes of exposure that should be considered when assessing the dose to man from radionuclides released to the environment. Transport of radionuclides through terrestrial food chains is usually evaluated via computer models designed for situations where the concentrations of radionuclides in food products and environmental media are assumed to be in equilibrium.[20 21]

USNRC Regulatory Guide 1.109 provides such a methodology, and has been adopted in this analysis. By use of output from JOSHUA DOSTOMAN MOBILNUC (projection of transport of radionuclides via percolating rainwater resulting in contamination of the hydrological system) projections of Maximum Exposed Individual dose via foodchain pathways can be made. The approach is based upon the premise that contaminated water would be used as a source for irrigation of crops, leading to soil contamination within the vegetable crop root zone. Herbivores will consume the crops as forage and drink contaminated water. The Maximum Exposed Individual will, in turn, consume these contaminated food stuffs (milk, meat, vegetables, water) at "Reference Man"[22] annual consumption rates. This is a "worst case" situation and hence a conservative approach. For the hydrological system being modeled below the 600-Area Burial Ground, the following may be assumed:

- Groundwater contamination/Maximum Exposed Individual
- Tributary contamination/Individual at the site boundary
- Savannah River contamination/dose to a population using the Savannah River as a public drinking water supply.

Coupled with foodchain pathways, a five vector analysis can be made to assess the environmental impact of radionuclide migration from the 600-Area Shallow Land Burial facility. The foodchain methodology is illustrated in Appendix Figure B and a summary of input parameters and details of the calculation are presented in Appendix E.

The foodchain analysis requires nuclide- or element-specific factors for predicting concentrations in terrestrial foods from those in vegetation or soil. These include the following:

- B_{iJ}, the soil to plant concentration factor, the ratio of the concentration of an element in fresh vegetation to that in dry soil
- F_m, the transfer coefficient to cow's milk, the fraction of the element ingested daily by a foraging cow that is secreted in one liter of cow's milk
- F_f, the transfer coefficient to cow's meat, the fraction of the element ingested daily by the foraging herbivore that is transported to one kilogram of herbivore's muscle.

USNRC Regulatory Guide 1.109[19] provides a summary of elemental transfer factors for a large number of radionuclides associated with the nuclear fuel cycle. A recent review by Y. C. Ng,[23] who established much of the original data,[14 24 25] provides a useful update on this type of information.

In the absence of site specific data, the Regulatory Guide and updated values on transfer coefficients[23] have been used as input parameters for predicting concentrations in foods, and subsequent impact by ingestion of food stuffs by the Maximum Exposed Individual for the case of the use of contaminated surface water for irrigation. Appendix E gives a detailed example of a FOODCHAIN calculation for Sr-90. Figure 2 illustrates that drinking water consumption can make an important contribution to dose, but is not the most significant pathway among foodchain vectors for several radionuclides. Hence, in Maximum Exposed Individual Analysis, other foodchain pathways must be included for a comprehensive treatment of potential environmental impact of contaminated water in the hydrosphere.

1.4.2.3 Land Occupation Scenarios

1.4.2.3.1 HOMEFARM

Prior DOSTOMAN analyses[1-7] have been based exclusively on the limited population home farm scenario for the specified use of the burial ground as a four-adult agricultural site after burial ground decommissioning. The analytical basis of this analysis is well documented from prior work[1-8] and is in computer storage as JOSHUA DOSTOMAN HOMEFARM. This is a multiple pathway analysis in which direct vegetative root penetration into shallow land buried waste is a key pathway to exposure. Direct root penetration and plant uptake are in competition with numerous other pathways (Appendix C). For Sr-90, the transfer coefficients of each pathway leading to Man's GI intake is illustrated in Figure 3, based upon the prior work of Wilhite[4,8] and Root, et al.,[7] on "Reference Man" consumption rates.[22] The relative magnitude of these GI transfer coefficients would suggest that crop and animal ingestion rates (the GI transfer coefficients) would overwhelm other pathways (i.e., recreation, water consumption, and intrusion) in contribution to individual dose.

Coupled with JOSHUA DOSTOMAN HOMEFARM projections from the Sr-90 Base Case (Root, et al.[7]), the significance of vegetative pathways to dose is illustrated in Figure 4, presented as Sr-90 intake to Man's GI tract as a function of pathway. The logarithmic scale helps to illustrate that fruit and vegetable consumption (contaminated due to root penetration of buried waste) far outweigh other pathways in the HOMEFARM scenario. The Maximum Exposed Individual dose to bone was projected[7] to be 800 mrem/person (annual dose commitment) and 15 rem/person for continuous land occupation after 100 year institutional control.

1.4.2.3.2 COMMFARM

JOSHUA DOSTOMAN COMMFARM (schematic: Appendix D) is an extension of HOMEFARM to apply the land occupation analysis to larger population groups. It is assumed that the burial ground would be used, after institutional control, as a corn production plot with distribution of the product to a population large enough to consume the produce (~3000). The pathways of significance are hydrological movement downward to deep soil in competition with plant root penetration of waste and subsequent plant uptake. Root distribution and plant uptake factors for Sr-90 are the same as HOMEFARM base case projections[7] and NRC data[14]. South Carolina Crop Statistics[28] provide basic input on corn productivity for the Aiken/Barnwell county regions of South Carolina.

1.4.3 The Code of Federal Regulations Criteria

Numerous government standards exist for limits on exposure of individuals to the harmful effects of ionizing radiation. These criteria are as diverse as the exposure scenarios being considered for analysis of the health risk of shallow land burial of Sr-90. Hence, the criteria applicable to a given scenario will be dependent upon the primary pathways to dose under consideration in scenario analysis. For example, in MOBILNUC/contaminated water analysis, the only pathway applicable is drinking water dose. However, since we are analyzing the situation of shallow land burial of nuclear waste in the nuclear fuel cycle, two standards are conceivably meaningful:

- The land disposal standard[16]
- The fuel cycle standard[29]

In addition, since intrusion into the groundwater for drinking water consumption could be considered a "Maximum Exposed Individual" exposure situation, the "intruder" aspects of 10 CFR 61[16] could also be interpreted as applicable. Generally, model projections of dose should be compared against the lowest dose criteria of any applicable standard.

A summary of applicable standards for each scenario are presented in Table 2. The graphical presentation of results will also illustrate applicable CFR criteria.

1.4.4 The Concept of the Probability of a Scenario

Based upon published NRC waste management objectives and philosophy,[30] environmental impact assessment of shallow land burial facilities by transport model scenario analysis has an element of "probability" associated with the scenario to be examined. For example, in our own SRL experience, prior analyses[1-7] and attempts at drawing conclusions and recommendations on burial ground performance have depended exclusively on the small population land occupation scenario. This is a worst case, highly improbable event, since it assumes that institutional control of the only nuclear materials production facility in the U.S. would be lost at some time in the distant future, with subsequent occupation of the site by the public for agricultural use productive to the public. In addition, use of the site as a burial ground has altered the soil properties to a poor agricultural medium (i.e., the surface soil is now subsurface and vice-versa). However, the probability of radionuclide movement and groundwater/tributary stream contamination, with individuals at the plant boundary or beyond consuming contaminated water, is significantly greater. This holds true because the latter situation:

- is not site control related
- is not land use dependent
- has occurred, as exemplified by tritium movement.[31]

Hence, the probability of nuclide hydrological transport and groundwater contamination, as exemplified by MOBILNUC projections, is greater than nuclide uptake via land occupation analysis, as exemplified by HOMEFARM. Therefore, model projections by way of scenario analysis must be weighted accordingly.

A quantitative statement on the probability of an event is generally a subjective exercise, but guidelines for probability projections have been provided by Cohen.[30] Using Cohen methodology and suggestions, the four scenarios have been weighted with a probability of occurrence factor as follows:

• MOBILNUC	1000
• MOBILNUC/FOODCHAIN	100
• HOMEFARM	1
• COMMFARM	1

In the discussion to follow, the scenario analyses will be presented on an unweighted and weighted basis. The weighted basis analysis will be presented on a relative scale: relative to the land occupation cases as a "probability" of one.

1.5 RESULTS AND DISCUSSION OF MODEL PROJECTIONS

1.5.1 Results as a Function of Scenario

1.5.1.1 Compendium

Based upon the discussion of the DOSTOMAN Transport Equations as presented in Section 1.4.2, Sr-90 in shallow land burial has been examined via four transport equations indicative of each scenario:

- Contamination of the hydrological system/drinking water dose.
- Hydrological system contamination/crop irrigation using contaminated water/FOODCHAIN dose.
- Land occupation by a family of four adults with use of the burial ground for agricultural purposes with subsequent dose via crop and animal consumption.
- Land occupation for site-wide agricultural purposes with distribution of the product to a large regional adult population with subsequent dose via consumption of contaminated crops.

Results for the four scenarios are summarized in Figure 5 using Sr-90 Base Case model parameters,[7] where applicable. Also shown in Figure 5 are the model scenario projections weighted for the probability of the event, as discussed in Section 1.4.4. Each scenario will be discussed in detail, with key parameter sensitivity illustrations, in the subsections to follow. The results of Figure 5 imply the "HOMEFARM" land occupation case projects to the highest dose consequence to an individual. This is the worst case situation, even when adjusted for event probability. As discussed in Section 1.4.2.3, the primary pathway leading to dose in this case is root penetration of buried waste due to shallow land trench depth in the current burial ground. These model results clearly mandate that control of site vegetation over the burial ground is a necessary management practice for SRP low-level waste burial operations.

The results of Figure 5 also illustrate that the more highly probable events — the groundwater contamination scenarios — project to dose consequences which are several orders of magnitude below the most stringent government regulations.

Detailed results on each scenario will be presented in the following sections.

1.5.1.2 Transport Projections to the Groundwater System (No Site Occupancy; Influence on Drinking Water Supplies)

The results for Sr-90 movement to the hydrological system contiguous to the 600-Area burial ground are summarized in Table 3, as a function of distribution coefficient. For an average literature K_d of 160, soil adhesion is extremely high, requiring long time periods (>300 years) for ultra low levels (<1 pCi/yr) of Sr-90 to reach the groundwater. Hence, high soil adhesion, coupled with radioactive decay, results in very low levels of Sr-90 projected to reach the groundwater, Four Mile Creek, or the Savannah River, with an upper limit of water contamination of $<10^{-15}$ µCi/mL, a factor of 10^6 less than the Drinking Water Standard (8.0×10^{-9} µCi/mL).[17] For a Maximum Exposed Individual consuming groundwater from a burial ground well at "Reference Man" annual consumption rates of 730 L/yr,[22] the dose-to-bone, the critical organ for Sr-90, is $<10^{-4}$ mrem/person (50-year dose commitment).

The worst case assumption of localized mobility due to factors such as:

- lower soil pH and
- water soluble complexing agents (ligands)

were also modeled. Both factors have previously been reported[10 32] to lower Sr-90 distribution coefficient. Hence, K_d was varied as input to the transport equation from a value of 50 (Sr-90 movement: 0.3% of percolating rainwater; 0.5% of groundwater velocity) to as low as K_d = 1.0 (extreme case: Sr-90 movement ~14% of percolating rainwater and ~20% of groundwater rate). The value of 50 for Sr-90 distribution coefficient is also consistent with SRP site specific measurements on burial ground soil with trench/well water samples as reported by J. P. Ryan.[32 33] Results for hydrological transport of Sr-90 under these exteme cases of low soil adhesion are also summarized in Table 3, and illustrated in Figure 6, assuming the entire decayed Sr-90 inventory of 13,000 Ci [COBRA records plus Technical Standard rate of 500 Ci/yr through the year 2000] were subject to low soil adhesion conditions.

For K_d = 50, soil adhesion and radioactive decay still predominate to control Sr-90 levels projected to reach the groundwater system. Groundwater contamination is $<3 \times 10^{-13}$ µCi/mL, 10^4 less than the Federal standard.[17] Hence, drinking water dose to the Maximum Exposed Individual is still extremely low at $<2 \times 10^{-5}$ mrem/person.

For $K_d = 50$, soil adhesion and radioactive decay still predominate to control Sr-90 levels projected to reach the groundwater system. Groundwater contamination is $<3 \times 10^{-13}$ μCi/mL, 10^4 less than the Federal standard.[17] Hence, drinking water dose to the Maximum Exposed Individual is still extremely low at $<2 \times 10^{-3}$ mrem/person.

Only in the <u>extreme case</u> of maximum Sr-90 mobility (K_d = 1.0) does water contamination slightly exceed Federal guidelines. Groundwater concentrations were projected, under this situation, be $<1 \times 10^{-8}$ μCi/mL. The Sr-90 bone dose for the drinking water pathway is 6.0 mrem/person. Due to dilution, Four Mile Creek and Savannah River contamination levels are projected to be well below Federal guidelines, particularly as soil adhesion increases.

In all cases examined by the MOBILNUC transport equation, projected water contamination never exceeds the Federal regulatory occupational guide (10 CFR 20)[27 34] of 3.0×10^{-7} μCi Sr-90/mL (2.1 rem/person for drinking water dose).

Projections on hydrological transport of Sr-90 as a function of soil adhesion, along with dose consequence (Figure 6) illustrate another principle generic to intermediate-lived radionuclides. As soil adhesion of Sr-90 increases, a time delay to reach tributary and/or the Savannah River enters into the calculation. This fact, coupled with inherent radioactive decay, causes the <u>relative relationship between groundwater and tributary contamination</u> to change. Hence, soil in the unsaturated zone retards the migration of Sr-90. This retardation increases with increasing K_d, resulting in a lower Sr-90 flux (Ci/yr) to other parts of the hydrological system. Coupled with decay, the extend of outlying stream contamination (and dose) <u>decreases</u> as soil adhesion increases.

For the population of 70,000 residing on the Savannah River (near Savannah, GA) which utilizes river water as a drinking water supply,[12 15] the <u>maximum</u> population dose commitment would be 2.1×10^{-1} man-rem to the critical organ (bone). The average background radiation effect to the same population would be 7.0×10^3 man-rem. The maximum population dose is based upon an upper limit of Savannah River contamination of 5×10^{-13} μCi/ml.

. Hence, based upon JOSHUA DOSTOMAN MOBILNUC projections of Sr-90 contamination of the hydrological sysem below and continguous to the 600-Area burial ground, the dose consequence to the

- Maximum Exposed Individual (Groundwater)
- Individual at the site boundary (Four Mile Creek)
- Population (Savannah River)

is minor relative to Federal regulatory guidelines and background radiation.

1.5.1.3 Contaminated Water/FOODCHAIN Analysis (NRC Methodology for Use of Contaminated Water For Crop Irrigation)

1.5.1.3.1 FOODCHAIN Dose Projections for Sr-90 in Shallow Land Burial

Using JOSHUA DOSTOMAN MOBILNUC projections (Table 3, and Figure 6) as input, estimates of the dose consequence of ingestion of Sr-90 in foodstuffs, contaminated by use of Sr-90 containing surface water for crop irrigation, have been made and are summarized in Figure 7, for the case of relatively mobile Sr-90 (soil adhesion K_d = 50) moving to the groundwater and outlying streams. This case was chosen as an extreme situation with the total Sr-90 burial ground inventory (13,000 Ci) subject to a higher mobility than most site specific K_d's would imply,[10 32 33] and hence is another conservative calculation.

The total five-vector FOODCHAIN dose-to-bone increases an order of magnitude to 3×10^{-2} mrem/person, relative to the drinking water dose (2×10^{-3} mrem/person, Figure 6), primarily by consumption of crops grown in contaminated soil. Details of the FOODCHAIN results are given in Appendix E. The total FOODCHAIN dose is still inconsequential relative to the 10 CFR 61 land disposal standard of 25 mrem/person.[16 29] However, the results well illustrate that other food chain vectors should be accounted for in Maximum Exposed Individual analyses.

This calculation considered the potential movement of the <u>entire</u> Sr-90 inventory in shallow land burial under <u>higher</u> mobility conditions than generally reflected by site-specific measurements. With contaminated water projections applied to a five vector food chain analysis (by established USNRC methodology), the projections on dose effect of Sr-90 to the critical organ (bone) were well within Federal regulatory guidelines.

Assuming the drinking water population of 70,000 near Savannah, Ga. utilized Sr-90 contaminated river water as a source for localized crop irrigation and obtained all foodstuffs locally from crops, herbivores, and fish subjected to Sr-90 water contamination (NRC 1.109 Regulatory Guide Methodology[19]), the population dose commitment would be 0.5 man-rem to the whole body and 2.1 man-rem to bone. The background radiation dose to the same population would be 7.0×10^3 man-rem. The expected number of additional health effects due to whole body population exposure is 0.00023 per year (i.e., a small fraction of one health effect per year). Appendix E also provides the details on the Sr-90 FOODCHAIN/health effects calculation.

Hence, MOBILNUC/FOODCHAIN projections on Sr-90 movement into the biosphere from shallow land burial imply minor dose consequence to the Maximum Exposed Individual and the population at risk.

1.5.1.4 Land Occupation Scenarios

Based upon Sr-90 base case assumptions (Table 1), as summarized by Root, et al.,[7] the Maximum Exposed Individual dose to bone was projected to be 800 mrem/person (annual dose commitment), in excess of the 10 CFR 20 criteria of 500 mrem/person. The cumulative dose for year after year site occupancy was considerably higher at 15 rem per person.[7] This is a consequence of vegetative root penetration of buried waste in shallow trenches as the most significant vector for Sr-90 transport (Figure 4) under direct burial site occupation conditions.

1.5.1.4.1 HOMEFARM — Sr-90 Dose Projections as a Function of Sr-90 Inventory in Buried Waste

The prior analyses[7] were based upon the assumption that current inventories of Sr-90 in buried waste (9000 decayed curies through 1981 based on COBRA records) would be supplemented each year at SRP Technical Standard[12] burial rates (500 Ci/yr) through the year 2000, to give rise to a total decayed Sr-90 inventory of 13,000 Ci. At this point in time, the shallow land burial facility would be closed due to lack of additional burial space and institutional control (100 years) would become operative. The conservative HOMEFARM dose projections suggest the current Sr-90 Technical Standard limits to be on the high side.

The recent five-year history of fission product disposal by shallow land burial at SRP has been at the rate of <1100 Ci/yr (COBRA records), 2% of that inventory being Sr-90. This corresponds to a five-year historical rate of <25 Ci/yr for Sr-90. If this historical rate of disposal is, in fact, maintained through the year 2000; the total Sr-90 decayed inventory would be reduced by a factor of two, to 6000 Ci. The consequence of this source term reduction, as projected by JOSHUA DOSTOMAN HOMEFARM, is illustrated in Figures 8 (GI Intake), 9 (One-Year-Dose Commitment) and 10 (50-Year-Dose Commitment) as a function of projected Sr-90 inventory in shallow land burial in the year 2000.

The COBRA plus five-year historical rate of disposal inventory (6000 Ci) would project to a Sr-90 bone dose to an individual of 370 mrem/person/year (annual dose commitment), within 10 CFR 20 guidelines.[27] Other projected burial rates are also shown and illustrate that burial rates less than the current Technical Standard are required to meet annual dose criteria.

Based upon the highly conservative HOMEFARM scenario, the Sr-90 burial rate and Technical Standard could be revised to 150 Ci/yr. This is still reasonable relative to the recent five-year history of Sr-90 disposal in earthen trenches.

The dose commitment results (Figures 9 and 10) also illustrate another principle of great importance. The 10 CFR 20 standard of 500 mrem must be interpreted as an upper dose limit per person per year (i.e., acceptable dose for one year of exposure). This is particularly important for Sr-90 with long biological half-life and retention in bone ($t_{1/2}$ = 18,000 days or 49.3 years).[18] To illustrate, if an individual ingests a quantity of Sr-90 into the GI tract of 1.5×10^{-6} Ci, the bone dose in the first year is 500 mrem/person $[(1.5 \times 10^{-6}$ Ci/p)(330 mrem/μCi)[14] = 500 mrem/p], but the lifetime effect as reflected by the 50-year dose commitment is 11.4 rem/p [1.5 μCi (7580 mrem/μCi)[14] = 11.4 rem/p]. 1.5 μCi/person ingestion rates are typical of the levels projected by HOMEFARM calculations for Sr-90 in the 600-Area burial ground (Figure 8). If the 10 CFR 20 standard of 500 mrem is, in fact, a lifetime dose criteria, then current COBRA inventories would project to individual doses of 7.6 rem/person (Figure 10), well in excess of the 10 CFR 20 criteria. This implies that Sr-90 in shallow land burial would have to be managed by factors other than annual burial rate limits (i.e., overburden, institutional control, etc.).

Generally, the 500 mrem/person standard is interpreted[14,30] as an annual dose commitment or annual dose limit to be applied to annual dose calculations. The annomally arises in that much documentation exists[35-37] in which <u>lifetime effect calculations</u> are analyzed against <u>annual dose criteria</u>.

1.5.1.4.2 COMMFARM — Sr-90 Dose Projections to a Large Adult Population

Use of the extended populations commercial farm scenario for the plausible land use of the 195-acre burial ground as a corn production farm with product distribution to a population of 3000 results in a population dose commitment of 1800 man-rem. The average background radiation dose to the same population would be 300 man-rem. The 10 CFR 20 maximum exposed individual limit to the same population would be 1500 man-rem. The affected population dose is based on the use of the entire burial site as a commercial farm with productivity and product distribution based upon regional information on South Carolina crop statistics.[28] The commercial farm utilizes groundwater for site irrigation. Transfer factors accounting for crop decay, harvest dust and harvest litter were included. Workers on the site were exposed to possible contamination by inhalation of dust and soil and consumption of irrigation water. The upper limit of worker exposure was 3×10^{-3} mrem/worker/year, mostly due to water consumption (70%). The population at risk receives a dose as a consequence of crop contamination from soil and the assumption of root penetration of buried waste.

1.5.2 Scenario Results as a Function of Dosimetry Data Base

NUREG 0172[18] has historically provided the dosimetry data base for calculation of dose-to-man from model projections of nuclide curie intake to man's gastrointestinal tract (ingestion pathways). In the course of this work, two updates on the basic dosimetry models, published in ICRP II,[38 39] were made available:

1. A NUREG 0172 update by Hoenes and Soldat[40] based on improved model formulation and upgrading of metabolic parameters. The Sr-90 dose commitment factor increased 15% with this new formulation.

2. ICRP 30,[41] an entirely new dosimetry model extending the basic ICRP II formulation to include organ-organ interactions as well as incorporating the extensive literature on nuclide physiology in man, since the inception of ICRP II. The Sr-90 dose commitment factors decrease ~30% by the ICRP 30 formulation.

A more extensive analysis of ICRP 30 relative to other dosimetry models is available in the literature.[42]

The effect of dosimetry data base on the Sr-90 scenario results is presented in Figure 11. If ICRP 30 becomes widely accepted, the worst case DOSTOMAN HOMEFARM projected dose is less than the most liberal standard (10 CFR 20), but still greater than land disposal or nuclear fuel cycle criteria.

1.5.3 Land Occupation Results as a Function of Key Model Parameters

The land occupation cases have been shown to be the most conservative or worst case situations among plausible burial ground scenarios. Prior sensitivity analysis[1 43] by Plackett-Burman statistical methods[44] have illustrated numerous model parameters to play a principal role in influencing model dose projections. From the standpoint of Sr-90 HOMEFARM projections, those input parameters most subject to uncertainty or model user's choice are summarized in Table 4. These are also model parameters not necessarily subject to SLB management practices. They include:

- **Sr-90 Source Term.** Subject to available records and assumptions on future disposal rates.

- **Waste to Soil Leach Rates.** Subject to available experimental data and rainwater percolation rates.

- **Crop Uptake Factors.** Subject to vegetative choice in the scenario and available literature or site-specific data.

- **Groundwater Velocity.** Subject to available site-specific measurements or observations on outcropping of tracer elements.

- **Vegetative Root Distribution.** Subject to choice of vegetation in the scenario and available literature data on root penetration with depth.

- **Soil Adhesion Distribution Coefficients.** Subject to nuclide-specific literature data or site-specific measurements for nuclides of interest.

Table 4 summarizes the range of the above parameters which have been input to the worst case HOMEFARM calculations for the purpose of a parametric sensitivity analysis. The rationale and/or available literature references for selection of parameter values are also given.

Sr-90 source term has been previously discussed (Section 1.5.1.4) and is included herein to illustrate its importance relative to other parameters.

Buried waste to soil nuclide leach rate, or release rate, is a key parameter input to the transport equation since it reflects the "triggering mechanism" leading to nuclide environmental movement and is most subject to uncertainty, unless valid nuclide-specific, waste-specific, site-specific data are available. The waste lysimeter programs[49] will, in part, provide useful data on nuclide release rates. To date, specific Sr-90 data are not yet available from this program but data on other nuclides suggest rates of $<10^{-4}$/Yr. Consequently, the SRP data on equipment exhumation[13] has been commonly used in prior DOSTOMAN HOMEFARM analyses[1-7] and has been used in the Sr-90 Base Case projections.[7] Based on the work of Rogers,[46] the Base Case value (10^{-2}/yr) is conservative. A less conservative value (10^{-5}/yr) has been examined, again based upon the Rogers[46] evaluation.

For the key pathway of vegetative uptake, three values on the Sr-90 in corn plant/soil concentration factors are listed:

- The Root, et al. Base Case[7] references point input which was based upon NRC[14] values for 12 species of vegetables.
- Recent SRP site specific measurements[47] on uptake of Sr-90 by corn grown over the 600-Area burial trenches.
- The NRC data base on Sr-90 uptake by corn[19] used in Regulatory Guide 1.109, recently updated by Y. C. Ng.[23]

This provides a significant range on corn uptake factors which may have an influence on dose projections, in light of the importance of this pathway (Figure 4, Section 1.4.2.3).

Groundwater flow rates are quite subject to controversy since the historical result — 40ft/yr — as documented in the EIS on Waste Management Operations,[12] is not in agreement with recent measurements on the outcrop of tritium,[31] which migrates at the same rate as groundwater. Hence, a value of 80ft/yr (12.5 years to move a distance of 1000 feet) has also been used to illustrate the influence on HOMEFARM projections.

Vegetative crop root distribution with depth enters into the DOSTOMAN approach[4,8] since the land occupation scenarios assume growth of crops over the shallow land burial earthen trenches with potential for root penetration of the buried waste. This, of course, is subject to the type of crop chosen in the scenario. Corn was originally selected[4,8] because of its ability for deep penetration[4,8] and propensity for nuclide uptake.[14] A second crop — snap beans — native to the area,[28] with shallow root penetration,[48] and modest Sr-90 concentration factors[14,23] is used in the HOMEFARM calculation to illustrate the differences in model projections.

Sr-90 soil adhesion properties, as reflected by the soil to water distribution coefficient, become particularly important for short-lived Sr-90,[6,52] as illustrated in Figure 12. The Sr-90 Base Case value of 160 (literature average) is a reflection of relatively high soil adhesion with long travel time to the groundwater, relative to Sr-90 half-life. However, as the values decrease, the potential for movement to the groundwater increases. This was particularly emphasized in the analysis of hydrological transport via MOBILNUC projections (Section 1.5.1.2). The value of 50 for K_d in the secondary HOMEFARM calculation was selected based upon recent site-specific measurements of J. Ryan[33] for trench/well water measurements with SRP soil. This is believed to reflect a <u>localized</u> low K_d situation characteristic of the localized chemical properties of the water used in the measurements — not a site-wide characteristic. However, the value is used in place of the Sr-90 Base Case input[7] to illustrate the influence on HOMEFARM projections.

A summary of parameter sensitivity in the HOMEFARM scenario is presented in Figure 13. For each parameter, the first "bar" represents the Sr-90 Base Case.[7] The additional data represent the effect on the Sr-90 Base Case for a change in the parameter as input to the model. Waste to soil leach rate and model user's choice of vegetative crop in the scenario are the most significant factors influencing dose projections. The most controversial input — groundwater flow rate — has little influence in HOMEFARM since the model projects that soil retention in the unsaturated zone will predominate and permit root penetration of waste to remain as the critical pathway for Sr-90 intake by man. Model projections relative to the CFR standards are also illustrated.

A very interesting example of choice of scenario "conservatism" can also be examined. The Sr-90 Base Case[7] has been frequently referred to as a "worst case" calculation since much of the input data reflects conservative conditions:

- maximum Sr-90 inventory
- high release rate
- direct land occupation
- maximum root penetration
- maximum plant uptake factors.

To illustrate the opposing point of view — the "least conservative" assumptions within the same scenario — model input was modified to reflect:

- Inventory based on five-year historical rate (5800 Ci)
- Lower leachrate (10^{-5}/yr)[46]
- Minimum root penetration with depth (snap beans)[48]
- Low plant uptake factors (3×10^{-2})[23]
- Outcrop-based ground water flow rates (80 ft/yr)[31]
- Lower soil adhesion ($K_d = 50$)[33] favoring movement away from the zone of root penetration

The results (Figure 14) well illustrate the influence of model user's choice of "degree of conservative input" to the calculation, with a dose estimate of 6 mrem/person/Yr for the least conservative case. The results are also weighted for the "probability" of the event as discussed in Section 1.4.4.

1.5.4 HOMEFARM Results as a Function of Burial Ground Management Practices

Some of the input to the transport equation includes factors which are not physical data or physical property related and, hence, are referred to as "burial ground management practices or options." These are factors which will frequently influence burial ground operating costs if implemented (generally increase costs). Hence, they can be evaluated relative to the environmental incentive for such implementation (i.e., a cost versus benefit analysis) Several management options have been examined in analysis of Sr-90 in SLB to illustrate the potential environmental incentive, as projected by DOSTOMAN calculations.

They include:

- **Sr-90 Inventory.** Subject to management decisions on future burial limits as reflected by SRP technical standards.
- **Institutional Control Period.** Subject to management decisions on site scrutiny after burial ground decommissioning.
- **Site Overburden.** Subject to management decisions on decommissioning steps necessary to "protect the public".
- **Burial Trench Depth.** Although fixed for current operations, subject to management decisions on burial ground operations prior to site closure. Also, an important factor for future SRP burial sites.

Sr-90 source term has been previously discussed (Section 1.5.1.4) and is included herein to illustrate its relationship to other management options.

Institutional control period reflects the time over which management will maintain site scrutiny prior to so-called "use by the public." 10 CFR 61,[16] the NRC Land Disposal Standard, recommends 100 years. This is an important control factor since the extent of nuclide radioactive decay is influenced by this management alternative.

Burial ground overburden — currently four feet[12] — is a distinct managerial option since it reflects a decision to be considered, generally after site closure, as a step possibly necessary for continued protection of the public. It is generally a reflection of a decision as a result of an environmental impact analysis — dictating a critical pathway for potential exposure of an individual. Such is the case in this report.

Burial ground trench depth — currently 4-20 ft[12] — must always be considered in relation to groundwater levels, particularly with shallow water tables at SRP. Since the 600-Area burial ground site closure is ~10 years in the future (point at which the burial ground area is full), trench depth remains a factor for management scrutiny — subject to environmental incentive versus operating costs of deeper burial. Trench depth becomes a most important factor for consideration of future burial sites at SRP. The Greater Confinement Disposal programs at SRL[50] and other DOE sites[37] reflect this option.

A summary of results of Sr-90 DOSTOMAN HOMEFARM projections as a function of burial ground management options is presented in Figure 15. Institutional control becomes important due to the Sr-90 decay factor. Overburden (15 ft.) and trench depth (15-30 ft) both reflect the critical pathway leading to Sr-90 dose: root penetration of buried waste. All of these options have a greater influence in controlling dose, relative to inventory management.

The management option calculations illustrate:

- The flexibility of the model
- The burial ground management practices which should receive attention prior to site closure.
- The greater confinement disposal options of importance for proposed new low-level waste burial sites.

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TABLE 1

Sr-90 Key Base Case Model Parameters[7]

Parameter	Value	Basis or Reference
Source Term	13,000 Ci	COBRA + 500 Ci/Yr thru the year 2000
Soil Adhesion, K_d	160	Average of literature data, (9-11)
Unsaturated Zone Percolation Rate	7ft/yr	(3-8, 12)
Groundwater Flow Rate	40ft/yr	(3-8, 12)
Sr-90 Release Rate	10^{-2}/yr	(3-8, 12)
Unsaturated Soil Porosity	0.5	(3-8, 12)
Unsaturated Soil Bulk Density	3.2	(3-8, 12)
Crop Uptake Factor	0.5	Average of NRC data, (14)
Fruit Tree Uptake Factor	0.2	Average of NRC data, (14)
Grass Update Factor	0.6	NRC, (14)
Groundwater Soil Porosity	0.5	(3-18, 12)
Groundwater Soil Bulk Density	2.0	(3-8, 12)
Crop/Root Distribution	Corn	(3-8)

TABLE 2

Code of Federal Regulations Criteria

Scenario	Limiting CFR Standard	Limit mrem/P	Reference
Contaminated Water	Drinking Water	4-25	16,17
Contaminated Water/Foodchain	Fuel Cycle	25	29
	Land Disposal	25	16
HOMEFARM	10 CFR 20/Public	500	27
	NRC Land Disposal/ Intruder	500	16
COMMFARM	10 CFR 20/Public	500	27
——	Background Radiation	100-200	12,15

TABLE 3

Sr-90 Hydrological Transport Projections*

$MPC)_W$ 10 CFR 20 — 3.0×10^{-7} μCi/mL**

$AAC)_W$ EPA — 8.0×10^{-9} μCi/mL***

K_d	Stream	Conc(μCi/ml)	Drinking Water Dose (mrem/p/yr) Whole Body	Bone
160	Gd Water	$<10^{-15}$	$<10^{-5}$	$<10^{-4}$
	4MC	$<10^{-22}$	$<10^{-12}$	$<10^{-12}$
	Sav R	$<10^{-25}$	$<10^{-14}$	$<10^{-13}$
50	Gd Water	3×10^{-13}	4×10^{-4}	2×10^{-3}
	4MC	1×10^{-20}	2×10^{-11}	7×10^{-11}
	Sav R	3×10^{-23}	5×10^{-13}	2×10^{-12}
1	Gd Water	1×10^{-8}	1×10^{0}	6×10^{0}
	4 MC	2×10^{-10}	3×10^{-1}	1×10^{0}
	Sav R	5×10^{-13}	7×10^{-4}	3×10^{-3}

* MOBILNUC Transport Equation (Appendix Figure A)

** 10 CFR 20, Federal Occupational Guide for "Standards for Protection Against Radiation" and "Concentration in Air and Water Above Natural Background" as updated in 25 FR 10914 Aug. 1, 1980.

*** EPA-570/9-76-003 National Interim Primary Drinking Water Regulations

TABLE 4

Variation of HOMEFARM Model Parameters

Parameter	Valve	Basis or Reference
• Sr-90 Source Term	13,000 Ci 8,000 Ci 5,800 Ci	COBRA + Tech Stds COBRA + Recommended Limit COBRA + 5-yr History
• Waste to Soil Leach Rate	10^{-2}/Yr 10^{-5}/Yr	Holcomb (13) Vern Rogers (46);(52)
• Crop Uptake Factor	0.50	Root, et al. (7) NRC Average (14)
	0.15	SRP Site Specific (47)
	0.035	NRC Reg. Guide (19) Y. Ng (23)
• Groundwater Velocity	40ft/yr	ERDA-1537 (12)
	80ft/yr	Update Based on Observed Outcrop (31)
• Crop Root Distribution	Corn Snap Beans	Wilhite (4, 8) (48)
• Soil Adhesion Distribution Coeff	K_d = 160 K_d = 30	Root, et al. (7) J. Ryan (32,33) W. Prout (10) Inoue (45)

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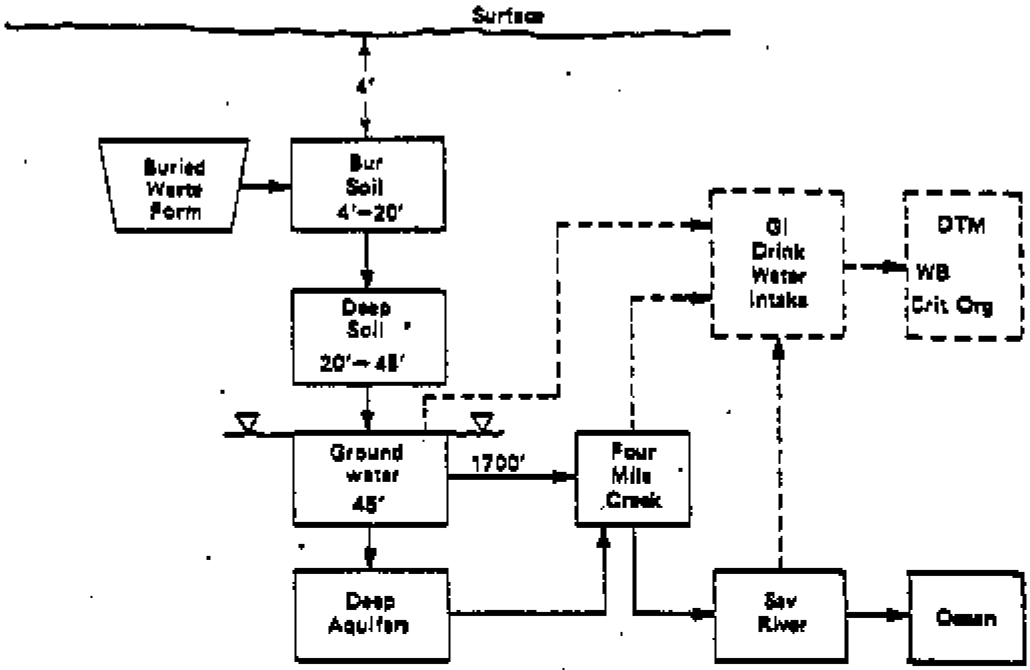


INPUT

Meteorology
- Average Annual Rainfall
- Runoff
- Evapotranspiration
- Percolating Rainwater Rate

General
- Nuclide Decay Constant
- Nuclide Leach Rate
- Source Term
- Distribution Coefficient
- Rate Rel to Percolating Rainwater
- Rate Rel to Ground Water
- Soil Density
- Soil Porosity & Permeability
- Hydraulic Conductivity
- Hydrostatic Gradient

Flowrates
- Ground Water
- Tributary
- Sav River
- Rainfall — Ground Water

Dosimetry Data
- Whole Body
- Critical Organs
- Drink Water Consumption Rate

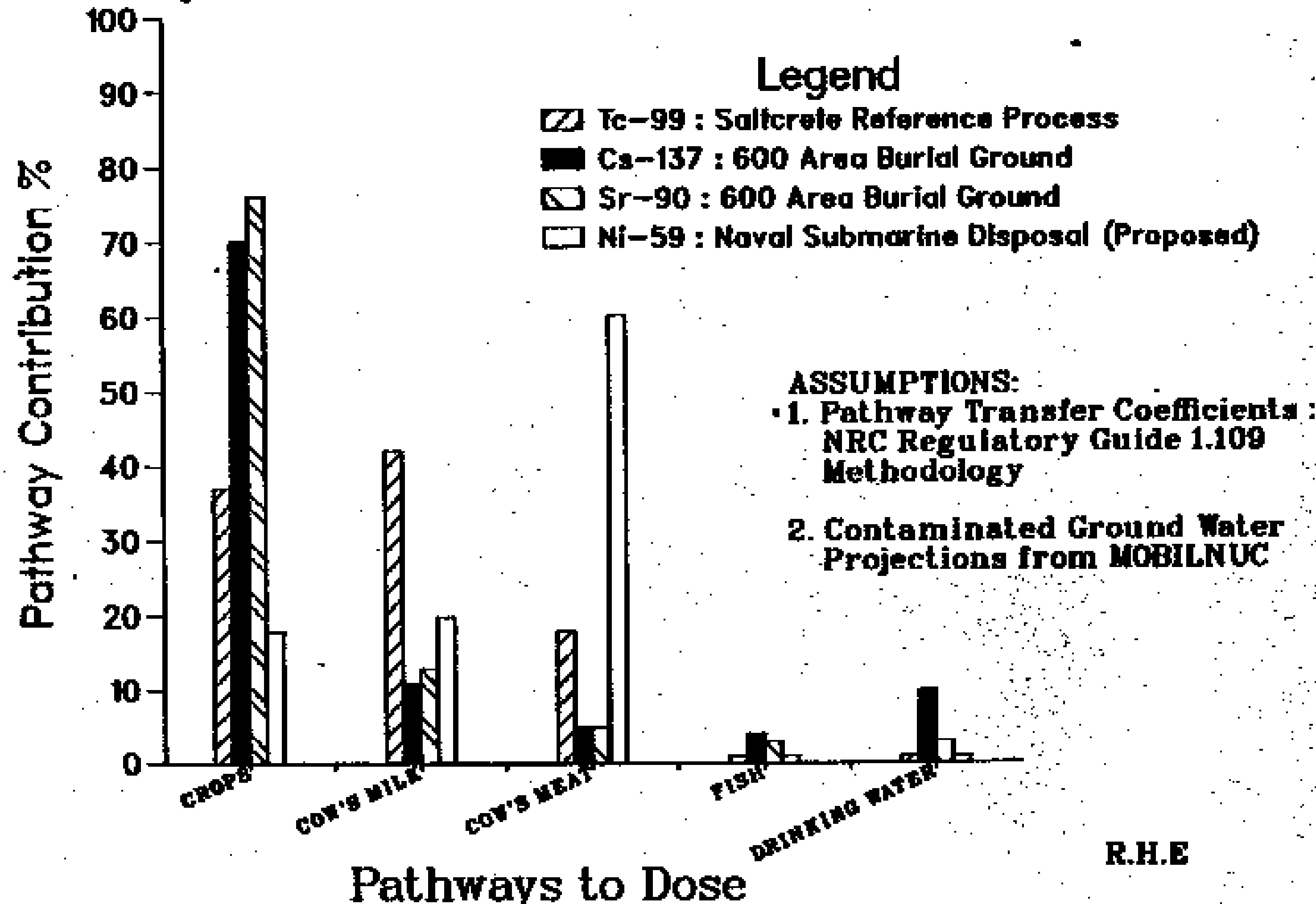
Dimensions
- Site Area
- Landfill — Ground Water
- Ground Water — Tributary

OUTPUT
- Nuclide Hydrological Flux (Ci/Yr)
- Material Balance
- Drinking Water Concentrations
- Intake to GI by Consumption of Drinking Water
- Dose to:
  - Whole Body
  - Critical Organs

FIGURE 1

600 Area Burial Ground/Hydrological Transport Diagram

Figure 2
FOODCHAIN Pathways
Pathway Contribution as a Function of Radionuclide



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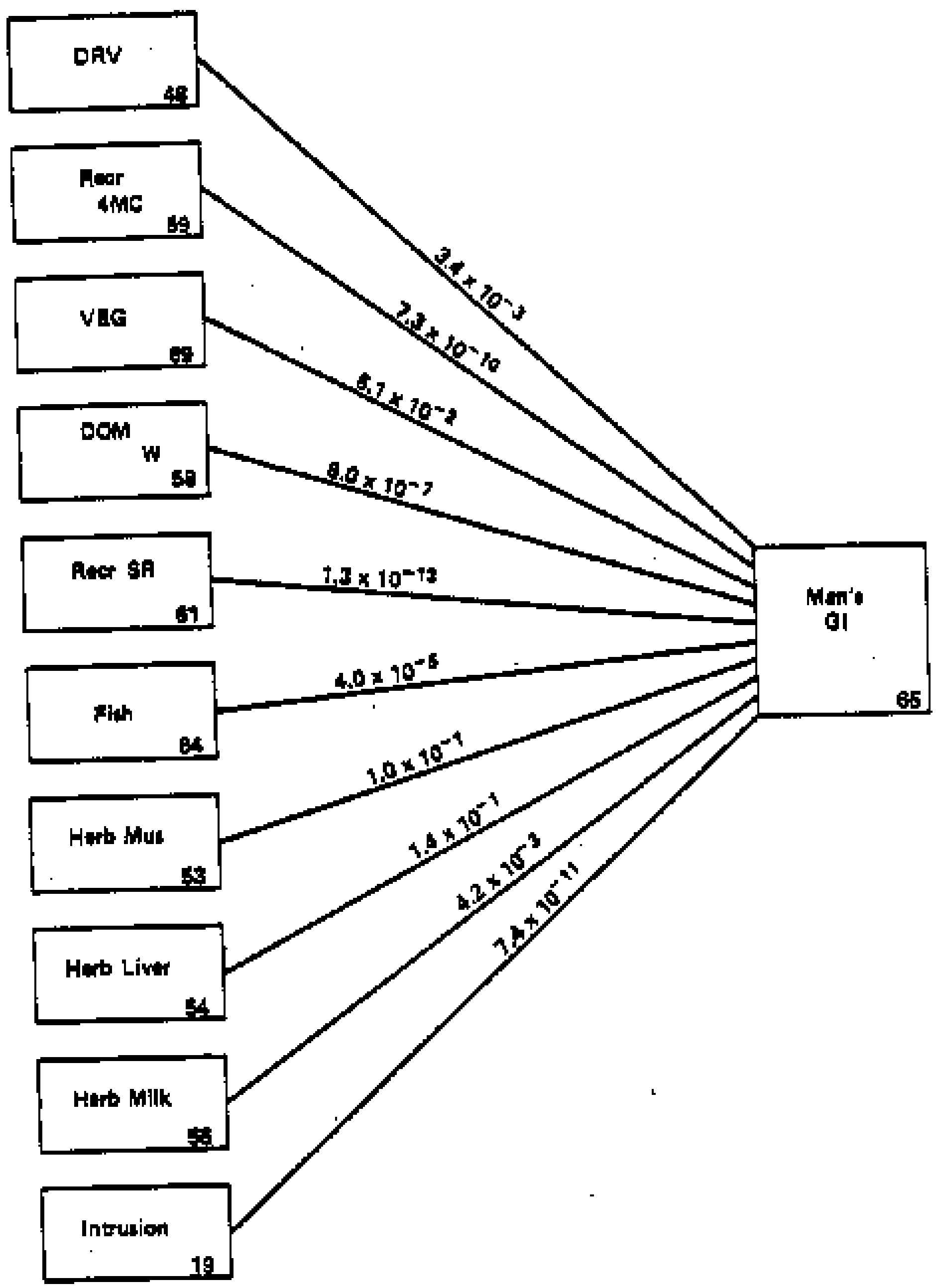
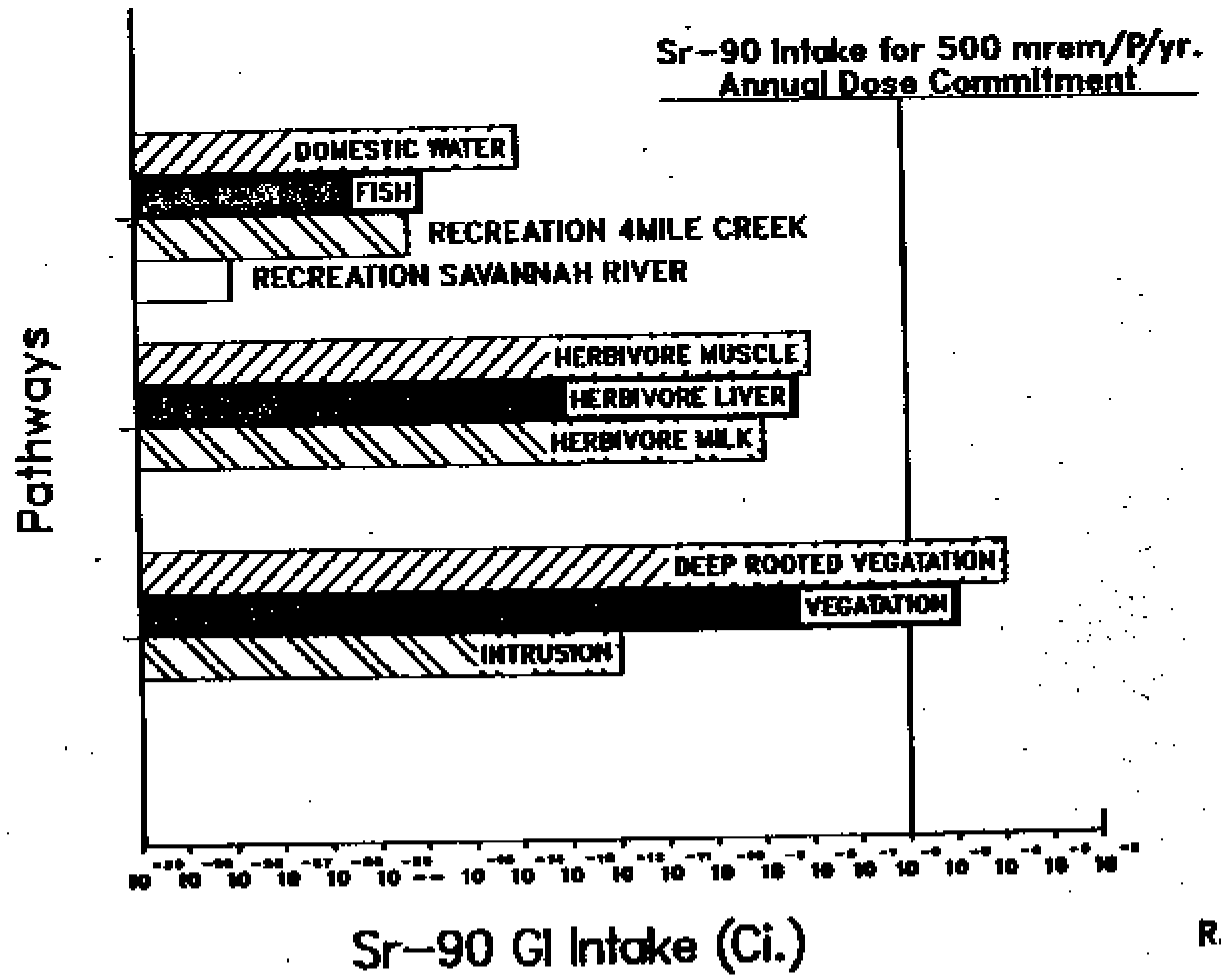


FIGURE 3

Pathways to GI Tract: Land Occupation Scenario

Figure 4
600 Area Burial Ground
Sr–90 HOMEFARM Projections
Pathway Analysis



R.H.E

Figure 5
600 Area Burial Ground
Sr–90 Dose Projections as a Function of Scenario

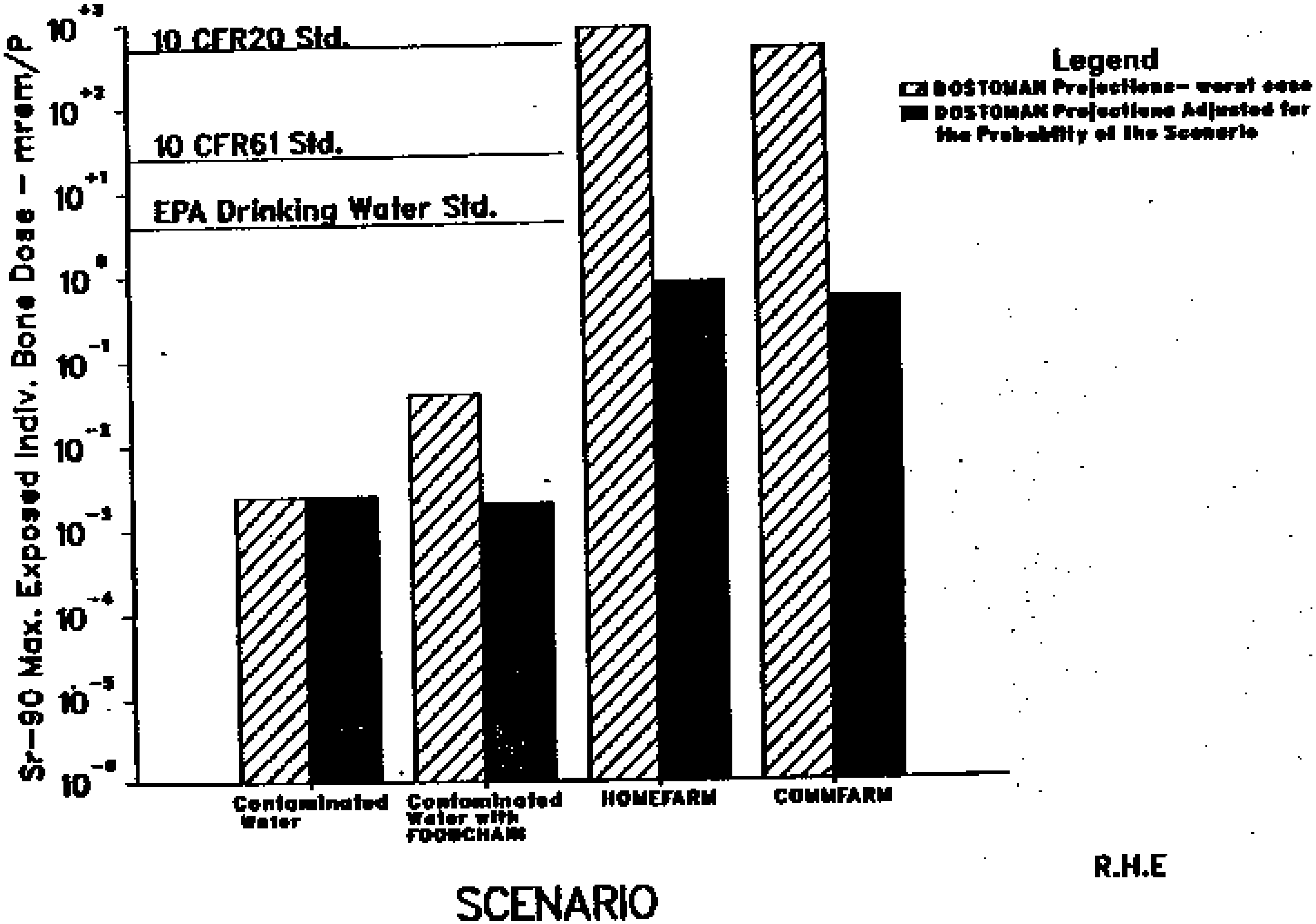
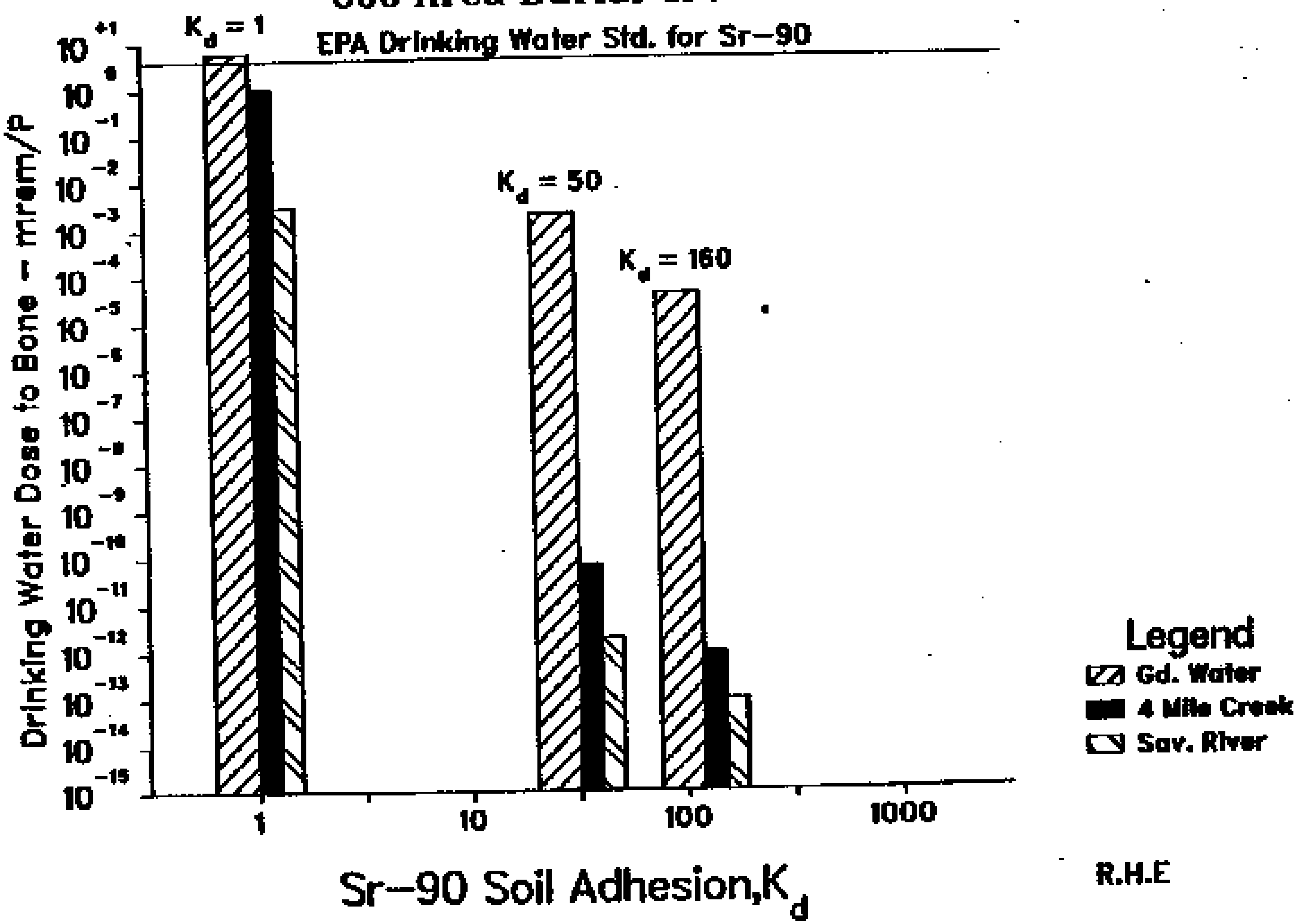
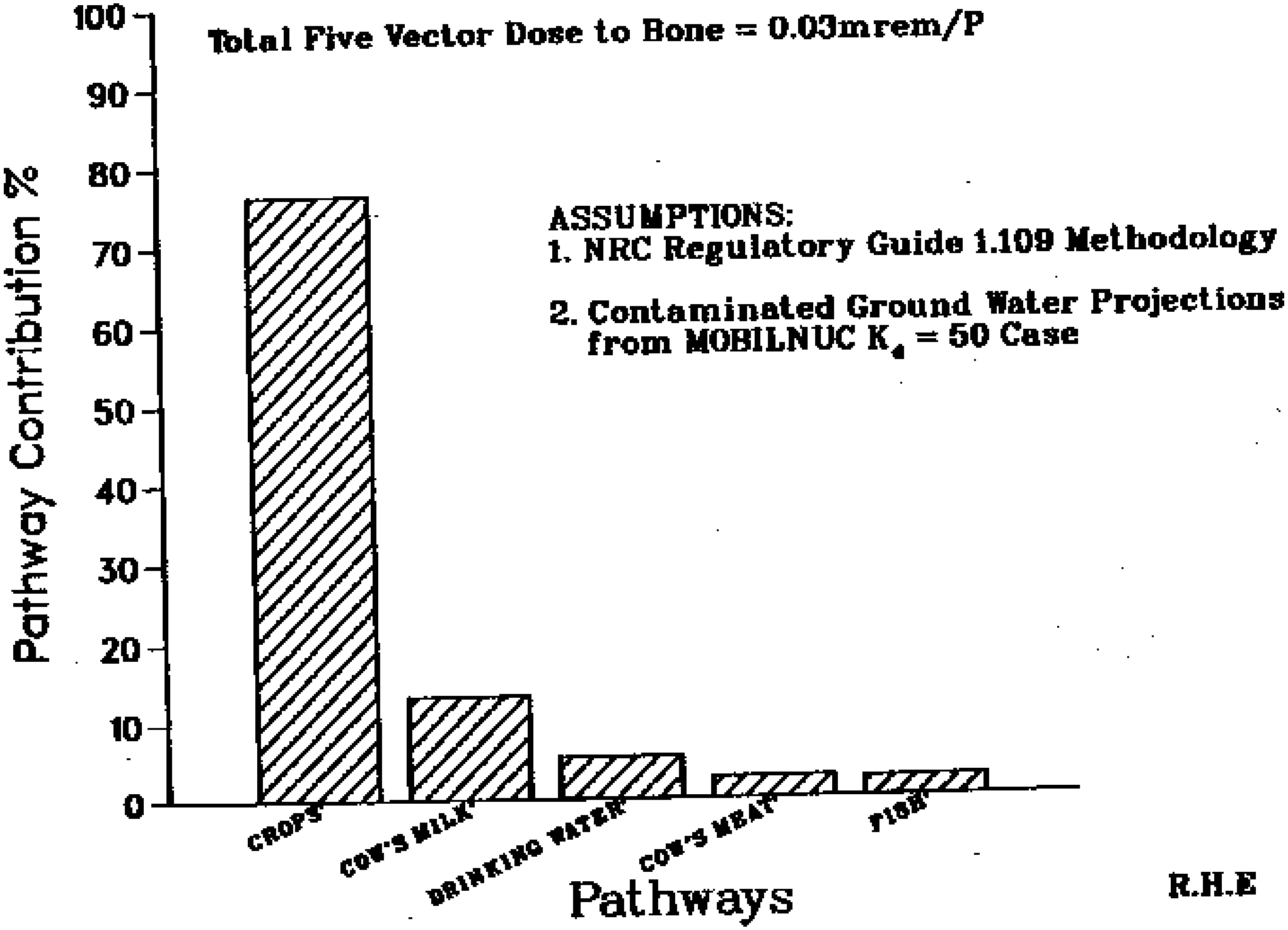


Figure 6
Sr−90 K_d Projections on Hydrological Transport
600 Area Burial Ground



R.H.E

Figure 7
600 Area BURIAL GROUND
Sr-90 Hydrological Transport via FOODCHAIN Pathways



R.H.E

Figure 8
600 AREA BURIAL GROUND
Sr–90 HOMEFARM Scenario Projections – Maximum GI Intake

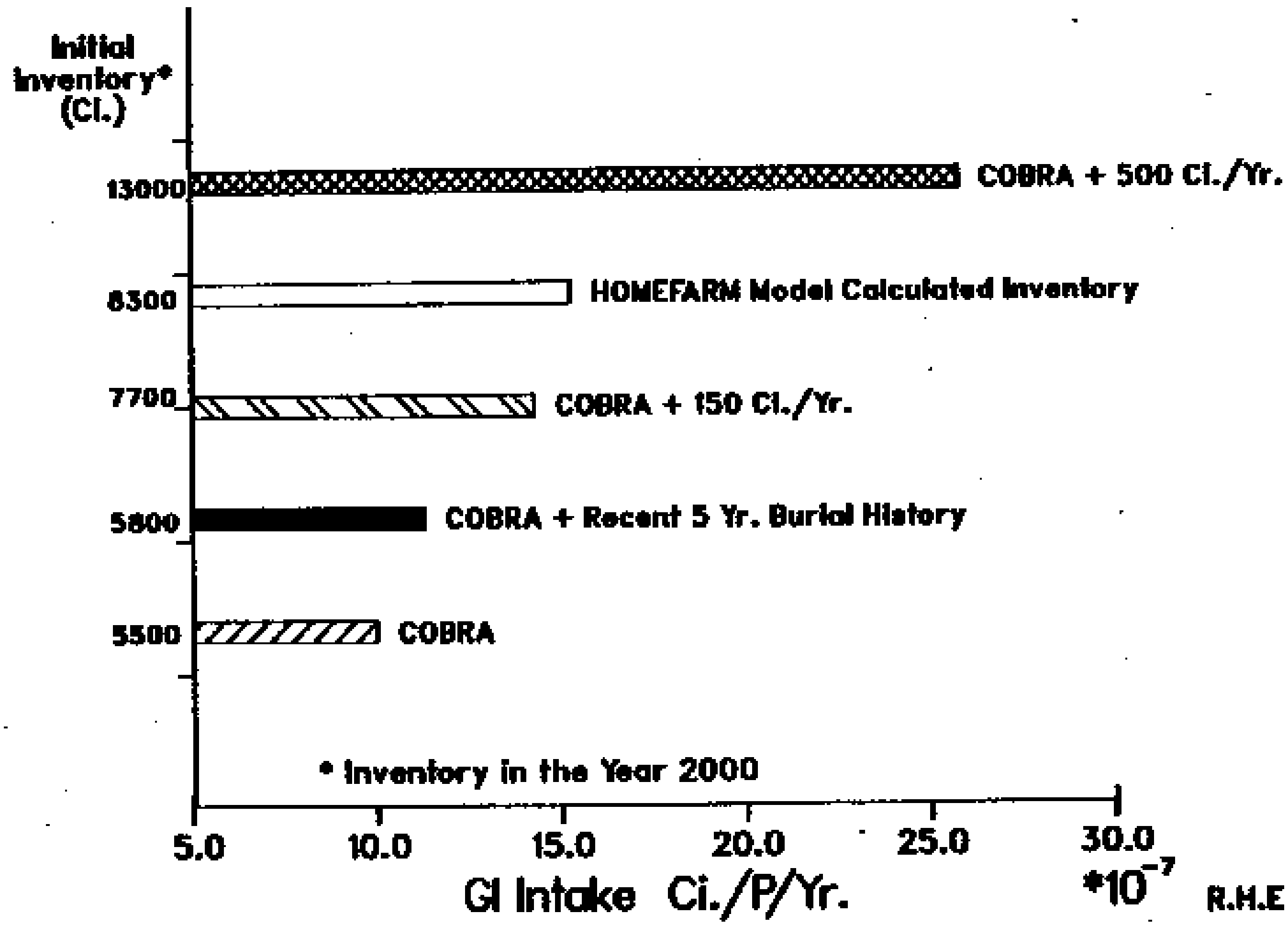
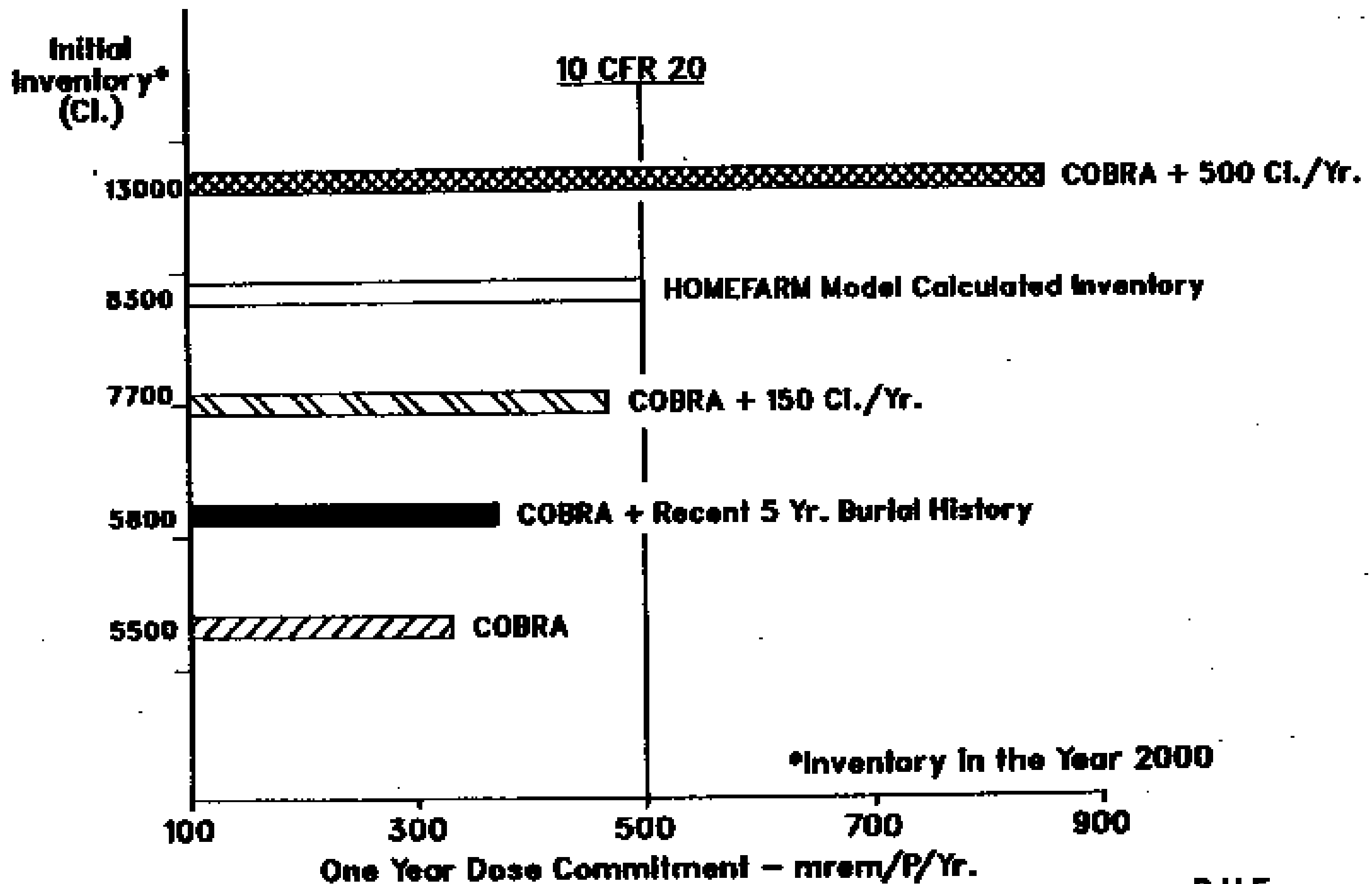
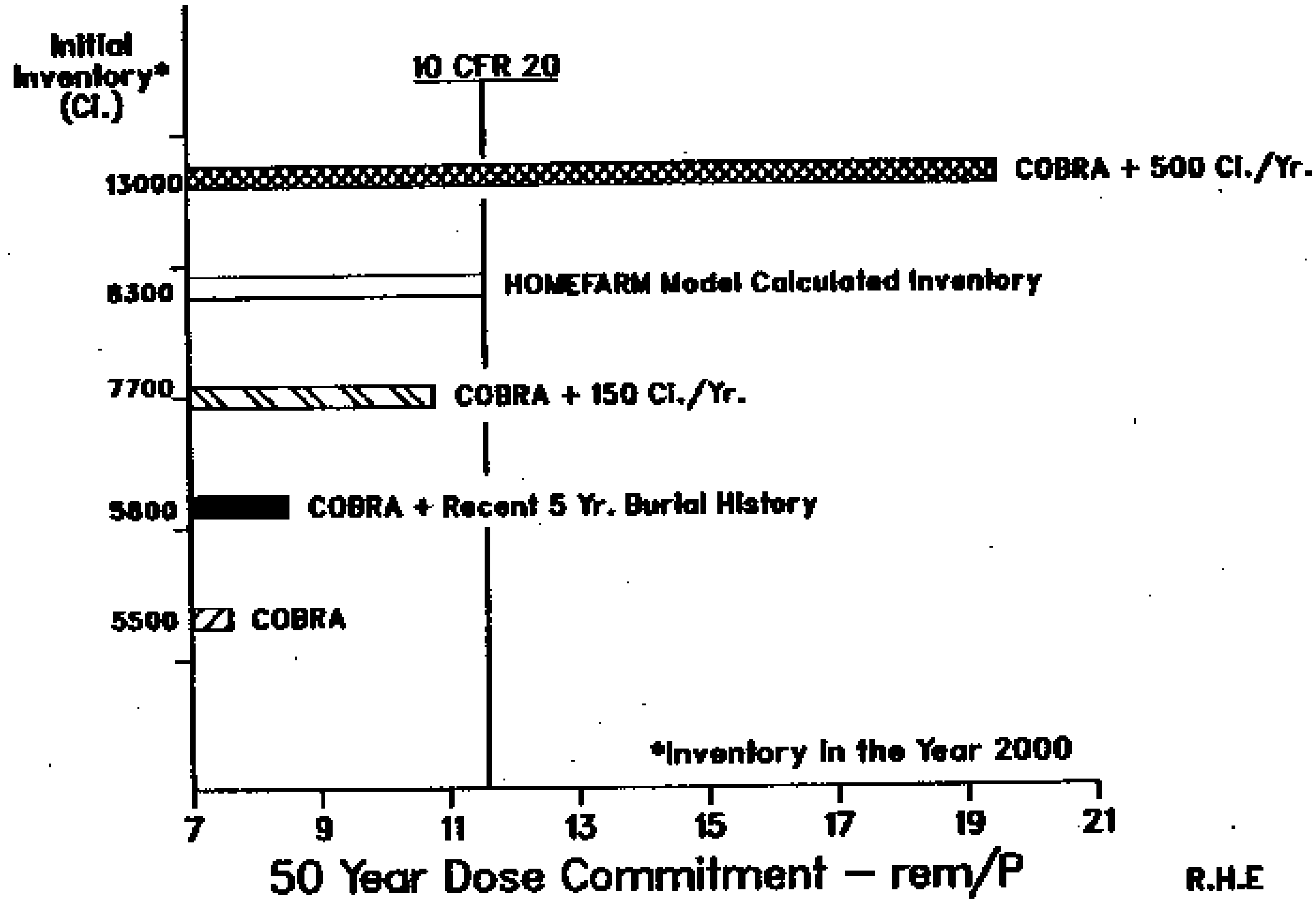


Figure 9
600 AREA BURIAL GROUND
Sr–90 HOMEFARM Scenario Projections – One Year Dose Commitment



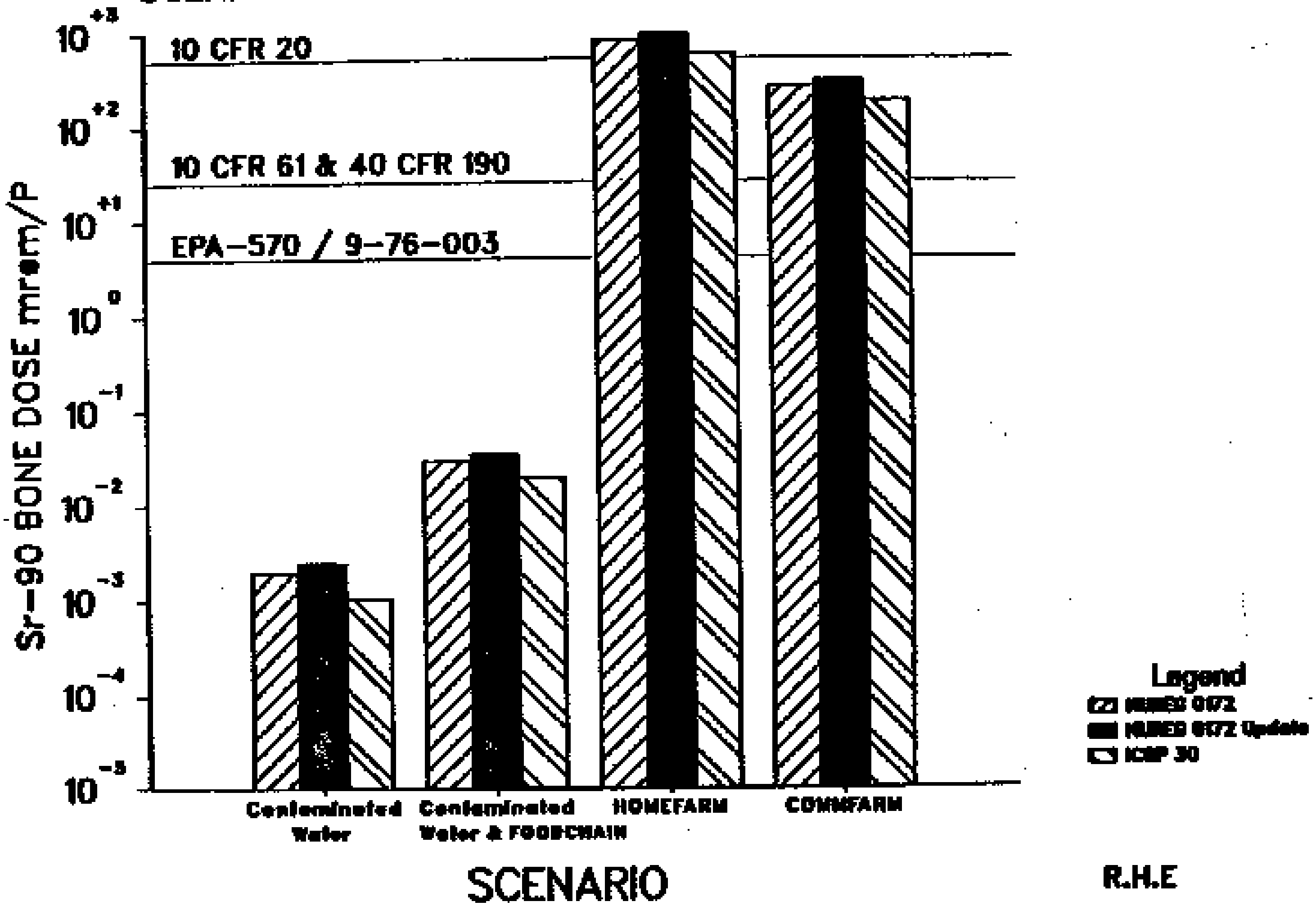
R.H.E

Figure 10
600 AREA BURIAL GROUND
Sr–90 HOMEFARM Scenario Projections – 50 Year Dose Commitment



R.H.E

Figure 11
Sr–90 in 600 Area Burial Ground
SCENARIO PROJECTIONS vs. DOSIMETRY DATA BASE



R.H.E

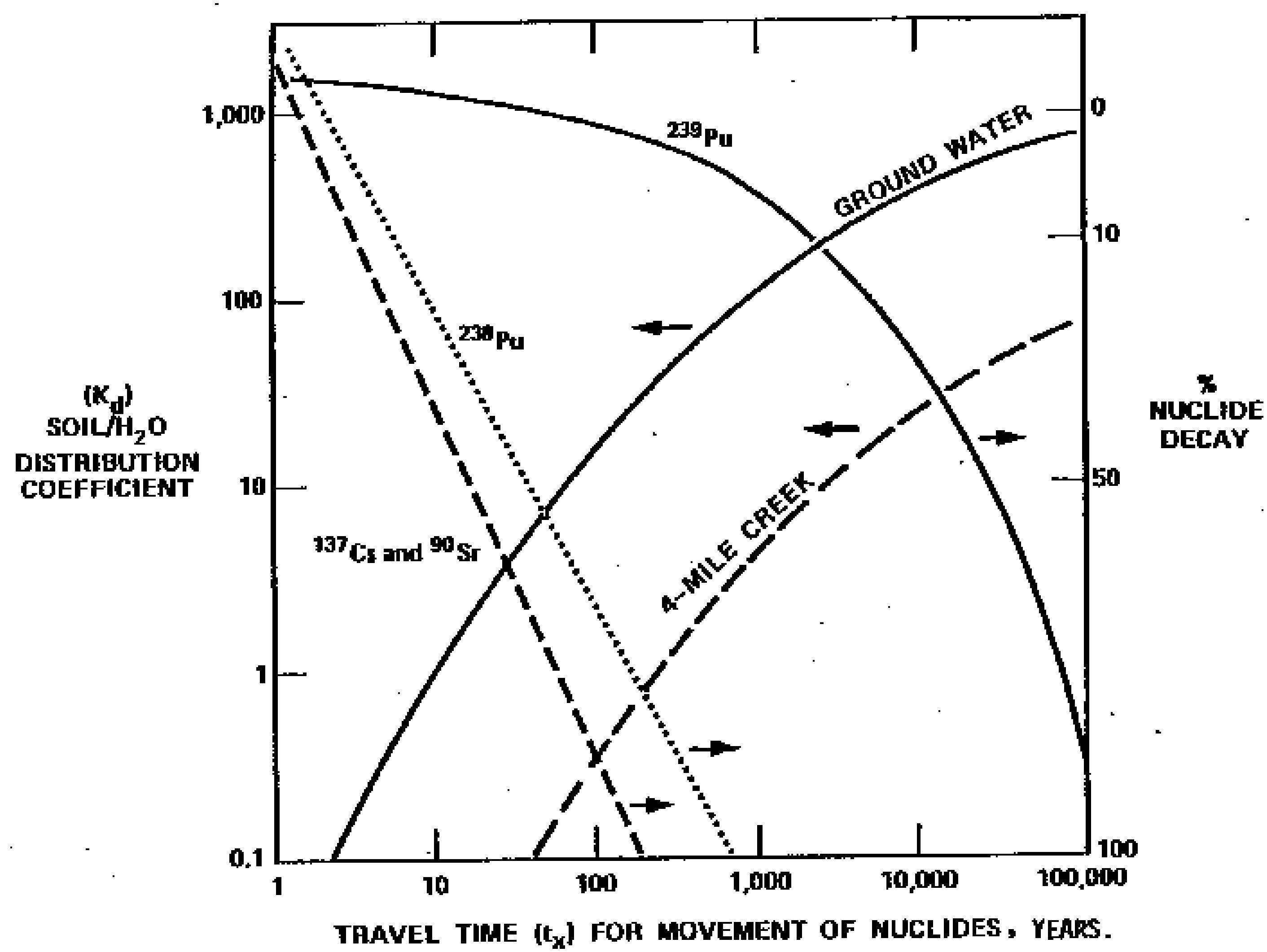
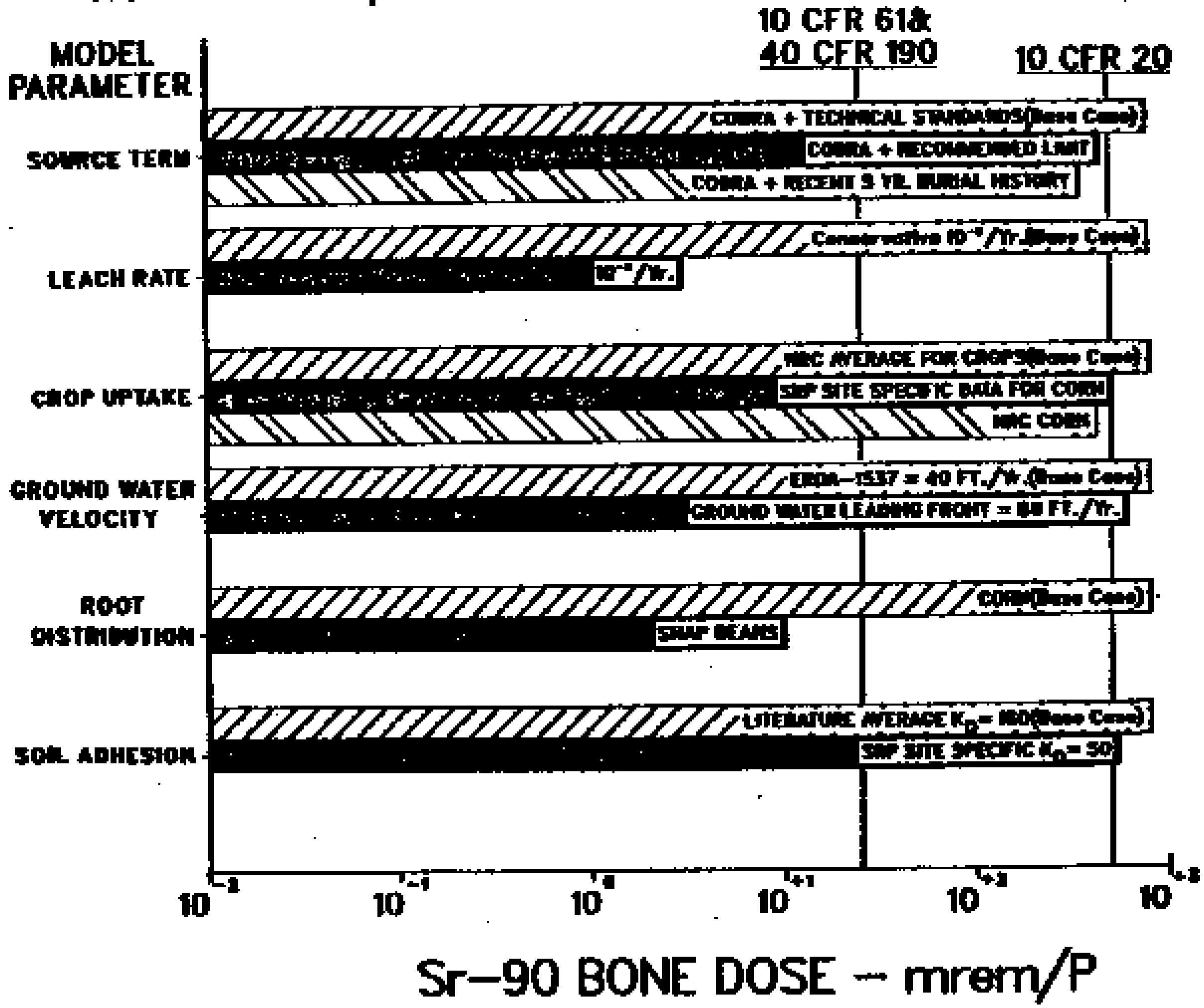


FIGURE 12

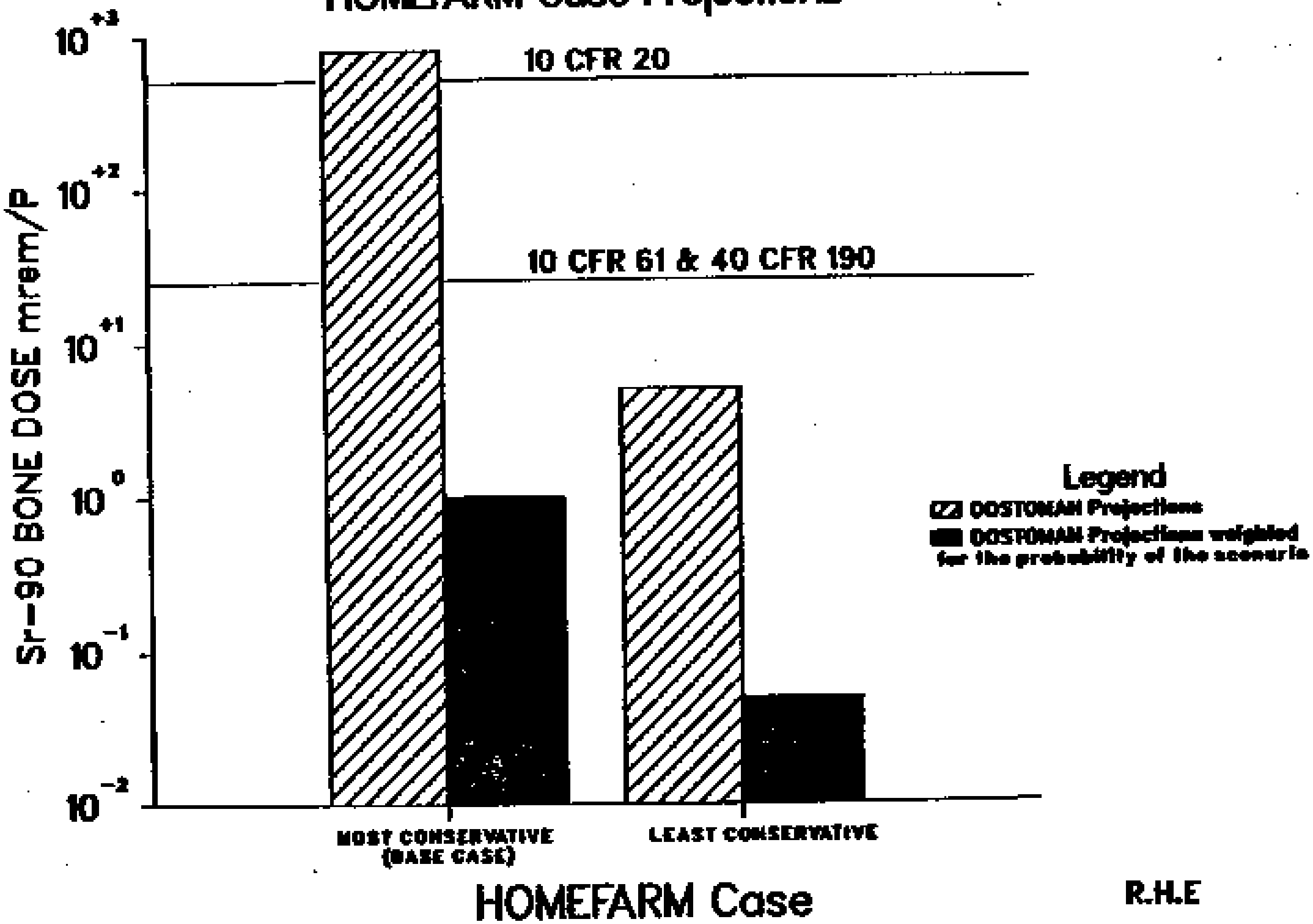
The Significance of Nuclide Soil/Water Distribution Coefficients

Figure 13
Sr–90 in 600 Area Burial Ground
HOMEFARM Projections as a Function of Key Model Parameters



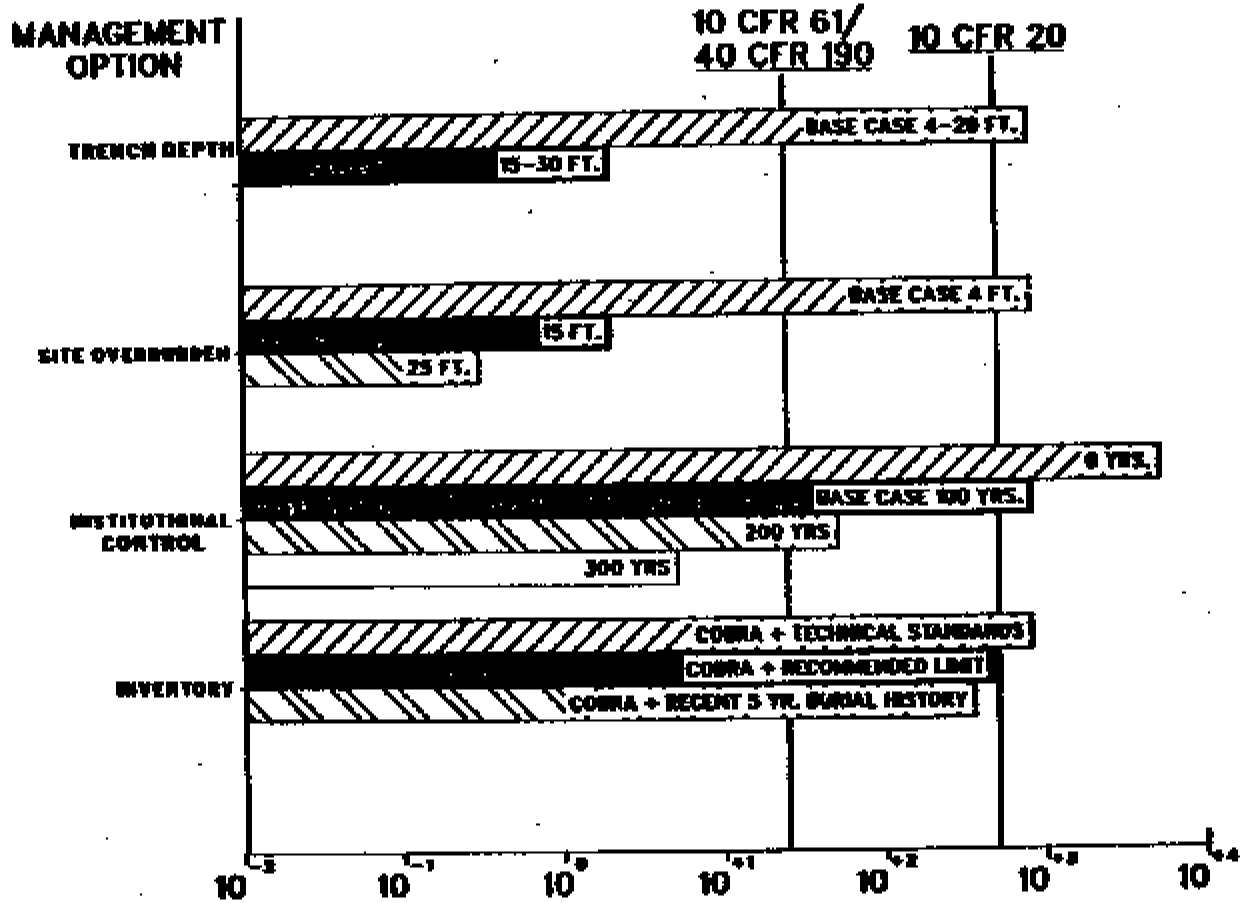
R.H.E

Figure 14
Sr–90 in 600 Area Burial Ground
HOMEFARM Case Projections



R.H.E

Figure 15
Sr–90 in 600 Area Burial Ground
BURIAL GROUND MANAGEMENT PRACTICES



Sr–90 BONE DOSE – mrem/P

R.H.E

APPENDICES

A. MOBILNUC Matrix

B. FOODCHAIN Matrix

C. HOMEFARM Matrix

D. COMMFARM Matrix

E. MOBILNUC/FOODCHAIN Calculation Example for Sr-90

F. The Sr-90 Dose Commitment Equation

A. The "MOBILNUC" MATRIX*

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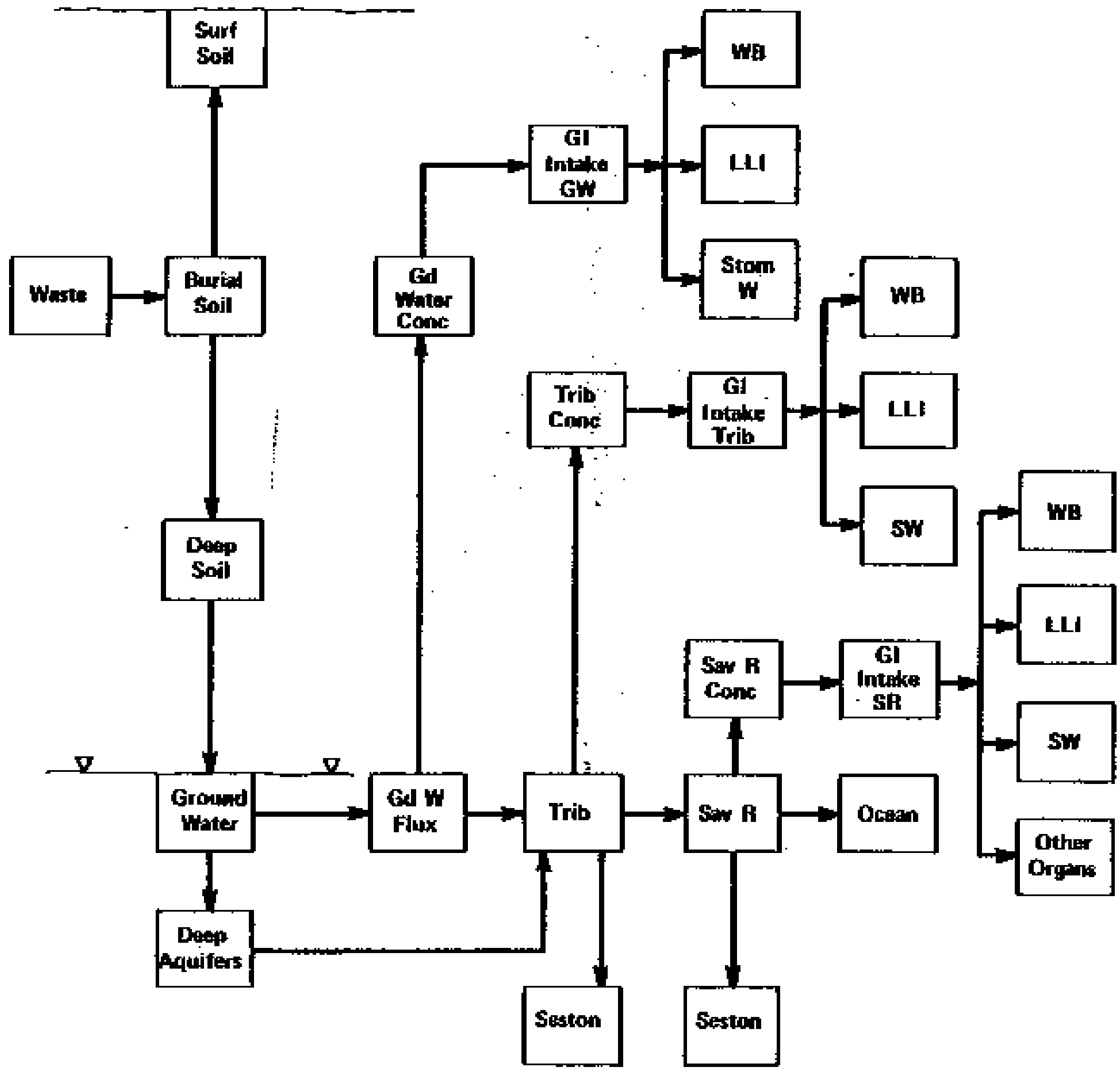
* Nuclide Hydrological Transport Equation for Land Disposal Facility

THE "MOBILNUC" MATRIX*



*Nuclide Hydrological Transport Equation for Land Disposal Facility

B. The "FOODCHAIN" Matrix*

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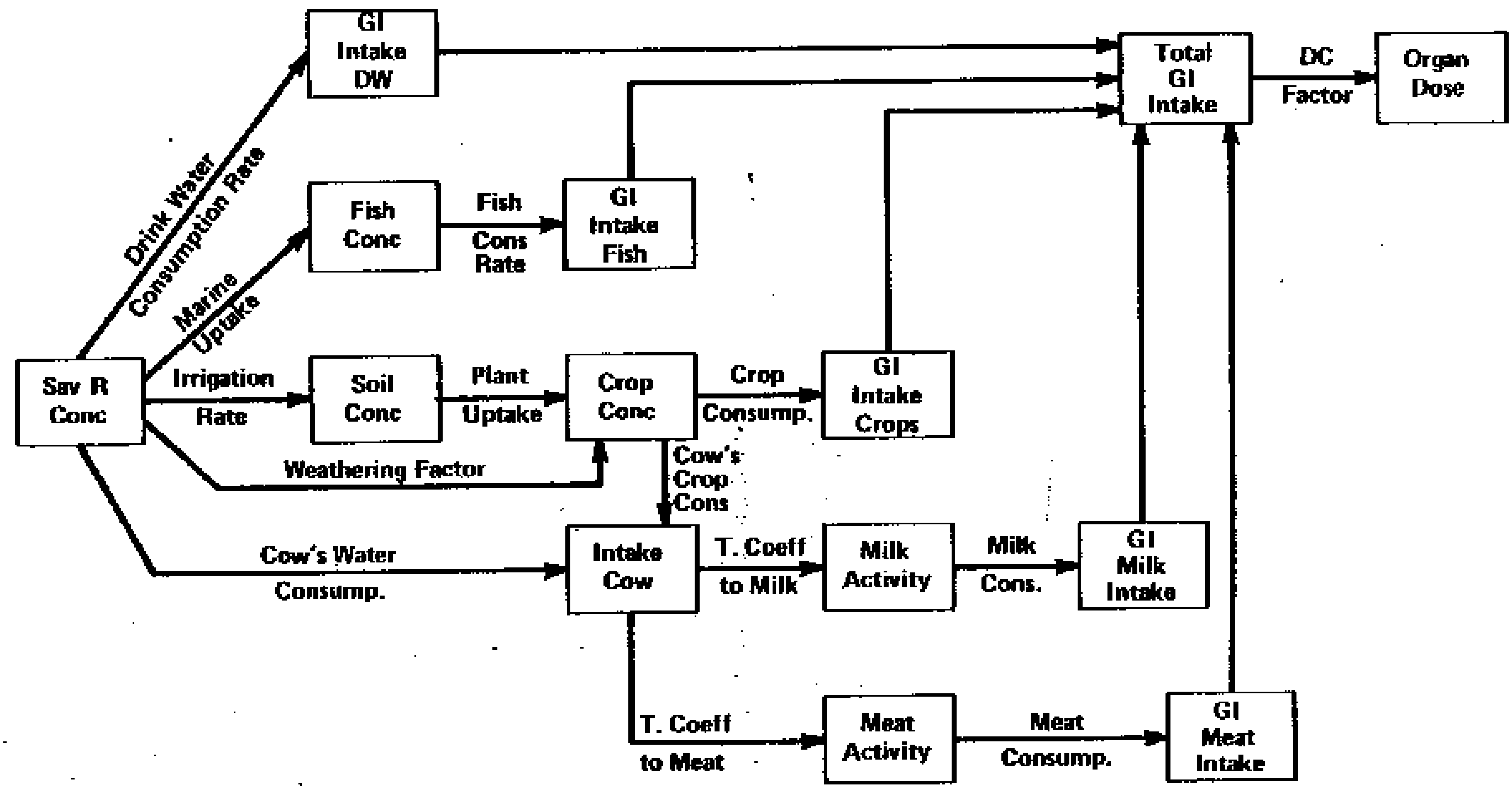
* NRC Regulatory Guide 1.109 Methodology
Use of Contaminated Water for Crop Irrigation
Foodchain Vectors: Drink Water, Fish, Crops, Animal's Milk, and Meat

THE "FOODCHAIN" MATRIX*



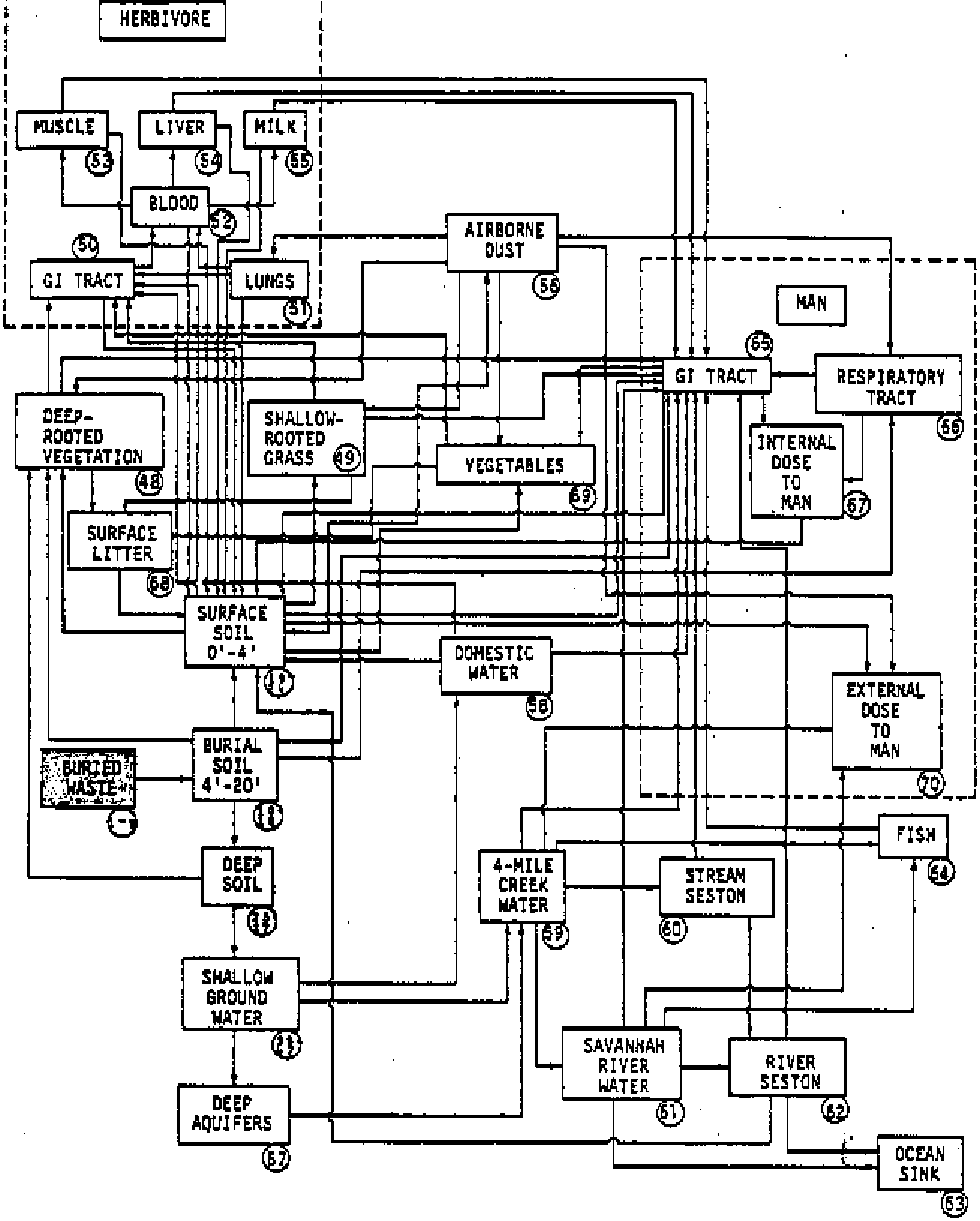
*NRC Reg Guide 1.109 Methodology

Use of Contaminated Water for Crop Irrigation

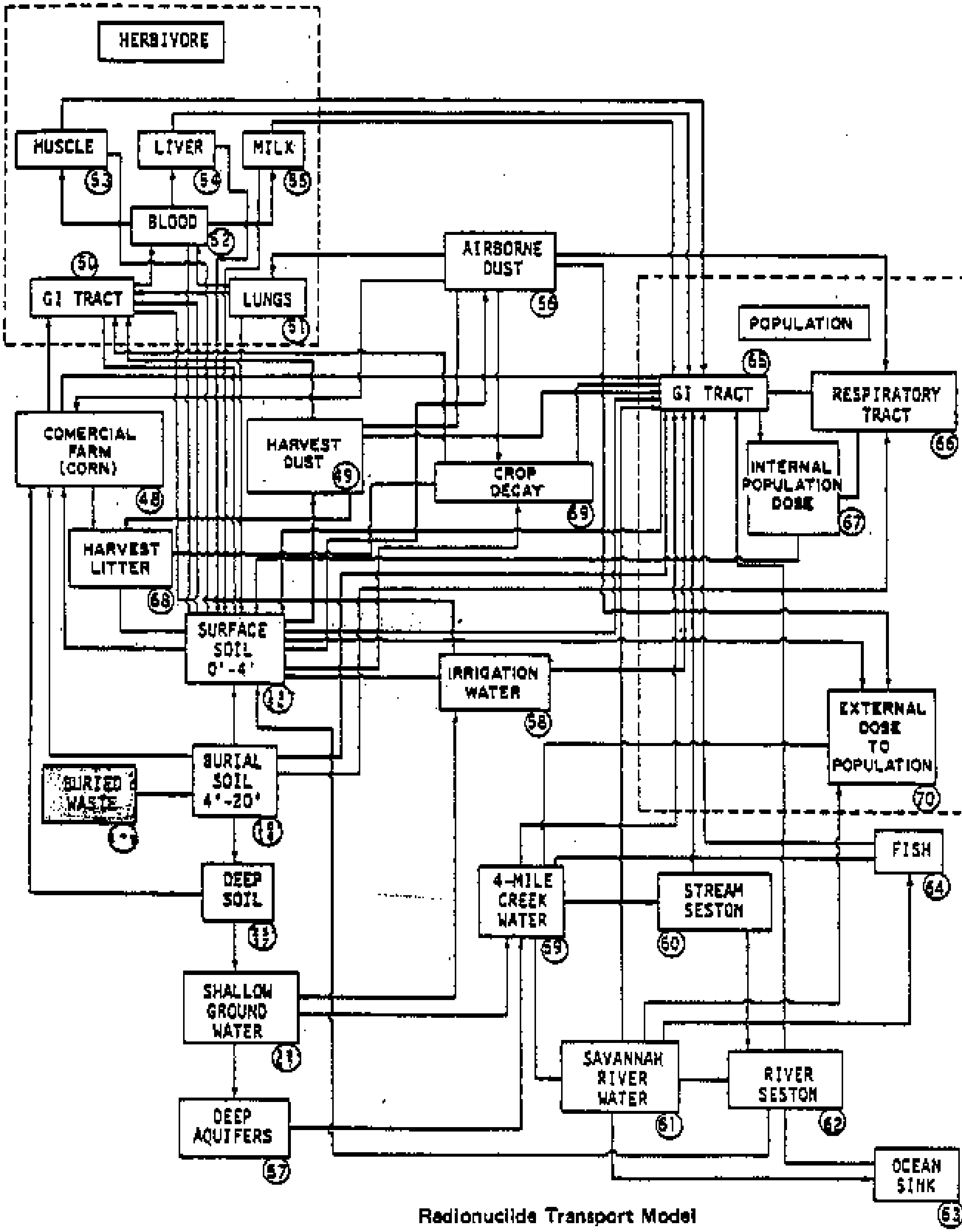
Foodchain Vectors: Drink Water, Fish, Crops, Animal's Milk, and Meat

C. HOMEFARM Radionuclide Transport Model

RADIONUCLIDE TRANSPORT MODEL



D. COMMFARM Radionuclide Transport Model



Radionuclide Transport Model

E. MOBILNUC/FOODCHAIN CALCULATION EXAMPLE FOR SR-90

The various water-related pathways that are considered are as follows:

1. Water consumption (730 liters per year, Ref. 22);

2. Freshwater fish consumption (6.9 Kg per year, Ref. 22);

3. Consumption of crops grown on irrigated soil (240 Kg per year, Table E-4, Reference 19, is assumed to be taken from an area affected by contamination);

4. Consumption of milk from cows that hypothetically consume contaminated water and crops (200 liters per year, Table E-4, Reference 19, is assumed to be from an area affected by contamination); and

5. Consumption of meat from animals that hypothetically consume contaminated water and crops (95 Kg per year, Table E-4, Reference 19, is assumed to be from an area affected by contamination).

The flux of Strontium-90 to the water table was projected from MOBILNUC to be 9.5×10^{-8} Ci/yr, diluted by the minimum flow of infiltrating rain water. That is,

$$\frac{9.5 \times 10^{-8}\ \text{Ci/yr}}{3.2 \times 10^{11}\ \text{ml/yr}}(10^{6}\ \mu\text{Ci/Ci}) = 3 \times 10^{-13}\ \mu\text{Ci/mL},$$

which is shown in Table 3 for the $K_d = 50$ case.

This concentration is lower than the Reference 27 unrestricted area limit for Sr-90 (3×10^{-7} μCi/ml) by a factor of 1,000,000. On this basis, it might be expected that individual total body exposures would not exceed about 5×10^{-4} mrem per person, since the limits of Reference 27 prevent annual total body exposures from exceeding approximately 500 mrem (i.e., 500 mrem/person ÷ 1,000,000 = 5×10^{-4} mrem/p). However, each exposure pathway is evaluated separately in the following discussion and the sum of all such pathways yields the conservative estimate of 7.4×10^{-3} mrem per person for the total body exposure of an average individual. The following discussion also calculates the exposure to bone (bone is the organ that would receive the maximum exposure) for an average individual to be 3.0×10^{-2} mrem/p.

A. WATER CONSUMPTION PATHWAY

i. Annual hypothetical intake of Sr-90

$$= (730\ \text{liters/yr})\left(\frac{1000\ \text{mL}}{\text{liter}}\right)\left(3 \times 10^{-13}\ \frac{\mu\text{Ci}}{\text{mL}}\right)$$

$$= 2.2 \times 10^{-7}\ \mu\text{Ci/yr}$$

ii. Annual exposure, total body

$$= (2.2 \times 10^{-7}\ \mu\text{Ci/yr})(1.86 \times 10^{0}\ \text{rem}/\mu\text{Ci})^{18}(10^{3}\ \text{mrem/rem})$$

$$= 4.1 \times 10^{-4}\ \text{mrem/yr}$$

iii. Annual exposure, bone

$$= (2.2 \times 10^{-7}\ \mu\text{Ci/yr})(7.58 \times 10^{0}\ \text{rem}/\mu\text{Ci})^{18}(10^{3}\ \text{mrem/rem})$$

$$= 1.7 \times 10^{-3}\ \text{mrem/yr}$$

B. FRESHWATER FISH CONSUMPTION PATHWAY

i. Average hypothetical concentration of Sr-90 in freshwater fish

$$= \left(3 \times 10^{-13}\ \frac{\mu\text{Ci}}{\text{ml}}\right)\left(50\ \frac{\text{Ci/g}}{\text{Ci/ml}}\right)\left(\frac{1000\ \text{g}}{\text{Kg}}\right)$$

$$= 1.5 \times 10^{-8}\ \mu\text{Ci/Kg}$$

ii. Annual intake of Sr-90

$$= \left(6.9\ \frac{\text{Kg}}{\text{yr}}\ \text{fish}\right)\left(1.5 \times 10^{-8}\ \frac{\mu\text{Ci}}{\text{Kg}}\right) = 1.0 \times 10^{-7}\ \mu\text{Ci/yr}$$

iii. Annual exposure, total body

$$= \left(1.0 \times 10^{-7}\ \frac{\mu\text{Ci}}{\text{yr}}\right)(1.86 \times 10^{0}\ \text{rem}/\mu\text{Ci})(10^{3}\ \text{mrem/rem})$$

$$= 1.9 \times 10^{-4}\ \text{mrem/yr}$$

iv. Annual exposure, bone

$= (1.0 \times 10^{-7}\ \mu Ci/yr)(7.58 \times 10^{0}\ rem/\mu Ci)(10^{3}\ mrem/rem)$

$= 7.6 \times 10^{-4}\ mrem/yr$

C. PATHWAY DUE TO CONSUMPTION OF CROPS GROWN ON IRRIGATED SOIL

The method of calculation follows that of Equation (4), page 1.109-3 of Reference 19.

i. Irrigation rate

$= 50$ inches per year

$= 8.3$ inches per month for a six-month irrigation period

$= 0.29\ liter/m^2$ per hour, during six months of irrigation

ii. Assumed period of long-term buildup of soil contamination = 15 years, Table E-15, Reference 19

iii. Hypothetical concentration in soil after 15 years, based on a surface density of 240 Kg per square meter of soil (Table E-15, Reference 19)

$$= \frac{(0.29\ liter/m^2\ hr)(4380\ hrs/yr)(15\ yrs)(3 \times 10^{-13}\ \mu Ci/ml)(1000\ ml/liter)}{240\ Kg/m^2}$$

$= 3.0 \times 10^{-8}\ \mu Ci/Kg$ Soil

iv. Hypothetical concentration in crops grown in this soil, considering uptake via roots, and a transfer coefficient of 0.2 for Sr-90, Reference 47

$= (3.0 \times 10^{-8}\ \mu Ci/Kg)(0.20)$

$= 6.0 \times 10^{-9}\ \mu Ci/Kg$ Crop

v. Hypothetical activity of Sr-90 on plant surfaces, based on 25 percent of the deposited activity being retained on the crops, and a rate constant of 0.0021 per hour (14-day half-life) for removal of activity on plant or leaf surfaces by weathering (Table E-15, Reference 19).

$$= (3 \times 10^{-13}\ \frac{\mu Ci}{ml})(\frac{0.29\ liter}{m^2\text{-}hr})(\frac{1000\ ml}{liter})\ (0.25)\ (\frac{1}{0.0021/hr})$$

$= 1.1 \times 10^{-8}\ \mu Ci/m^2$

ii. Assumed period of long-term buildup of soil contamination = 15 years, Table E-15, Reference 19

iii. Hypothetical concentration in soil after 15 years, based on a surface density of 240 Kg per square meter of soil (Table E-15, Reference 19)

$$= \frac{(0.29 \text{ liter/m}^2 \text{ hr})(4380 \text{ hrs/yr})(15 \text{ yrs})(3 \times 10^{-13} \ \mu\text{Ci/ml})(1000 \text{ ml/liter})}{240 \text{ Kg/m}^2}$$

$= 3.0 \times 10^{-8}$ µCi/Kg Soil

iv. Hypothetical concentration in crops grown in this soil, considering uptake via roots, and a transfer coefficient of 0.2 for Sr-90, Reference 47

$= (3.0 \times 10^{-8}$ µCi/Kg$)(0.20)$

$= 6.0 \times 10^{-9}$ µCi/Kg Crop

v. Hypothetical activity of Sr-90 on plant surfaces, based on 25 percent of the deposited activity being retained on the crops, and a rate constant of 0.0021 per hour (14-day half-life) for removal of activity on plant or leaf surfaces by weathering (Table E-15, Reference 19).

$$= \left(3 \times 10^{-13} \frac{\mu\text{Ci}}{\text{ml}}\right)\left(\frac{0.29 \text{ liter}}{\text{m}^2\text{-hr}}\right)\left(\frac{1000 \text{ ml}}{\text{liter}}\right)(0.25)\left(\frac{1}{0.0021/\text{hr}}\right)$$

$= 1.1 \times 10^{-8}$ µCi/m^2

vi. Hypothetical activity of Sr-90 per Kg of crops, based on an agricultural productivity of 2 Kg/m^2 (Table E-15, Reference 19)(not including uptake via roots)

$= (1.1 \times 10^{-8}$ µCi/m$^2) \div (2$ Kg/m$^2)$

$= 5.5 \times 10^{-9}$ µCi/Kg

vii. Total hypothetical activity of Sr-90 Per Kg of crops

(= iv + vi)

$= (6.0 \times 10^{-9} + 5.5 \times 10^{-9})$ µCi/Kg

$= 1.2 \times 10^{-8}$ µCi/Kg

viii. Annual hypothetical uptake of Sr-90

$= (240\ Kg/yr)(1.2 \times 10^{-8}\ \mu Ci/Kg)$

$= 3.0 \times 10^{-6}\ \mu Ci/yr$

ix. Annual hypothetical exposure, total body

$= (3.0 \times 10^{-6}\ \mu Ci/yr)(1.86 \times 10^{0}\ rem/\mu Ci)(10^{3}\ mrem/rem)$

$= 5.6 \times 10^{-3}\ mrem/yr$

x. Annual exposure, bone

$= (3.0 \times 10^{-6}\ \mu Ci/yr)(7.58 \times 10^{0}\ rem/\mu Ci)(10^{3}\ mrem/rem)$

$= 2.3 \times 10^{-2}\ mrem/yr$

D. MILK CONSUMPTION PATHWAY

i. Cow's daily intake of crop (Table E-3, Reference 19)

$= 50\ Kg/day$

ii. Cow's daily intake of water (Table E-3, Reference 19)

$= 60\ liters/day$

iii. Cow's daily hypothetical intake of Sr-90

$= (50\ Kg/day)(1.2 \times 10^{-8}\ \mu Ci/Kg)(2.9^{*}) + (60\ liters/day)\left(3 \times 10^{-13}\ \frac{\mu Ci}{ml} \times \frac{1000\ ml}{liter}\right)$

$= 1.9 \times 10^{-6}\ \mu Ci/day$

iv. Sr-90 activity transfer coefficient in milk, Reference 23

$= 1.4 \times 10^{-3}\ \mu Ci/liter$ per $\mu Ci/day$

v. Hypothetical Sr-90 activity in milk

$= \left(\frac{1.4 \times 10^{-3}\ \mu Ci/liter}{\mu Ci/day}\right)(1.9 \times 10^{-6}\ \mu Ci/day)$

$= 2.7 \times 10^{-9}\ \mu Ci/liter$

---

* The factor of 2.9 accounts for the lower agricultural productivity of crops per unit area when the grass-cow-milk-man pathway is considered (Table E-15, Reference 19)

vi. Individual's hypothetical annual uptake of Sr-90 via milk consumption

$= (200 \text{ liters/yr})(2.7 \times 10^{-9} \ \mu\text{Ci/liter}) = 5.4 \times 10^{-7} \ \mu\text{Ci/yr}$

vii. Annual hypothetical exposure, total body

$= (5.4 \times 10^{-7} \ \mu\text{Ci/yr})(1.86 \times 10^{0} \text{ rem/}\mu\text{Ci})(10^{3} \text{ mrem/rem})$

$= 1.0 \times 10^{-3}$ mrem/yr

viii. Annual hypothetical exposure, bone

$= (5.4 \times 10^{-7} \ \mu\text{Ci/yr})(7.58 \times 10^{0} \text{ rem/}\mu\text{Ci})(10^{3} \text{ mrem/rem})$

$= 4.1 \times 10^{-3}$ mrem/yr

E. MEAT CONSUMPTION PATHWAY

The Sr-90 activity in all meat consumed is assumed to be equal to that of beef cattle.

i. Animal's daily intake of crop (Table E-3, Reference 19) = 50 Kg/day

ii. Animal's daily intake of water (Table E-3, Reference 19) = 50 liters/day

iii. Animal's hypothetical daily intake of Sr-90 (same as calculated for milk in previous section)

$= 1.9 \times 10^{-6} \ \mu\text{Ci/day}$

iv. Sr-90 activity transfer coefficient in meat (Table E-1, Reference 19)

$= 6 \times 10^{-4} \ \mu\text{Ci/Kg per } \mu\text{Ci/day}$

v. Hypothetical Sr-90 activity in meat

$$= \left(\frac{6 \times 10^{-4} \ \mu\text{Ci/Kg}}{\mu\text{Ci/day}}\right) \left(1.9 \times 10^{-6} \ \frac{\mu\text{Ci}}{\text{day}}\right)$$

$= 1.2 \times 10^{-9} \ \mu\text{Ci/Kg}$ Meat

vi. Annual hypothetical uptake of Sr-90 via consumption of meat

$= (1.2 \times 10^{-9} \ \mu\text{Ci/Kg})(95 \text{ Kg/yr})$

$= 1.1 \times 10^{-7} \ \mu\text{Ci/yr}$

vii. Hypothetical annual exposure, total body

$= (1.1 \times 10^{-7}\ \mu Ci/yr)(1.86 \times 10^{0}\ rem/\mu Ci)(10^{3}\ mrem/rem)$

$= 2.1 \times 10^{-4}$ mrem/yr

viii. Hypothetical annual exposure, bone

$= (1.1 \times 10^{-7}\ \mu Ci/yr)(7.58 \times 10^{0}\ rem/\mu Ci)(10^{3}\ mrem/rem)$

$= 8.3 \times 10^{-4}$ mrem/yr

F. SUM OF EXPOSURES VIA ALL PATHWAYS

i. Sum of hypothetical exposures, total body

$= 4.1 \times 10^{-4}$ mrem/yr (water) + 1.9×10^{-4} mrem/yr (fish)

+ 5.6×10^{-3} mrem/yr (crops) + 1.0×10^{-3} mrem/yr (milk)

+ 2.1×10^{-4} mrem/yr (meat)

$= 7.4 \times 10^{-3}$ mrem/yr

ii. Sum of hypothetical exposures, bone

$= 1.7 \times 10^{-3}$ mrem/yr (water) + 7.6×10^{-4} mrem/yr (fish)

+ 2.3×10^{-2} mrem/yr (crops) + 4.1×10^{-3} mrem/yr (milk)

+ 8.3×10^{-4} mrem/yr (meat)

$= 3.0 \times 10^{-2}$ mrem/yr

These hypothetical total exposures are considered to be very conservative because all of the released radioactive material is assumed to be carried in the water. Based on the observation discussed earlier in this section that the conservatively estimated Sr-90 water concentration would be lower than the Reference 27 limit by a factor of 1,000,000 to 1, the annual average individual total body exposure estimate of 7.4×10^{-3} mrem/yr is conservative by a factor of at least 30 to 1.

MAXIMUM ANNUAL POPULATION DOSE COMMITMENT

The hypothetical population dose commitment estimate is obtained by multiplying the average individual total body dose commitment 7.4×10^{-3} mrem per year by the appropriate affected population.

Downstream of the Savannah River site, the present population of water users is approximately 70,000 persons (Reference 12). The corresponding population whole body dose commitment would be

$$(7.4 \times 10^{-3} \text{ mrem/yr})(70{,}000 \text{ persons})(10^{-3} \text{ mrem/rem}) = 0.52 \text{ man-rem/yr}.$$

The population exposure to bone would be 2.1 man-rem per year.

Based on internal studies by the Savannah River Laboratory, this population is assumed to increase over the next century and a half, reaching a level five times the present population, or 350,000, after which it remains constant. This value can be assumed to be appropriate for the Savannah River site, so the corresponding population total body dose commitment would be

$$(7.4 \times 10^{-3} \text{ mrem/yr})(350{,}000 \text{ persons}) = 2.6 \text{ man-rem/yr}.$$

The corresponding population exposure to bone would be 10.5 man-rem per year.

EXPECTED HEALTH EFFECTS OF LAND DISPOSAL

For the current population of 70,000, the maximum total body population dose commitment of 0.5 man-rem per year, combined with a conservatively estimated relationship between low-level dose and population health effects (0.45×10^{-3} additional cancer cases per man-rem, cited in Appendix D of Reference 51), implies a total expected number of additional health effects of 0.00023 per year. That is

$$\left(\frac{0.5 \text{ man-rem}}{\text{year}}\right) \left(0.45 \times 10^{-3} \left(\frac{\text{additional cancer cases}}{\text{man-rem}}\right) = 0.00023 \text{ per year}$$

For the expanded future population of 350,000, the maximum total body population dose commitment of 2.6 man-rem per year, combined with a conservatively estimated relationship between low-level dose and population health effects (0.45×10^{-3} additional cancer cases per man-rem, cited in Appendix D of Reference 51), implies a total expected number of additional health effects of 0.0012 per year. That is,

$$\left(\frac{2.6 \text{ man-rem}}{\text{year}}\right) \left(0.45 \times 10^{-3} \frac{\text{additional cancer cases}}{\text{man-rem}}\right) = 0.0012 \text{ per year}$$

The interpretation of these results is that it would be very unlikely that even one person would be affected in any year in the distant future as a result of radiation exposure attributable to the land disposal of Sr-90. Consideration of the effects of various conservative assumptions used in this analysis suggest that the estimate of 0.00023 health effects per year is conservative by several factors of 10, since most of the radioactive Sr-90 eventually released to the disposal site would actually be expected to remain at the site, and most of the Sr-90 that would be transported away from the immediate area would be expected to be either absorbed within a short distance by soil particles or deposited in stream or river beds.

F. THE SR-90 DOSE COMMITMENT EQUATION

Calculation of Internal Radiation Dose

An individual who ingests radioactivity receives a radiation dose that is a function of several factors involving the amount and the species of radionuclide ingested. Depending on the species of radionuclide ingested, a variable amount will be absorbed through the gastrointestinal tract wall. Also, the body organ which receives the most significant dose will depend upon the species. After radionuclides enter the body, they decline in number through radioactive decay and through biological decay (the loss due to natural removal processes in the body). These effects are accounted for by calculating a dose conversion factor (DCF) that converts a radioactivity intake in curies to a dose in rem:

$$DCF = \frac{f_w\, R_d\, (\epsilon)\, (E) S}{e_e (m)(\lambda)} (1 - e^{-\lambda t})$$

where f_w = fraction of radionuclide ingested that reaches the organ of interest = 0.0225 for Sr-90 (reference 18)

R_d = disintegration rate = 3.7×10^4 dis/sec-μCi

ϵ = effective energy in organ of interest = 5.65 MeV/dis for Sr-90 (reference 18)

E = Energy conversion factor = 1.6×10^{-6} ergs/MeV

e_e = Radiation conversion factor = 100 ergs/gm-rem

m = mass of organ of interest = 7,000 gms for the bone (reference 22)

λ = effective decay constant = $\frac{\ln 2}{t_b} + \frac{\ln 2}{t_r}$ = .03795/year

t_b = biological decay half-life = 18,000 days for Sr-90 (reference 18)

t_r = radioactive decay half-life = 29.0 years.[18]

S = Second/Year Conv Factor = 3.15×10^7 Sec/Yr

The derivation of the equation for DCF is found in reference 12.

The DCF for Sr-90 is calculated by the above relationship to be $8.924 \times 10^6 (1-e^{-0.03795t})$ rem/curie. When an individual ingests radioactivity, this relationship can be used to calculate the dose received from Sr-90. The time over which an individual is receiving a radiation dose is typically taken as 50 years; for the home farm scenario it is assumed that each individual lives on the farm for 50 years, beginning in the year institutional control of the site is lifted. An individual who then ingests some radioactivity each year receives a contribution to the radiation dose from each year's intake. This is accounted for by calculating the bone dose contributed to each year of the 50-year residence time by each annual ingestion of Sr-90. In other words, for the first year's ingestion, the contribution to each of the 50 years is calculated; for the second year's ingestion, the contribution to each of the remaining 49 years is calculated; and so on. Each ingestion year's dose contribution is summed to give a total dose to the bone for any given year. This value is then the bone dose in rem per person for a given year and can be compared to maximum permissable limits. Summing the dose from each year gives the 50 year dose commitment for the individual, the total dose the individual receives during his 50-year residence time.

Note: $8.92 \times 10^6 (1-e^{-.03795\,t})$ Rem/Ci for $t = 50$ years

$= 8.92 \times 10^6 (0.85006)$ Rem/Ci

$= 7.58 \times 10^6$ Rem/Ci which agrees with NUREG 0172[18] 50 year Dose Commitment for Sr-90.

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APPENDIX D

SRL PUBLICATIONS AND TECHNICAL REPORTS ON USE OF THE COMPARTMENTAL PATHWAYS MODEL FOR ANALYSIS OF RADIONUCLIDE TRANSPORT

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