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RAGTIME: A FORTRAN IV Implementation of a Time-Dependent Model for Radionuclides in Agricultural Systems

First Progress Report

J. C. Pleasant
L. M. McDowell-Boyer
G. G. Kiliough

Prepared for the
U.S. Nuclear Regulatory Commission
Division of Safeguards, Fuel Cycle,
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FIRST PROGRESS REPORT

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NOTICE

This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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HIGHLIGHTS

RAGTIME is a FORTRAN IV program that calculates radionuclide concentrations in food crops, beef, and milk which are contaminated as a result of deposition of radioactivity on an agricultural area. Contamination of these foods is assumed to occur as a result of the deposition of radioactivity onto the surface of above-ground food crops, pasture grass, the soil surface below crops, and the soil surface or root mat below pasture grass, with ingrowth of radioactive daughters being computed explicitly. The input source of radioactivity may be prescribed by the user as a step function for each nuclide in the chain. The model employs time-dependent interception fractions for deposition of activity on food crops; the interception fractions for deposition on pasture grass or pasture soil are at present constants, but the facility for use of time-dependent values is provided. Seasonal aspects of the transfer of radionuclides between various compartments of the model include the provision for specifying the dates of emergence and harvest for various crop categories.

The system of differential equations describing the model is solved by use of a discrete-variable numerical integration (the GEAR package), and the accuracy of this solution is monitored by comparing the total radioactivity in the system as calculated by the numerical procedure with that calculated by use of an explicit solution of the Bateman equations.

This report discusses the development of the model which is presently on-going, and thus, does not represent the final version envisioned for implementation. Output for a sample run of the current version is provided in this report.

1. INTRODUCTION

A number of terrestrial food-chain transport models have been developed over the past several years for use in assessing ingestion dose to man from aerially deposited radionuclides.[1] Included among these is a transport model described in the U. S. Nuclear Regulatory Commission's (USNRC) Regulatory Guide 1.109, a model which NRC considers acceptable for assessing terrestrial transport of radionuclides released during normal operation of light-water-cooled nuclear power plants.[2] Limitations of these models with respect to dynamic seasonal considerations as well as radioactive daughter ingrowth prompted model development work, the initial progress of which is reported here.

RAGTIME (Radionuclides in AGricultural systems: a TIME-dependent model) computes radionuclide concentrations in food crops, beef, and milk which are contaminated by radionuclide deposition. The model assumes a known rate of deposition of radioactivity (microcuries per square meter per day, μCi m^{-2} day^{-1}) at a given environmental location and uses interception fractions S_1, S_2, S_3, and S_4 to calculate radioactivity input rates to the model compartments representing aboveground food, the soil surface below the food crop, pasture grass, and pasture soil or root mat, respectively, at that location. RAGTIME is basically an adaptation of the previously developed TERMOD code[3] to consider both seasonality of agricultural processes and the dynamics of daughter ingrowth of radionuclides during food-chain transport. Because the development of RAGTIME is still in progress, some parameters and concepts believed to be inadequate for the intended use of this code have been carried over from TERMOD until appropriate revisions can be made.

The system of linear ordinary differential equations describing the model accounts explicitly for ingrowth of radioactive daughters and provides for an input source of each member of a radionuclide chain. This system is solved by use of the GEAR package[4] for solution of systems of ordinary differential equations. A subroutine, CHECK, of RAGTIME provides a check on the accuracy of this solution. At each output time, CHECK makes use of an explicit solution of the Bateman equations to calculate the total amount of radioactivity in the system; this value is compared with the total obtained by summing the amounts of radioactivity in all model compartments as computed by the GEAR subroutine.

In Sect. 2 of this report, we describe in broad outline the RAGTIME methodology and present the equations which describe the model. Sections 3 and 4 provide details concerning the interception fractions S_1, S_2, S_3, and S_4 and the transfer coefficients of the system. Section 5 is devoted to a discussion of the use of the GEAR package in solving the system of differential equations of the model and to a description of the way the Bateman equations are used. Finally, a description of the RAGTIME computer code is provided in Sect. 6, giving details regarding input, logical structure, and calls to the GEAR subroutines as well as the procedure employed by subroutine CHECK to monitor the accuracy of the numerical solution.

As mentioned previously, there are a number of limitations of the present version of the RAGTIME model which remain to be addressed. Principal among planned refinements is the inclusion of the seasonal cycle in the dairy and beef pathways. Aside from an example run for the ^{90}Sr-^{90}Y chain, this report will not present a data base, the development of which is presently in progress. The present code uses an array of output times with a fixed size; whereas the integration interval may be of indefinite length, this fixed array limits the output density which is possible without recompilation. It may be desirable to remove this dependence on a fixed array in a future version.

Among planned revisions is the conversion of the RAGTIME code to the International System of Units (SI), thus effecting a change in the expression for radioactivity from curie (Ci) to becquerel (Bq), where

$$1\ \text{Ci} = 3.7 \times 10^{10}\text{Bq}. \tag{1.1}$$

The current version of the code uses Ci to represent activity, and the following documentation is consistent with this convention although the output may easily be converted to Bq using the relationship given above.

2. DESCRIPTION OF THE MODEL

The RAGTIME model is represented schematically in Fig. 2.1. The subscript i associated with the compartments E_i, S_i, P_i, etc. refers to the *ith* nuclide of a radionuclide decay chain. Certain of the transfer coefficients are nuclide-, or element-, dependent; this is also signified by the use of the subscript i, [e.g., $(\tau_{p,t})_i$]. The deposition source F_i represents the input source of radioactivity corresponding to the *ith* nuclide of a radionuclide chain. This source strength may vary with time and may be represented in the computer code as a step function for each nuclide in the chain. The fractions of input radioactivity which are intercepted by above-ground crops, soil surface below the food crop, pasture grass, and pasture soil are represented by S_1, S_2, S_3, and S_4, respectively. These fractions may be time-dependent with respect to growth dynamics of the crop land or pasture. In Sect. 3.1, we describe models for calculation of time-dependent interception fractions S_1 and S_2. The present version of the code uses values of S_3 and S_4 which are constant with respect to time; however, the same subroutine is used to return values for all interception fractions, so that a convenient method is available should the user desire to prescribe time-dependent values for S_3 and S_4.

A general outline of the terrestrial pathways considered in RAGTIME follows, along with a brief description of parameters used in implementing the computer simulation. A more rigorous definition and the rationale behind the particular quantifications used for each parameter are given in Sects. 3 and 4 of this report.

2.1 Radioactivity Transfer to Crops

Radioactivity deposited on the surface of the above-ground food crop passes to the soil surface below the food crop with an environmental half-time of usually less than 30 days.[5] We have used 14 days for this value [$\tau_{e,s} = \ln 2/(14 \text{ days}) = 0.0495 \text{ day}^{-1}$].[3,6] For transfer

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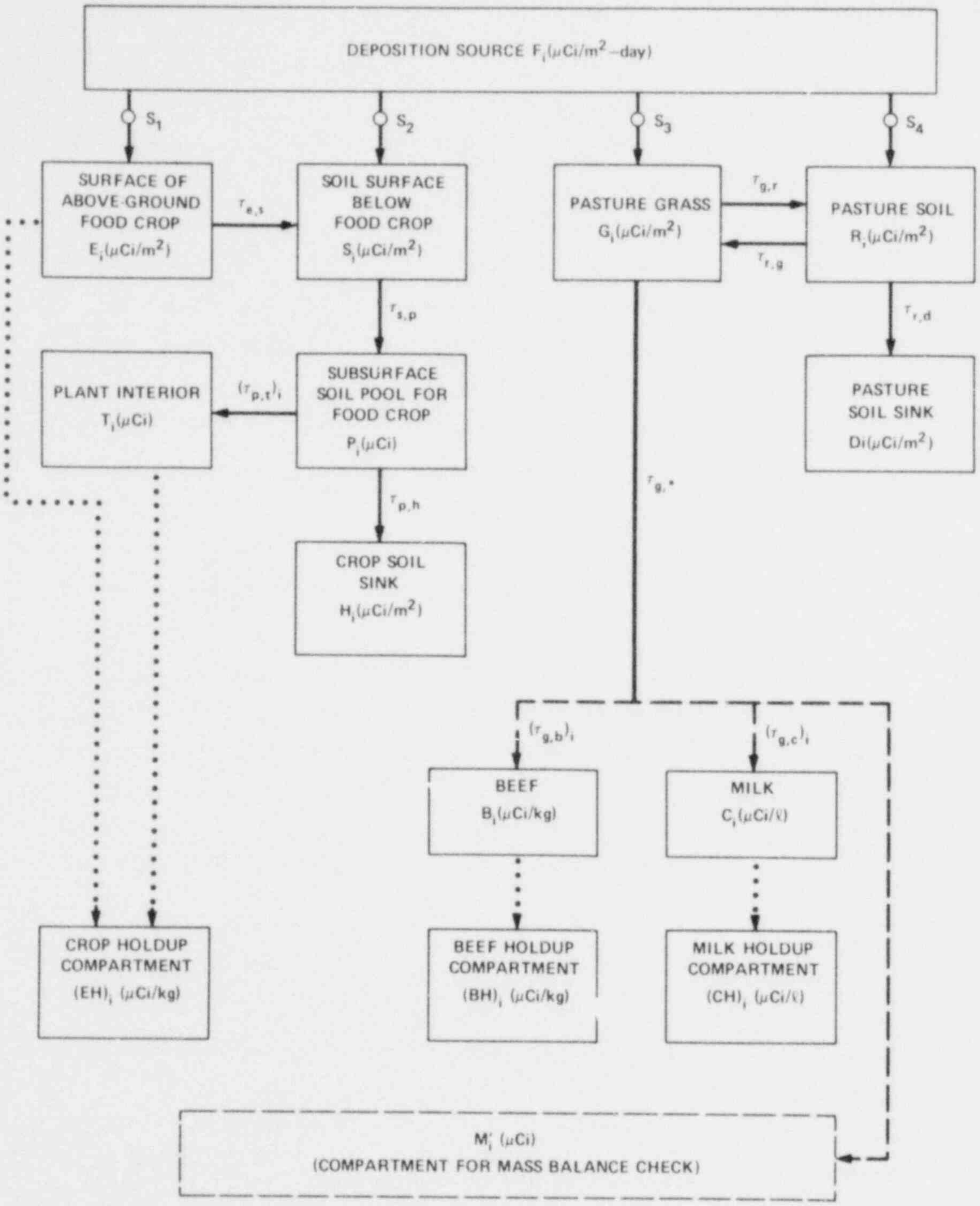

Fig. 2.1 Schematic representation of radioactivity transfer to food crops, milk, and beef as simulated by the RAGTIME computer code.

from the soil surface below the food crop to the subsurface soil pool, we have assumed a 1000-day environmental half-time, giving $\tau_{s,p}$ = ln 2/(1000 days) = 6.93×10^{-4} day^{-1}. Radioactivity in the subsurface soil pool is available for uptake by plant roots. The plant interior compartment T_i simulates radioactivity which is transferred to the edible parts of crops as a result of root uptake.

In Sect. 3.2 and Appendix B, we describe a model for calcultion of a nuclide-and time-dependent rate coefficient $(\tau_{p,t})_i$ representing this transfer of activity. We have assumed a loss rate of 4% per year from the subsurface soil compartment P_i to the soil compartment below the roots, H_i, giving $\tau_{p,h}$ = 0.04/(365 days) = 1.096×10^{-4} day^{-1} (Refs. 3,7). The dotted lines from compartments E_i (surface of above-ground food crop) and T_i (plant interior) to $(EH)_i$ (crop holdup compartment) represent harvest of crops.

The level of radioactivity in all compartments associated with crops at a given time is dependent on the histories of both the deposition source strength and on the growth of these crops. The effect of crop growth upon the activity level on crop surfaces (compartment E_i) is simulated through use of the time-dependent interception fraction $\mathcal{S}_1$. The time-dependent transfer coefficient $(\tau_{p,t})_i$ serves this function with regard to the plant interior compartment T_i. Before the emergence of plants, the value of $\mathcal{S}_1$ is zero, as is that for $(\tau_{p,t})_i$. At harvest time, the entire food crop is assumed to be stored in a holdup compartment $(EH)_i$, after which time the radioactivity concentration level in this food is assumed to be affected only by the radioactivity decay process. Thus, the activity level in the compartments representing crops in the field (compartments E_i and T_i) is zero except at times between the emergence and harvest of crops. Harvest of crops is simulated numerically by reinitialization of the state variables representing these compartments at harvest time, [i.e., the compartments E_i and T_i which represent activity associated with crops in the field are set to zero, and the compartment $(EH)_i$ representing harvested crops is assigned a value (in microcuries per kilogram) to reflect its receipt of all radioactivity from E_i and T_i].

2.2 Radioactivity Transfer to Beef and Milk

As in the case of transfer from the surface of the above-ground food crop to the soil surface, we have assumed a 14-day environmental, or retention, half-time for the loss of radioactivity from pasture grass to pasture soil [$\tau_{g,r}$ = ln 2/(14 days) = 0.0495 day^{-1}].[3,6] To account for uptake of radioactivity by pasture grass from soil, we have assumed a transfer rate of 1% per year from R_i to G_i [$\tau_{r,g}$ = 0.01/(365 days) = 2.74 x 10^{-5} day^{-1}].[3,7] As in the determination of $\tau_{p,h}$, a transfer rate of 4% per year from the pasture soil compartment R_i to the soil below the roots D_i [$\tau_{r,d}$ = 0.04/(365 days) = 1.096 x 10^{-4} day^{-1}] was assumed.[3,7] The rate coefficient for loss of activity from pasture grass resulting from grass consumption by a cow is denoted by $\tau_{g,\star}$. The derivation of a value for this coefficient is discussed in Sect. 4.1. The beef compartment B_i represents the concentration of activity in the muscle of a steer and C_i simulates the concentration of activity in milk in the udder of a cow. It is not assumed that the total loss from the pasture grass compartment, G_i, due to a cow's grass consumption is accounted for by gains to the beef and milk compartments B_i and C_i. Rather, the transfer coefficients $(\tau_{g,b})_i$ and $(\tau_{g,c})_i$ account for only portions of the total activity transferred to the cow through consumption of grass, those portions being the activity transferred to beef (B_i) and milk (C_i), respectively. The remainder of the loss from G_i due to a cow's consumption is considered only for the purpose of allowing a mass-balance check of total radioactivity in the system. This remainder, being the complement of $(\tau_{g,b})_i$ and $(\tau_{g,c})_i$ with respect to $\tau_{g,\star}$, is indicated in Fig. 2.1 as a dashed line drawn to the compartment M_i'. The compartment M_i' is used only in connection with the performance of a mass-balance check. Details concerning the procedure used by the code to perform this check are given in Sects. 5.2 and 6.3.

The dotted lines from the beef and milk compartments B_i and C_i to the holdup compartments $(BH)_i$ and $(CH)_i$, respectively, represent the effect of storage on the radionuclide concentration in these foods. At each output time, the computer prints, in addition to the activity concentrations of beef (B_i) and milk (C_i) at the given time, the concentration levels which these foods would reach if stored for a user-specified period of time (t_b^h for beef, t_c^h for milk). Thus, at a given output time t, $(BH)_i$ represents the activity concentration (μCi kg^{-1}) of nuclide i in beef at time $t + t_b^h$ which was stored from time t to time $t + t_b^h$, assuming a concentration level B_i at time t. The definition of $(CH)_i$ (μCi liter^{-1}) is similar. Since the determination of the values of $(BH)_i$ and $(CH)_i$ from those for B_i and C_i involves only the application of the process of radioactive decay (using the Bateman equations), the system of differential Eqs. (2.1) through (2.11) representing the model depicted in Fig. 2.1 does not contain equations corresponding to these holdup compartments. In Sect. 6.2 we present details concerning calls to a subroutine, RESDNS, which uses an explicit solution of the Bateman equations to calculate values for $(BH)_i$ and $(CH)_i$.

2.3 The System of Equations

The following system of equations describes the transfer of deposited radioactivity to food crops, beef, and milk as depicted in Fig. 2.1. As pointed out in Sect. 2.2, the compartments $(BH)_i$ and $(CH)_i$ are not represented by differential equations since their values are calculated using only the Bateman equations (see Sect. 6.2). Furthermore, the differential equation for the compartment M_i', which is used only in connection with a mass-balance check, is not included here but is discussed in Sect. 6.2. Definitions of the compartments used in the RAGTIME model follow the system of equations. Descriptions of all other quantities used in these equations along with the values used for certain of those which represent constants (at present) are given in Table 2.1. Values of nuclide-dependent and crop-specific parameters for a sample run of RAGTIME are given in Appendix B (Table B.1) along with a description of how these values are derived from empirical data.

Crop surface

$$\frac{dE_i}{dt} = \mathcal{S}_1 F_i(t) - (\lambda_i^R + \tau_{e,s})E_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} E_j \tag{2.1}$$

Crop soil surface

$$\frac{dS_i}{dt} = \mathcal{S}_2 F_i(t) + \tau_{e,s} E_i - (\lambda_i^R + \tau_{s,p})S_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} S_j \tag{2.2}$$

Crop soil pool

$$\frac{dP_i}{dt} = A\tau_{s,p} S_i - [\lambda_i^R + (\tau_{p,t})_i + \tau_{p,h}]P_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} P_j \tag{2.3}$$

Pasture grass

$$\frac{dG_i}{dt} = \mathcal{S}_3 F_i(t) - (\lambda_i^R + \tau_{g,r} + \tau_{g,*})\, G_i + \tau_{r,g} R_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} G_j \tag{2.4}$$

Pasture soil

$$\frac{DR_i}{dt} = \mathcal{S}_4 F_i(t) + \tau_{g,r} G_i - (\lambda_i^R + \tau_{r,g} + \tau_{r,d})R_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} R_j \tag{2.5}$$

Pasture soil sink

$$\frac{dD_i}{dt} = \tau_{r,d} R_i - \lambda_i^R D_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} D_j \tag{2.6}$$

Milk

$$\frac{dC_i}{dt} = (\tau_{g,c})_i G_i - (\lambda_i^R + \tau_{milk})C_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij} C_j \tag{2.7}$$

Beef

$$\frac{dB_i}{dt} = (\tau_{g,b})_i G_i - [\lambda_i^R + \tau_{beef} + (\tau_{exc})_i]B_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij} B_j \qquad (2.8)$$

Interior of crops

$$\frac{dT_i}{dt} = (\tau_{p,t})_i P_i - \lambda_i^R T_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij} T_j \qquad (2.9)$$

Crop soil sink

$$\frac{dH_i}{dt} = (\tau_{p,h}/A) P_i - \lambda_i^R H_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij} H_j \qquad (2.10)$$

Stored crops

$$\frac{d(EH)_i}{dt} = -\lambda_i^R (EH)_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij} (EH)_j \qquad (2.11)$$

The RAGTIME compartments are described as follows:

E_i	Radioactivity present on the surface of the above-ground food crop per square meter of surface on which the crop is grown (μCi m^{-2})
S_i	Radioactivity present at the soil surface below food crops (μCi m^{-2})
P_i	Radioactivity present in the subsurface soil pool associated with one man's food supply (μCi)
G_i	Radioactivity present in the pasture grass compartment (μCi m^{-2})
R_i	Radioactivity present in the pasture soil from ground surface to the root depth of the grass (μCi m^{-2})
D_i	Radioactivity present in the pasture soil below the root depth (μCi m^{-2})

C_i	Concentration of radioactivity in the milk (μCi liter^{-1})
B_i	Concentration of radioactivity in beef (μCi kg^{-1})
T_i	Radioactivity present in the interior of plants produced for human consumption (μCi)
H_i	Radioactivity present in the crop soil below the root depth (μCi m^{-2})
$(EH)_i$	Concentration of radioactivity in food which is stored following harvest of crops (μCi kg^{-1})
$(BH)_i$	Concentration of radioactivity in the beef holdup compartment (μCi kg^{-1})
$(CH)_i$	Concentration of radioactivity in the milk holdup compartment (μCi liter^{-1})

Table 2.1 Description of symbols used in the RAGTIME model

Symbol	FORTRAN Name	Description	Type[a]
A	A	Soil surface area (m^2) required to furnish food crops for one man	
A_g	ASUBG	Pasture area per cow (m^2)	
B_{ij}	B(I,J)	Radioactive branching ratio from species j to species i ($j < i$)	b
B_{iv}	BSUBIV(I)	Concentration of nuclide i per unit fresh weight in plant (μCi kg^{-1}) divided by concentration of nuclide per unit dry weight in soil (μCi kg^{-1})	b
d	SMALLD	Depth of plow layer (cm)	
D_g	DSUBG	Dry weight areal grass density (kg m^{-2})	
$F_i(t)$	F(I,T)	Input rate (μCi m^{-2} day^{-1}) for i*th* nuclide at time t (days)	b, c
$(F_f)_i$	FSUBF(I)	Fraction of the daily intake of nuclide i by a beef cow which appears per kg of flesh at time of slaughter (day kg^{-1})	b
$(F_m)_i$	FSUBM(I)	Fraction of the daily intake of nuclide i by a dairy cow which appears per liter of milk at equilibrium (day $liter^{-1}$)	b
λ_i^R	LAMRR(I)	Radioactive decay rate for i*th* nuclide (day^{-1})	b
M_b	MSUBB	Mass of muscle on a steer at time of slaughter (kg)	
ρ	RHØ	Density of the soil (g cm^{-3})	
S_1	S1	Interception fraction for surface of above-ground food crop	c, d

Table 2.1 (continued)

Symbol	FORTRAN Name	Description	Type[a]
S_2	S2	Interception fraction for soil surface below food crop (1 - S_1)	*c, d*
S_3	S3	Interception fraction for pasture grass (0.25)	
S_4	S4	Interception fraction for soil surface or root mat below pasture grass (0.75)	
τ_{beef}	TAUBEF	Fraction of the beef herd slaughtered per day (day^{-1})	
$\tau_{e,s}$	TAUES	Transfer coefficient from E_i to S_i (day^{-1})	
$(\tau_{exc})_i$	TAUEXC(I)	Excretion rate of stable isotope of the nuclide from the muscle of a steer (day^{-1})	*b*
$\tau_{g,*}$		Rate coefficient representing loss of radioactivity from pasture grass due to cow's consumption of grass (day^{-1}); defined to be $V_c/(A_g D_g)$	
$(\tau_{g,b})_i$	TAUGB(I)	Transfer coefficient from G_i to B_i (m^2 kg^{-1} day^{-1})	*b*
$(\tau_{g,c})_i$	TAUGC(I)	Transfer coefficient from G_i to C_i (m^2 liter^{-1} day^{-1})	*b*
$\tau_{g,r}$	TAUGR	Transfer coefficient from G_i to R_i (day^{-1})	
τ_{milk}	TAUMLK	Transfer rate of milk from the udder (day^{-1})	
$\tau_{p,h}$	TAUPH	Transfer coefficient from P_i to H_i (day^{-1})	
$(\tau_{p,t})_i$	TAUPT(I)	Transfer coefficient from P_i to T_i (day^{-1})	*b, c, d*

Table 2.1 (continued)

Symbol	FORTRAN Name	Description	Type[a]
$\tau_{r,d}$	TAURD	Transfer coefficient from R_i to D_i (day^{-1})	
$\tau_{r,g}$	TAURG	Transfer coefficient from R_i to G_i (day^{-1})	
$\tau_{s,p}$	TAUSP	Transfer coefficient from S_i to P_i (day^{-1})	
t_b^h	TIMBH	Holdup time for beef (days)	
t_c^h	TIMCH	Holdup time for milk (days)	
U	U	Milk capacity of the udder (liters)	
V_c	VSUBC	Dry weight consumption per day by a cow (kg day^{-1})	

[a] No type specified means parameter is nuclide- and time-independent.

[b] Nuclide-dependent.

[c] Time-dependent.

[d] Crop-specific parameters necessary to derive these quantities are described and quantified in Appendix B of this report.

3. PARAMETERS DESCRIBING TRANSFER TO CROPS

Modes of contamination of edible portions of crop plants include the interception and retention of aerially depositing radionuclides by crops as well as root uptake following deposition onto crop soils. In addition, interception and retention by crops of radionuclides resuspended from soil may contribute to the contamination of foodstuffs, although this pathway is not represented in the model at present. The relative importance of each of these modes of contamination will depend on many factors including the mobility of the radionuclide in soil, the availability of the nuclide for root uptake, the radiological half-life (-lives) involved, as well as the types of crops being considered.

In developing a model to describe these pathways of contamination, it is ncessary to consider seasonal cycles of crops (i.e., when the crops are and are not present during the year) as well as the time dependency of parameters describing contamination. Much of this time dependency is due to physiological and morphological changes in plants due to growth and maturation, and to changes which may be occurring in the chemical form of the radionuclide which is deposited either on plant or soil surfaces. Although time dependency due to chemical transformations has not been considered to date, the present model can potentially incorporate parameters of this type. At present, the time dependency of the interception parameters S_1 and S_2 (see Fig. 2.1) and of the root uptake parameter $(\tau_{p,t})_i$ have been studied, and preliminary approaches to characterizing the dynamic nature of these parameters are discussed below.

A holdup compartment, $(EH)_i$, is utilized in this model in order to account for radioactive decay and daughter buildup that may occur between harvest of crops and consumption by man (Fig. 2.1). The length of this interval is left to the user's discretion.

3.1 Time-dependent Aerosol Interception (S_1 and S_2)

The interception of airborne radionuclides by edible portions of crop plant will depend on these major factors:

1. the surface area exposed to depositing particles,
2. the shape of the edible portion and its orientation to depositing particles, and
3. the particle density of the depositing material.

Because some of these parameters are specific for different plant species, edible crops have been divided into categories representing plant parts with similar morphological characteristics. The following categories have been recognized:

1. root crops and other crops with protected edible parts,
2. leafy vegetables,
3. exposed-grain crops,
4. cylindrical vegetables, and
5. spherical vegetables.

Ideally, empirical data regarding interception of airborne particles over the growth cycles of crops should be used to represent the time dependency of this mode of contamination. However, because data of this type are not readily available, certain simplifying assumptions were made to account for the factors affecting interception. It is hoped that the adequacy of these assumptions will be tested at a later date through validation studies and sensitivity analyses.

At present, we have attempted to model the dynamics of interception by assuming that interception is a direct function of the projected surface area of the edible portion, and that interception occurs at a 90° angle to the plane of the projected surface area. The time dependency of interception thus relies on the relationship of the projected surface area of the edible portion to the mass of that portion during plant growth. This relationship may be characterized either through the use of empirical data – for example, that obtained by the Stanford Research Institute[9] for several crops – or by assuming the density of the vegetative matter remains constant during growth and using geometric procedures to derive projected areas as a function of plant growth.

The mathematical representation of the crop compartment E_i, which intercepts depositing radionuclides, was given in Sect. 2.3 [Eq. (2.1)] as

$$\frac{dE_i}{dt} = \mathcal{S}_1 F_i(t) - (\lambda_i^R + \tau_{e,s})E_i + \lambda_i^R \sum_{j=1}^{i-1} \mathcal{B}_{ij}E_j \ .$$

The fraction $\mathcal{S}_1$ of depositing radionuclides intercepted by the edible portion may be defined in two ways, depending on whether this fraction represents an empirically derived or theoretical (geometric) relationship with time. An empirical approach is

$$\mathcal{S}_1 = S_L^o m^{(1-n_L)} w \ , \tag{3.1}$$

where

S_L^o and n_L = empirical constants,

m = time-dependent mass of the plant part (g dry-weight),

w = number of plant parts per square meter.

An example of a time-dependent curve for m is given in Appendix B. This representation of $\mathcal{S}_1$ is adapted from a document prepared by the Stanford Research Institute,[9] which supplies values for the empirical constants $\mathcal{S}_1$ and n_L for certain plant species. The empirical constants were derived for considerations of specific surface area (m^2 g^{-1}) alone, for a given planting density w, and thus may be appropriate only for similar planting configurations. A geometric approach for estimating the relationship of $\mathcal{S}_1$ with time is provided by Miller,[9] where the change in projected surface area with time may be calculated by assigning a geometric configuration that best approximates the plant part of interest.

The output for a sample run of RAGTIME, which considers grains in compartment E_i (surface of above-ground crops) and is listed in Appendix B, was obtained by using the empirical approach for estimating the time dependency of S_i. Empirical constants, used in Eq. (3.1), are also available for edible parts of a few other plant species, including beans, cabbage, peppers, and squash.[9]

The value of S_2, shown in Fig. 2.1, representing deposition of airborne radionuclides onto the soil surface below the food crop (S_i), is calculated by assuming that

$$S_2 = 1 - S_1 \ . \tag{3.2}$$

It is recognized that this approach may overestimate the soil deposition since inedible parts of food crops will intercept depositing radionuclides. Radionuclides intercepted by inedible portions may all eventually reach the soil when the field is plowed following harvest, less any radioactive decay during retention on plant surfaces.

3.2 Time-dependent Root Uptake $(\tau_{p,t})_i$

Time dependence of root uptake is especially important when considering radioactive daughter ingrowth and soil depletion of a particular radionuclide. It is expected that root uptake will be a function of the increase in biomass of a plant or plant part over time as well as of the physiological stage in the life cycle of the plant. Both biomass increase and physiologic maturation may involve active and passive processes by which plant tissues incorporate elements. Many essential elements are both actively and passively acquired, while other elements may only be passively acquired. Because many radionuclides are radioactive isotopes or chemical analogs of essential elements, root uptake rates should be described in an element-, as well as time-, dependent sense.

Literature reviewed to date indicates a paucity of data regarding time-dependent root uptake of most elements. What is available indicates that the shape of the uptake curve, however, is similar to that of the growth curve for some elements and crop species studied.[10-16] Therefore, the approach adopted in RAGTIME is either to characterize uptake rates by edible portions of crops on the basis of any empirical data available, or to assume that the uptake rate follows growth curve for the edible portion in the absence of empirical uptake data.

The uptake curve obtained via either of these two approaches is then adjusted such that the concentration in the edible portion for a chosen harvest time is related to the soil concentration at that time by the empirically derived concentration factor, B_{iv}. The value for B_{iv} is obtained from empirical studies which measure the final crop concentration with respect to a soil concentration believed to be approximately constant throughout the growth cycle. Thus, for elements whose concentrations are significantly decreased in the root zone either by movement downward into the soil sink or uptake by crops, concentration factors derived from initial soil concentrations and final crop concentrations may not be appropriate.

3.3 Time-independent Parameters ($\tau_{e,s}$, $\tau_{s,p}$ and $\tau_{p,h}$)

Retention, both initial and long-term, of intercepted radionuclides will depend on[8]

1. the surface characteristics of the edible portion,
2. the particle size,
3. the wind velocity, and
4. the relative humidity and amount of rainfall.

The effect each of these will have on retention will vary from site to site, and thus, the value of $\tau_{e,s}$, the retention coefficient, may vary greatly. For the present, we have assumed an average, time-dependent value of $\tau_{e,s}$ of 0.0495 day^{-1}, consistent with that provided in TERMOD,[3] until further research into this parameter can be undertaken.

The movement of radionuclides deposited on surface soil to the root zone has been characterized in TERMOD as $\tau_{s,p}$. The definition and value of this parameter has been carried over to RAGTIME, pending future investigation into its appropriateness. It is possible that this parameter might best be described in a time-dependent sense, with empirical data being derived from soil distribution coefficients, or K_d's, available in the literature. Because these K_d's are element-specific, it may also be necessary to incorporate nuclide-specificity into the definition of $\tau_{s,p}$.

The downward movement of radionuclides out of the root zone into the soil sink is again characterized by a time- and nuclide-independent parameter, $\tau_{p,h}$, adopted from TERMOD. As with $\tau_{s,p}$, further research into the appropriateness of the value and interpretation of this parameter is pending.

4. PARAMETERS DESCRIBING TRANSFER TO BEEF AND MILK

Contamination of beef and milk may occur as a result of the interception or root uptake of depositing radionuclides by forage crops, and the subsequent ingestion by beef or dairy cattle. The RAGTIME code, to date, considers that this contamination occurs only through grazing of exposed pasture grasses by cattle. Thus, the loss and/or buildup of radionuclides present in stored feeds and hay, upon which cattle may depend for a large portion of the year, are not considered at this time. Furthermore, inhalation of radioactivity by cattle is not yet treated explicitly.

4.1 Contamination of Pasture Grass

As with food crops (Sect. 3), pasture grass (G_i) may be contaminated through interception of depositing radionuclides, including resuspended particulates, and through root uptake of nuclides deposited on the soil or root mat (R_i) below the pasture grass. At present, a pasture exposed to depositing radionuclides is assumed to maintain an approximately constant plant biomass throughout the year, and that the interception fraction for grasses, S_3, remains constant. The assumed value of S_3, equal to 0.25, is equivalent to the value originally used in TERMOD,[3] and falls in the range of empirical measurements reported by Chamberlain[17] for initial retention (where sampling is done immediately after contamination) by grasslands. This parameter would be expected to vary with plant density and other environmental factors, and thus represents an average value here. The fraction, S_3, is applied directly to the aerosol source term, F_i (see Fig. 2.1), and thus the model does not explicitly account for interception of radionuclides resuspended from the soil or root mat below the pasture grass.

The fraction S_4, in Fig. 2.1, represents the fraction of depositing activity not initially intercepted by grass leaves and thus the fraction deposited on the surface soil or root mat below the leaves. Therefore, this value is assigned a constant value of 0.75, being defined as follows:

$$S_4 = 1 - S_3 \ . \tag{4.1}$$

The value of the parameter $\tau_{r,g}$, representing additional input into the pasture grass compartment from surface soil, is consistent with the TERMOD value[3] adopted from a paper by Menzel,[7] which indicates that an upper limit for uptake of radionuclides in the surface soil by a single crop is 1%. Considered on an annual basis, $\tau_{r,g}$ becomes 2.74×10^{-5} day^{-1}.

Three aspects of root uptake by pasture grasses have not been considered at present. First, the element dependency of this parameter, $\tau_{r,g}$, has been neglected, yet may be quite important when root uptake is significant with respect to foliar contamination. Second, an additional mode or root absorption of radionuclides which does not involve the soil may be quite significant. This latter mode of uptake involves the radionuclide availability for uptake from the root mat, which is a "thatch" of dead and decomposing tissues around the plant-base region in which grasses may root.[7] Finally, the time dependency of $\tau_{r,g}$ has not been investigated. All of these aspects will be addressed as work continues on RAGTIME.

Loss of radionuclides from the grass compartment, G_i (see Fig. 2.1), may occur through ingestion of grass by grazing cattle ($\tau_{g,*}$), radioactive decay (λ_i^R), and by weathering of surface-deposited radionuclides ($\tau_{g,r}$). The value of $\tau_{g,r}$ is assumed to be equivalent to the weathering coefficient, $\tau_{e,s}$, discussed in Sect. 3, and thus represents a 14 day half-time for retention of intercepted materials. This value is consistent with data reported by Chamberlain[17] for grasslands, although it may vary with seasons and climatic factors. In particular, this weathering coefficient, when measured, will incorporate loss of surface material due to shedding of the protective leaf cuticle during plant growth,[17] thus suggesting a seasonal and species dependency of $\tau_{g,r}$. As with $\tau_{e,s}$, $\tau_{g,r}$ is assumed to be time independent until further research dictates that a different approach should be taken.

The value of $\tau_{g,*}$ (day^{-1}) will depend on the rate of loss of radionuclides in pasture grass through consumption by grazing beef and dairy cattle. For this model, an average ingestion rate, V_c, of 10 kg day^{-1} dry matter was assumed, consistent with the value used in TERMOD.[3] Using this ingestion rate and a dry-weight areal grass density, D_g, of 0.15 kg m^{-2} (Ref. 3), we define the value of $\tau_{g,*}$ to be

$$\tau_{g,*} = \frac{V_c}{A_g D_g} = \frac{6.67 \times 10^{-1} \text{ day}^{-1}}{A_g} , \tag{4.2}$$

where

A_g = pasture area per cow (m^2).

At present, it is assumed that $\tau_{g,*}$ is constant throughout the year. Further work on incorporating seasonal aspects into the model will modify this approach.

The rate of loss of radionuclides from the surface soil (R_i) beneath pasture grass is represented by the parameter $\tau_{r,d}$. As with the similarly defined parameter, $\tau_{p,h}$, for crop soil (Sect. 3), an element-independent rate of 1.096×10^{-4} day^{-1} is used, as given in documentation of the TERMOD code.[3] Again, further research may indicate a more appropriate value or representation of this process.

4.2 Contamination of Beef and Milk

Transfer of radionuclides from pasture grass to beef or milk is parameterized by $(\tau_{g,b})_i$, in m^2 kg^{-1} day^{-1}, or $(\tau_{g,c})_i$, in m^2 liter^{-1} day^{-1}, respectively (see Fig. 2.1). These parameters represent transfer rates and are assumed to be time independent pending further investigation into data available regarding their time dependency. Element-specific values of $(\tau_{g,b})_i$ and $(\tau_{g,c})_i$ were calculated from empirically derived transfer coefficients,[18, 19] $(F_f)_i$ and $(F_m)_i$, which characterize the ratios between beef or milk concentrations of an element and the equilibrium concentration of that element in pasture grass or feed. By definition

F_f = the fraction of the daily intake of an element by a beef cow which appears per kg of flesh at time of slaughter (day kg^{-1}), and

F_m = the fraction of the daily intake of an element by a dairy cow which appears per liter of milk at equilibrium (day liter^{-1}).

Therefore, the empirical coefficients represent the theoretical coefficients only if pasture grass (or feed) is the only source of the element in question in the cow's diet. The parameter $(\tau_{g,b})_i$ was derived by assuming that the concentration in beef at time of slaughter approximates an equilibrium concentration, given an equilibrium concentration in pasture grass. Thus, if $(B^{eq}_{cow})_i$ is taken to represent the equilibbium concentration of an element, i, in the muscle of a single cow (μCi kg^{-1}), and G^{eq}_i is the equilibrium concentration in grass (μCi m^{-2}), then from the equilibrium equation

$$\frac{d(B_{cow})_i}{dt} = (\tau_{g,b})_i G^{eq}_i - (\tau_{exc})_i (B^{eq}_{cow})_i = 0, \tag{4.3}$$

it follows that

$$\frac{(B^{eq}_{cow})_i}{G^{eq}_i} = \frac{(\tau_{g,b})_i}{(\tau_{exc})_i} , \tag{4.4}$$

where

$(\tau_{exc})_i$ = loss rate of the element, i, from the muscle of a steer (day^{-1}). Since

$$(\tau_{g,b}) = \frac{(B^{eg}_{cow})_i}{G^{eq}_i} (\tau_{exc})_i \tag{4.5}$$

and

$$(F_f)_i = \frac{(B^{eq}_{cow})_i}{(G^{eq}_i \times V_c/D_g)} \quad , \qquad (4.6)$$

where

V_c = dry-weight grass consumption per day by a cow (10 kg day^{-1}),

D_g = dry-weight areal grass density (0.15 kg m^{-2}),

it follows that the expression for $(\tau_{g,b})_i$ is related to $(F_f)_i$ by:

$$(\tau_{g,b})_i = \frac{(F_f)_i(\tau_{exc})_i V_c}{D_g} \quad , \qquad (4.7)$$

Assuming the animal's diets to consist solely of pasture grass, the loss rate of the element from the muscle of a steer, $(\tau_{exc})_i$, may be interpreted to represent both the element-specific metabolic turnover, as well as the element-independent dilution of the concentration due to increase in muscle mass during growth. This approach has been adopted from the TERMOD code[3] for the present, but will probably be revised to reflect a dynamic, rather than steady-state, approach to modeling this pathway as model development progresses. In doing so, the dilution due to growth may be handled explicitly rather than incorporated into a term such as $(\tau_{exc})_i$.

Similarly for $(\tau_{g,c})_i$, representing transfer of element, i, to milk (C_i),

$$(\tau_{g,c})_i = \frac{(F_m)_i(\tau_{milk})V_c}{D_g} \quad , \qquad (4.8)$$

where

τ_{milk} = the element-independent loss rate from the udder (2 day^{-1}).

The value of τ_{milk} in this case corresponds to the frequency of milking, assumed to be twice daily, and other losses are considered negligible. Equation (4.8) was derived in a manner similar to Eq. (4.7), from

$$\frac{d(C_{cow})_i}{dt} = (\tau_{g,c})_i G_i^{eq} - \tau_{milk}(C_{cow}^{eq})_i = 0, \tag{4.9}$$

and

$$(F_m)_i = \frac{(C_{cow}^{eq})_i}{(G_i^{eq} \times V_c/D_g)} \; . \tag{4.10}$$

Again, dynamics related to maturation and milking practices for a single cow have been neglected at this time, but will be considered as model development progresses.

The equation describing radionuclide concentrations in the beef compartment as whole [Eq. (2.8)], given in Sect. 2.3 of this report, as

$$\frac{dB_i}{dt} = (\tau_{g,b})_i G_i - [\lambda_i^R + \tau_{beef} + (\tau_{exc})_i]B_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij}B_j$$

differs from that for a single cow given in Eq. (4.3) due to the presence of an additional element-independent loss parameter, τ_{beef}. The interpretation of this aspect of the beef compartment has been adopted here from TERMOD,[3] in that the compartmental equation considers losses from beef in the herd as a whole by including the term, τ_{beef}, to account for slaughter of contaminated cattle. This interpretation then implies instantaneous replacement of the slaughtered portion with uncontaminated cattle and a subsequent reduction or loss of radioactivity from the compartment. The uncontaminated cattle then begin to accumulate radioactivity at a rate determined by $(\tau_{g,b})_i$. If, however, the radionuclide concentration in the beef compartment is to be used as an indication of man's radiation exposure via ingestion of beef, the present methodology may underestimate concentrations in beef of cattle being slaughtered. That is, this latter portion of the herd will likely be the more mature segment which has been exposed to contaminated pasture for the greatest length of time, although the concentration calculated will be an average of all members of the herd. In light of this potential deficiency, work is ongoing to revise the homogeneous herd concept, where uncontaminated and contaminated beef are indiscriminately mixed to produce an average concentration in the beef which may be lower than that in cattle ready for slaughter.

The milk compartment may also be interpreted to represent concentrations in milk obtained from the dairy herd as a whole. In this case, however, instantaneous replacement of milk removed from the udder by uncontaminated milk does not result in a reduction in concentration below that to which man might be exposed, because each lactating cow, as well as the herd, is subject to this same removal process. That is, while slaughtering will not affect the radionuclide concentration in beef of any particular cow, milking will affect the concentration in milk of each individual lactating cow in the herd, and thus can be considered when considering the herd as a whole.

For both milk and beef compartments, radionuclide loss and buildup of daughters due to radioactive decay during storage prior to human consumption is considered. Compartments $(CH)_i$ and $(BH)_i$, representing concentrations of each nuclide in milk and beef, respectively, following storage were devised to provide this information.

5. SOLUTION OF THE SYSTEM OF DIFFERENTIAL EQUATIONS

5.1 Use of the GEAR Subroutine

The system of differential Eqs. (2.1) through (2.11) is solved in the RAGTIME code by use of the GEAR package[4] for solution of systems of ordinary differential equations. The subroutine CALC of RAGTIME makes a call to the subroutine GEAR of the GEAR package at each output time to determine the values of the state variables,

$$E_i, S_i, P_i, G_i, R_i, D_i, C_i, B_i, T_i, H_i, \text{ and } (EH)_i ,$$

where i = 1 to n (the number of nuclides in the chain) at the given time. In the notation of the GEAR package, the system of differential Eqs. (2.1) through (2.11), with i varying from 1 to n, has the form

$$dY/dT = F(Y,T)$$

where Y = [Y(1), Y(2), ..., Y(N)] is the state vector at time T, with N representing the number of state variables. The present version of RAGTIME uses N = 12 x n state variables (n = the number of nuclides in the chain). The correspondence between RAGTIME state variable names and those used in the GEAR package is shown in Table 5.1.

The user of the GEAR package furnishes a subroutine DIFFUN(N,T,Y, YDØT) which computes the function YDØT = F(Y,T), the right-hand side of the system of ordinary differential equations, where N, T, and Y are as described above. The correspondence indicated above between RAGTIME state variable names and those used by the GEAR package implies a similar correspondence between the two notations for derivatives (Table 5.2).

The notation used in subroutine CALC of RAGTIME for a call to the GEAR subroutine for values of the state variables at the time TØUT is

```
CALL GEAR (DIFFUN, PEDERV, N, TO, HO, YO, TØUT, APS, MF, INDEX)
```

Table 5.1 Definition of RAGTIME state variables in terms of GEAR package notation

RAGTIME state variable	GEAR package notation
E_i	Y[12(i - 1) + 1]
S_i	Y[12(i - 1) + 2)
P_i	Y[12(i - 1) + 3)
G_i	Y[12(i - 1) + 4]
R_i	Y[12(i - 1) + 5]
D_i	Y[12(i - 1) + 6)
C_i	Y[12(i - 1) + 7]
B_i	Y[12(i - 1) + 8]
$(EH)_i$	Y[12(i - 1) + 9]
T_i	Y[12(i - 1) + 10]
H_i	Y[12(i - 1) + 11]

Table 5.2 Definition of RAGTIME derivatives in terms of GEAR package notation

RAGTIME derivatives	GEAR package notation
dE_i/dt	YDOT[12(i - 1) + 1]
dS_i/dt	YDOT[12(i - 1) + 2]
dP_i/dt	YDOT[12(i - 1) + 3]
dG_i/dt	YDOT[12(i - 1) + 4]
dR_i/dt	YDOT[12(i - 1) + 5]
dD_i/dt	YDOT[12(i - 1) + 6]
dC_i/dt	YDOT[12(i - 1) + 7]
dB_i/dt	YDOT[12(i - 1) + 8]
$d(EH)_i/dt$	YDOT[12(i - 1) + 9]
dT_i/dt	YDOT[12(i - 1) + 10]
dH_i/dt	YDOT[12(i - 1) + 11]

where the parameters have the following meanings:

(1) DIFFUN is the name of the subroutine described above, which is declared external in subroutine CALC.

(2) PEDERV is also a subroutine which is declared external in CALC. Under certain options available to the user of the GEAR subroutine, this subroutine is used to define the N by N Jacobian matrix of partial derivatives. However, under the option used by RAGTIME, PEDERV is a dummy subroutine.

(3) N is the number of state variables (i.e., N = 12 x n in our case).

(4) T0 is the initial value of T, the time variable (used only on the first call).

(5) H0 is the step size for T (used only on the first call).

(6) Y0 is a vector of length N (= 12 x n) containing the initial values of Y. This vector is used for input only on the first call.

(7) TOUT is the value of T at which output is desired.

(8) EPS is the relative error bound (used only on the first call unless INDEX = -1).

(9) MF is a parameter used to indicate the basic method to be used for integration (Adams method or the stiff method of GEAR) and the method of iteration.

(10) INDEX is an integer used to indicate the type of call. Initially, INDEX is set to 1. The value returned for INDEX is 0 unless the integration was halted for some reason. For meanings of the values -1, -2, -3, or -4, for an output value of INDEX, see a listing of the GEAR package.

5.2 Use of the Bateman Equations as a Check

Since RAGTIME uses a numerical method for solution of the system of differential Eqs. (2.1) through (2.11), it is desirable to have a procedure for checking the accuracy of this solution. Fortunately, it is possible to calculate the total amount of radioactivity in the system at any given time using an explicit solution of the Bateman equations. This value can then be compared with the corresponding value calculated by summing the amounts of radioactivity in the various compartments of the model as calculated by use of the GEAR package. Close agreement of these two values is a necessary but not sufficient condition that the numerical solution of the model equations is accurate to the degree desired. In particular, one should keep in mind that a large relative error in a compartment whose radioactivity contribution is small compared to other compartments would be masked by this summing procedure. Nevertheless, the comparison of total radioactivity as calculated in these two ways provides valuable assistance in evaluating the numerical method since, as most practitioners of numerical analysis would admit, the use of such methods is still largely an empirical science. In particular, this comparison can provide guidance for the selection of appropriate options and parameter values to be used in calls to the GEAR subroutine.

The Bateman equations describe the decay process of a radionuclide chain. Consider a chain of radionuclide species indexed i = 1, ..., n in a comparment into which the exogenous inflow rate of the *ith* species is given by $I_i(t)$(μCi day^{-1}) and which is subject to first-order removal processes with removal constant, λ_i^B (day^{-1}). Then the following system of differential equations describes the decay process in this compartment:

$$\frac{dA_i}{dt} = -(\lambda_i^R + \lambda_i^B)A_i + \lambda_i^R \sum_{j=1}^{i-1} B_{ij}A_j + I_i(t), \quad i = 1, \ldots, n \qquad (5.1)$$

where

$A_i(t)$ = radioactivity (μCi) of the *ith* nuclide at time t (day),

λ_i^R = decay constant (day^{-1}) for the *ith* nuclide,

λ_i^B = removal constant (day^{-1}) for the *ith* nuclide,

B_{ij} = radioactive branching ratio from species j to species i, $j < i$,

$I_i(t)$ = exogenous inflow rate for species i (μCi day^{-1}).

For the purpose of checking the total amount of activity in the RAGTIME compartments against the value as predicted using the Bateman equations, we may regard the total exogenous inflow rate for species i into the system to be the product of the deposition source $F_i(t)$ (μCi m^{-2} day^{-1}) and the quantity

$$S_1A + S_2A + S_3 A_g + S_4A_g = (S_1 + S_2)A + (S_3 + S_4)A_g \ , \qquad (5.2)$$

where

A = soil surface area (m^2) assumed for the above-surface food crop,

A_g = soil surface area (m^2) assumed for the pasture grass compartment.

Subroutine CHECK of RAGTIME makes a call to subroutine TRAFUN for the purpose of calculation of the total radioactivity in the system at various times. TRAFUN requires that the function representing the exogenous input rate be a step function of time, which dictates that $F_i(t)$ be a step function. Furthermore, TRAFUN requires that the exogenous input rate be prescribed as a doubly dimensioned array rather than as a FORTRAN function. We thus reserve for Sect. 6.3 an explicit description of the call by CHECK to TRAFUN, in order to make use of our description in Sect. 6.1 of the doubly dimensioned inflow rate matrix

FF which is defined in subroutine INPUT and whose values are used to define both the deposition source function $F_i(t)$ [in FORTRAN, F(I,T)] and the doubly dimensioned exogenous input rate matrix P which is used as an input parameter to TRAFUN.

6. THE RAGTIME CODE

6.1 Input

The subroutine INPUT reads values for user-supplied data required by RAGTIME. The first value read is that for NUMNUC, the number of nuclides in the chain. Next read are the names of the nuclides [NAMNUC(I), I = 1 to NUMNUC] and the initial ground deposition source (microcuries per square meter) for each nuclide [FO(I), I = 1 to NUMNUC]. Following these steps values are read for MP and for the arrays

TIMEP(KP), KP = 1 to MP

and

FF(I,KP), I = 1 to NUMNUC, KP = 1 to MP

where

FF(I,KP) = inflow rate of species I (microcuries m^{-2} day^{-1}) for the time interval TIMEP(KP) to TIMEP(KP+1) if KP < MP,

FF(I,MP) = inflow rate at times subsequent to TIMEP(MP).

The matrix FF defines the exogenous input of radioactivity into the system. This matrix is used to define values of the fallout source function $F_i(t)$ [in FORTRAN, FUNCTIØN F(I,T)]. Also FF is used in subroutine CHECK to define the exogenous input rate matrix P as discussed in Sects. 5.2 and 6.3. Next read are the number (NUMBRA) of and values for the radioactive branching ratios. The FORTRAN notation B(I,J) is used to denote the radioactive branching ratio from species J to species I(J < I). If NUMBRA = 0, no branching ratios are read. If NUMBRA $\geq$ 1, then one card is read for each nonzero branching ratio, the READ statement and its associated FØRMAT being

```
      READ(RDR,50) PARNUC,DAUNUC,BRATIØ
   50 FØRMAT(A8,5X,A8,5X,E13.6)
```

where PARNUC is the name of the "parent" and DAUNUC the name of the "daughter." For example, the card

```
BI210        PØ210          1.0
↑            ↑           ⏟⏟⏟⏟⏟⏟⏟
col. 1       col. 14     cols. 27-40
```

is used to input the branching ratio 1.0 from ^{210}Bi to ^{210}Po. The input subroutine assigns the value BRATIØ to the element B(I,J) of the matrix of branching ratios in such a manner that B(I,J) represents the branching ratio from the nuclide NAMNUC(J) to NAMNUC(I).

Following input of the branching ratios, information regarding desired output times is read. The entire integration interval is specified as consisting of a number (NINTVL) of subintervals, with INCR(I) denoting the interval between successive output times for the subinterval indexed by I. The right endpoint of the subinterval indexed by I is denoted by ENDTIM(I). The READ statement and its associated FØRMAT statement for input of these quantities is

```
   READ(RDR,90) INCR(I),ENDTIM(I)
90 FØRMAT(E13.6,I6)
```

In subroutine CALCIN, the arrays INCR and ENDTIM are used to define values for the entire array of output times TIM(I), I = 1 to NTIM.

Values for the radionuclide-dependent parameters listed in Table 6.1 are read next. For definitions of these parameters, see Table 2.1. One card is read for each of these parameters, the cards being read in the order indicated in Table 6.1 for each value of I, with I varying from 1 to NUMNUC. The format for each card is (10X,E13.7).

We now consider the input of nuclide-independent parameters. The main program of RAGTIME handles any number of radionuclide chains. The first executable statement of MAIN is

```
   READ(RDR,10) NCHAIN
10 FØRMAT(10X,I2)
```

Table 6.1 Radionuclide-dependent input parameters for RAGTIME

Parameter symbol	FORTRAN name
λ_i^R	LAMRR(I)
$(F_m)_i$	FSUBM(I)
$(F_f)_i$	FSUBF(I)
B_{iv}	BSUBIV(I)
$(\tau_{exc})_i$	TAUEXC(I)

where NCHAIN is the number of chains to be considered. Following this read statement, the main program makes calls to the subroutine INPUT, ØUTDAT, CALCIN, HARVST, CALC, and CHECK in this order for each chain under consideration. In order to avoid the necessity of inputting the nuclide-independent parameters for each chain, a flag, IFLAG, is set in MAIN and passed as a parameter in the call to INPUT [CALL INPUT(IFLAG)] to enable a branch to be made around the input of these parameters for calls subsequent to the first one. Values are read for the nuclide-independent parameters listed in Table 6.2. For definitions of these parameters, see Table 2.1. One card is read for each of these parameters, the format being (10X,E13.7).

The final segment of code in INPUT reads values for certain GEAR subroutine parameters (see Sect. 5.1).

6.2 Logical Structure of the Code

After calling subroutine INPUT for input of data related to a given chain, the main program calls ØUTDAT for a printout of these data. Next a call is made to subroutine CALCIN, which calculates the values of certain coefficients used in the system of differential Eqs. (2.1) through (2.11). These coefficients, the numbers of the equations in which they occur, and their FORTRAN designations are as follows:

Table 6.2 Nuclide-independent input parameters for RAGTIME

Parameter symbol	FORTRAN name
A	A
A_g	ASUBG
d	SMALLD
D_g	DSUBG
M_b	MSUBB
ρ	RHO
τ_{beef}	TAUBEF
τ_{milk}	TAUMLK
$\tau_{e,s}$	TAUES
$\tau_{g,r}$	TAUGR
$\tau_{p,h}$	TAUPH
$\tau_{r,d}$	TAURD
$\tau_{r,g}$	TAURG
$\tau_{s,p}$	TAUSP
U	U
V_c	VSUBC
t_b^h	TIMBH
t_c^h	TIMCH

Coefficient	Occurs in equation	FORTRAN name
$\lambda_i^R + \tau_{e,s}$	2.1	LAMA(I)
$\lambda_i^R + \tau_{s,p}$	2.2	LAMS(I)
$\lambda_i^R + \tau_{g,r} + \lambda_{g,*}$	2.4	LAMG(I)
$\lambda_i^R + \tau_{r,g} + \tau_{r,d}$	2.5	LAMR(I)
$\lambda_i^R + \tau_{milk}$	2.7	LAMC(I)

Subroutine CALCIN also defines values of the array of output times TIM(I), I = 1 to NTIM as discussed in Sect. 6.1. Following the call to CALCIN, the main program calls subroutine HARVST in which emergence and harvest times for crop plants are specified. The FORTRAN name for the number of harvests considered is NHARV. Subroutine HARVST assigns values to NHARV and to the arrays EMERGE(I), I = 1 to NHARV, and HARTIM(I), I = 1 to NHARV, where

EMERGE(I) = date (days) for I*th* emergence time for plants,

HARTIM(I) = date (days) for I*th* harvest time for plants.

After calling HARVST, MAIN calls subroutine CALC which serves the following functions [(1)-(4)]:

(1) Initializes and prints definitions of compartments E_i, S_i, P_i, G_i, R_i, C_i, B_i, T_i, $(EH)_i$, $(BH)_i$, and $(CH)_i$.

(2) Assigns values to GEAR subroutine parameters INDEX, T0, H0, and N (Sect. 5.1).

(3) Assigns values to the arrays TR(INUC), TB(INUC), and PRØRAT (INUC), INUC = 1 to NUMNUC, where

TR(INUC) = radioactive half-life (days) of nuclide INUC,

TB(INUC) = biological half-time (days) of nuclide INUC (a large value is assigned to approximate a biological removal factor of zero),

PRØRAT(INUC) = (constant) production rate for nuclide INUC.

These arrays are used as input parameters to the subroutine RESDNS, which is called by CALC for calculation (using an explicit solution of the Bateman equations) of the radioactivity level in the holdup compartments $(BH)_i$ and $(CH)_i$ as discussed in Sect. 2.2. The array PRØRAT is used to specify the production rate in compartment $(BH)_i$ and is therefore assigned zero values since no exogenous input is assumed for this compartment.

(4) Following steps (1) through (3), subroutine CALC executes a loop,

```
DØ 4 I = 1,NTIM
```

in which the values of the state variables defined by Eqs. (2.1) through (2.11) as well as the holdup compartments $(BH)_i$ and $(CH)_i$ are computed and printed. At each time TØUT = TIM(I), a call is made to the GEAR subroutine,

```
CALL(DIFFUN,PEDERV,N,TO,HO,YO,TØUT,EPS,MF,INDEX)
```

for calculation of values of the state variables E_i, S_i, P_i, G_i, R_i, D_i, C_i, B_i, T_i, H_i and $(EH)_i$, where i = 1 to the number (NUMNUC) of nuclides in the chain. These values are returned in the array YO, with the same correspondence between RAGTIME state variable names and GEAR package names as indicated in Sect. 5.1; for example, the value of E_i is given by YO[12(i - 1) + 1].

At each output time, CALC calculates and saves in the array TØTUCI the total activity in the system corresponding to each nuclide. We define

TØTUCI(I,INUC) = total activity (microcuries) in the system corresponding to nuclide INUC at time TIM(I).

If we assume A square meters of land devoted to crop production and A_g square meters of pasture grass, the appropriate multiplicative factors for converting the values in the various compartments to microcuries are given in Table 6.3. The values of these conversion factors are obvious for all except compartments C_i, B_i, and $(EH)_i$. For the milk compartment C_i, we assume one cow for each A_g square meters of pasture grass, with an udder capacity of U liters per cow. Similarly, the conversion factor for the beef compartment follows from our assumption of M_b kilograms of muscle per steer, with one steer per A_g square meters of pasture grass. The conversion factor $M_f^0/1000$ for the crop holdup compartment $(EH)_i$ is based on the definition

M_f^0 = total mass (grams) of crop per A m^2 at harvest time.

The compartment M_i' is used only in connection with a mass-balance check. This compartment serves to account for the loss to the system of activity from the beef and milk compartments B_i and C_i as well as the complement of the activity represented by transfer coefficients $(\tau_{g,b})_i$ and $(\tau_{g,c})_i$ with respect to $\tau_{g,*}$. The differential equation for M_i' is

Table 6.3 Conversion factors used to convert compartmental concentrations to total activity

Compartment	Units	FORTRAN name	Conversion factor
E_i	μCi m^{-2}	YO[12(i - 1) + 1]	A
S_i	μCi m^{-2}	YO[12(i - 1) + 2]	A
P_i	μCi	YO[12(i - 1) + 3]	1
G_i	μCi m^{-2}	YO[12(i - 1) + 4]	A_g(ASUBG)
R_i	μCi m^{-2}	YO[12(i - 1) + 5]	A_g(ASUBG)
D_i	μCi m^{-2}	YO[12(i - 1) + 6]	A_g(ASUBG)
C_i	μCi $liter^{-1}$	YO[12(i - 1) + 7]	U
B_i	μCi kg^{-1}	YO[12(i - 1) + 8]	M_b(MSUBB)
$(EH)_i$	μCi kg^{-1}	YO[12(i - 1) + 9]	$M_f^0/1,000$
T_i	μCi	YO[12(i - 1) + 10]	1
H_i	μCi m^{-2}	YO[12(i - 1) + 11]	A
M_i	μCi	YO[12(i - 1) + 12]	1

$$\frac{dM_i'}{dt} = \tau_{beef} M_b B_i + \tau_{milk} U C_i - \lambda_i^R M_i' + \Big[V_c/D_g - (\tau_{g,b})_i M_b - (\tau_{g,c})_i U \Big] G_i, \tag{6.1}$$

where

M_b = mass of muscle on a steer at time of slaughter (kg),

U = milk capacity of the udder (liters).

The other parameters were defined and discussed in Sects. 2, 3, and 4 of this report. The first two terms on the right-hand side of this equation represent gains to M_i' resulting from losses to compartments B_i and C_i through slaughter of cattle and milking of cows, respectively. The third term accounts for radioactive decay in M_i'. The last term represents the loss to compartments G_i which is not accounted for by the terms $(\tau_{g,b})_i G_i$ and $(\tau_{g,c})_i G_i$ in Eqs. (2.7) and (2.8), respectively.

With MFO as the FORTRAN name for M_f^0, the FORTRAN statement defining TØTUCI(I,1) is therefore

```
     TØTUCI(I,1) = YO(1)*A + YO(2)*A + YO(3) + YO(4)*ASUBG
    1            + YO(5)*ASUBG + YO(6)*ASUBG + YO(7)*U + YO(8)*MSUBB
    2            + YO(9)*(MFO/1000.) + YO(10) + YO(11)*A + YO(13),
```

(6.2)

the generalization for TØTUCI(I,INUC) being obvious.

After defining values of the array TØTUCI(I,INUC) for a given I and for INUC = 1 to NUMNUC, calls are made to subroutine RESDNS for the calculation of values of the beef and milk holdup compartments $(BH)_i$ and $(CH)_i$. The statements executing these calls are

```
    CALL RESDNS(TIMBH,NUMNUC,TR,TB,B,PRØRAT,QOBEF,QBEF,QWIGL,IDIM)
    CALL RESDNS(TIMCH,NUMNUC,TR,TB,B,PRØRAT,QOMLK,QMLK,QWIGL,IDIM)
```

where TIMBH, TIMCH, NUMNUC, TR, TB, B (matrix of branching ratios) and PRØRAT are as defined previously. On input, the arrays QOBEF and QOMLK contain the values in the beef and milk compartments B_i and C_i, respectively, at the current time TIM(I). The concentration levels (μCi kg^{-1}) which beef and milk would reach if stored for the period of time (days) specified by TIMBH and TIMCH are returned in the arrays QBEF and QMLK, respectively. The array QWIGL contains residence values (μCi-days) on output and is not used by RAGTIME. The parameter IDIM specifies the maximum dimensions for the matrix of branching ratios as defined in RESDNS (REAL BRANCH(IDIM,IDIM)). Following these calls to RESDNS, values of the various compartments, including the holdup compartments for beef and milk, are printed for the current time.

The final section of code within the I-loop determines whether or not the current time, TIM(I), is a harvest time, and if so, reinitializes the state variables E_i, T_i, and $(EH)_i$ to simulate harvest. First the following call is made to subroutine QUERY:

```
CALL QUERY(TIM(I),IANS)
```

This subroutine searches the array of harvest times, HARTIM, and returns IANS = 1 if TIM(I) is a harvest time, IANS = 0 if not. If TIM(I) is a harvest time, the crop holdup compartment $(EH)_i$ is reinitialized to the value

$$\frac{\text{total activity (μCi) in compartments } E_i \text{ and } T_i}{\text{total mass (kg) of crop at harvest time}} = \frac{AE_i + T_i}{M_f^0 \times 0.001} \tag{6.3}$$

after which the compartments E_i and T_i are set to zero. After completion of the I-loop, control returns to the main program.

As pointed out in Sect. 5.1, the system of differential Eqs. (2.1) through (2.11) is defined in subroutine DIFFUN. The GEAR package makes calls to DIFFUN for values of YDØT at various times as described in Sect. 5.1. The deposition source function $F_i(t)$ of Eqs. (2.1), (2.2), (2.4), and (2.5) is defined by means of the FORTRAN function F(I,T). This function is defined in terms of the inflow rate matrix

FF(I,KP), I = 1 to NUMNUC, KP = 1 to MP

as described in Sect. 6.1.

The final subroutine called by MAIN is subroutine CHECK. Details concerning this subroutine are discussed in the following section.

6.3 Subroutine CHECK

The last subroutine called by MAIN is subroutine CHECK. This subroutine calculates and prints values of

TØTUCI(ITIM,INUC) = total activity (μCi) due to nuclide INUC at time TIM(ITIM) as calculated in subroutine CALC by calls to the GEAR subroutine (discussed in Sect. 6.2)

ACT(INUC,ITIM) = total activity (μCi) due to nuclide INUC at time TIM(ITIM) as calculated by subroutine TRAFUN, using the Bateman equations,

and the percentage error

```
(TØTUCI(ITIM,INUC)) - ACT(INUC,ITIM)*100./ACT(INUC,ITIM)
```

for times TIM(ITIM), ITIM = 1 to NTIM. The call to TRAFUN is as follows:

```
CALL TRAFUN(NUMNUC,TR,TB,B,MP,TIMEP,P,NTIM,RTIM,AWIGL,ACT,IDIM)
```

The meanings of NUMNUC, TR (radioactive half-lives), TB (biological half-times), B (matrix of branching ratios), MP (Sect. 6.1), TIMEP (Sect. 6.1), NTIM (number of output times), and IDIM are as defined previously. The array RTIM is a real array whose values are the same as those for the double precision array TIM of output times. The matrix

P(INUC,KP), INUC = 1 to NUMNUC, KP = 1 to MP

defines the total exogenous input rate of each nuclide to the system for each of the time intervals TIMEP(KP), KP = 1 to MP. From the definition of the inflow rate matrix FF (Sect. 6.1) and our assumption of A square meters of crop production land and A_g square meters of pasture land, it follows that the correct expression for P(INUC,KP) is

P(INUC,KP) = FF(INUC,KP)*((S1 + S2)*A + (S3 + S4)*ASUBG)

Subroutine TRAFUN returns in the array ACT the total activity levels as computed using the Bateman equations. After the call to TRAFUN, the values of the arrays TØTUCI and ACT as well as the percentage errors are printed.

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REFERENCES

1. F. O. Hoffman, C. W. Miller, D. L. Shaeffer, C. T. Garten, Jr., R. W. Shor, and J. T. Ensminger, *A Compilation of Documented Computer Codes Applicable to Environmental Assessment of Radioactivity Releases*, ORNL/TM-5830, Oak Ridge National Laboratory, Oak Ridge, Tennessee (April 1977).

2. U. S. Nuclear Regulatory Commission, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I*, Regulatory Guide 1.109, Revision 1, USNRC, Washington, D. C. (October 1977).

3. R. S. Booth and S. V. Kaye, *A Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment*, ORNL/TM-3135, Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1971).

4. A. C. Hindmarsh, *GEAR: Ordinary Differential Equation System Solver*, UCID-30001, Revision 3, Lawrence Livermore Laboratory, Livermore, California (December 1974).

5. J. P. Witherspoon and F. G. Taylor, Jr., "Interception and Retention of a Simulated Fallout by Agricultural Plants," *Health Phys.* 19, 493-499 (1970).

6. J. D. Zimbrick and P. G. Voillequé, ed., *1967 CERT Progress Report, Controlled Environmental Radioiodine Tests at the National Reactor Testing Station*, Progress Report Number Four, IDO-12065, Idaho Falls, Idaho (December 1968).

7. R. G. Menzel, "Factors Influencing the Biological Availability of Radionuclides for Plants," *Fed. Am. Soc. Exptl. Biol. Proc.* 22, 1398-1401 (1963).

8. C. F. Miller and Hong Lee, *Operation Ceniza-Arena: The Retention of Fallout Particles from Volcan Irazu (Costa Rica) by Plants and People*, Part One, SRI-MU-4890, Stanford Research Institute, Menlo Park, California (January 1966).

9. C. F. Miller, *Operation Ceniza-Arena: Retention of Fallout Particles from Volcan Irazu (Costa Rica) by Plants and People*, Part Three, SRI-MU-4890, Stanford Research Institute, Menlo Park, California (December 1967).

10. C. R. Belcher and J. L. Ragland, "Phosphorus Absorption by Sod-Planted Corn (*Zea mays L.*) from Surface-Applied Phosphorus," *Agronomy J.* 64, 754-756 (1972).

REFERENCES (cont'd)

11. J. L. Brewster, K. K. S. Bhat, and P. H. Nye, "The Possibility of Predicting Solute Uptake and Plant Growth Response from Independently Measured Soil and Plant Characteristics," *Plant and Soil* 42, 197-226 (1975).

12. G. L. Pacques, R. L. Vanderlip, and D. A. Whitney, "Growth and Nutrient Accumulation and Distribution in Grain Sorghum. I. Dry Matter Production and Ca and Mg Uptake and Distribution," *Agronomy J.* 67, 607-616 (1975).

13. L. H. P. Jones and K. A. Handreck, "Studies of Silica in the Oat Plant," *Plant and Soil* 23, 79-96 (1977).

14. J. E. Miller, J. J. Hassett, and D. E. Koeppe, "Interactions of Lead and Cadmium on Metal Uptake and Growth of Corn Plants," *J. Environ. Qual.* 6, 18-20 (1977).

15. M. B. Page, J. L. Smalley, and O. Talibudeen, "The Growth and Nutrient Uptake of Winter Wheat," *Plant and Soil* 49, 149-160 (1977).

16. C. L. Parks, A. W. White and F. C. Boswell, "Effect of a Plastic Barrier Under the Nitrate Band on Nitrogen Uptake by Plants," *Agronomy J.* 62, 437-439 (1970).

17. A. C. Chamberlain, "Interception and Retention of Radioactive Aerosols by Vegetation," *Atmos. Environ.* 4, 57-78 (1970).

18. R. E. Moore, C. F. Baes III, L. M. McDowell-Boyer, A. P. Watson, F. O. Hoffman, J. C. Pleasant, and C. W. Miller, *AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides*, ORNL-5532, Oak Ridge National Laboratory, Oak Ridge, Tennessee (June 1979).

19. Y. C. Ng, C. S. Colsher, D. J. Quinn, and S. E. Thompson, *Transfer Coefficients for the Prediction of the Dose to Man via the Forage-Cow-Milk Pathway from Radionuclides Released to the Biosphere*, UCRL-51939, Lawrence Livermore Laboratory, Livermore, California (July 1977).

APPENDIX A
LISTING OF RAGTIME SOURCE CODE
AND
JOB CONTROL LANGUAGE

```
LEVEL 21.8 ( JUN 74 )                               OS/360  FORTRAN H

       COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                         SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE INPUT (IFLAG)
                C
                C
                C       SUBROUTINE INPUT INPUTS ALL THE DATA
                C
                C
  ISN 0003              COMMON /HOLTIM/ TIMBH,TIMCH
  ISN 0004              COMMON /INFLOW/ MP, TIMEP(30), FF(15,30)
  ISN 0005              COMMON /BRANCH/ B(15,15)
  ISN 0006              COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0007              COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                     *                  TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0008              COMMON /NAMES/ NAMNUC(15)
  ISN 0009              COMMON /NUMBRS/ NUMNUC
  ISN 0010              COMMON /TIME/ TIM(365),INCR(30),ENDTIM(30),NINTVL,NTIM
  ISN 0011              COMMON /SOURCE/ FO(15)
  ISN 0012              COMMON /GPARAM/ EPS,MF
  ISN 0013              COMMON /IODEV / PTR,RDR
                C
                C
                C
  ISN 0014              DOUBLE PRECISION  NAMNUC,PARNUC,DAUNUC,TIM,EPS
  ISN 0015              INTEGER  ENDTIM,PTR,RDR
  ISN 0016              REAL  MSUBB,INCR,LAMRR
                C
                C
                C
                C***
                C***  NUMNUC - THE NUMBER OF NUCLIDES IN THE CHAIN BEING STUDIED
                C***
  ISN 0017              READ (RDR,10) NUMNUC
  ISN 0018           10 FORMAT (I3)
                C***
                C***  NAMNUC - ARRAY OF THE NAMES OF THE NUCLIDES IN THE CHAIN.
                C***  FO     - INITIAL GROUND DEPOSITION SOURCE FOR NUCLIDE(I)
                C***            WHERE I VARIES FROM 1 TO THE NUMBER OF NUCLIDES
                C***            (MICROCURIES PER SQUARE METER)
                C***
  ISN 0019              DO 30 I = 1,NUMNUC
  ISN 0020                  READ (RDR,20) NAMNUC(I),FO(I)
  ISN 0021           20     FORMAT (A8,E13.6)
  ISN 0022           30 CONTINUE
                C
                C***  INFLOW RATES FOR VARIOUS SPECIES
                C***
                C***  READ VALUES FOR THE ARRAYS
                C***
                C***  TIMEP(KP), KP=1 TO MP, AND
                C***  FF(I,KP), I=1 TO NUMNUC, KP=1 TO MP, WHERE
                C***
                C***  FF(I,KP) = INFLOW RATE OF SPECIES I (UCI/M**2-DAY) FROM
                C***             TIMEP(KP) TO TIMEP(KP+1) IF KP .LT. MP
                C***             AND FF(I,MP) IS THE RATE AT TIMES SUBSEQUENT TO
                C***             TIMEP(MP).
  ISN 0023              READ (RDR,200) MP
  ISN 0024          200 FORMAT(I5)
```

```
ISN 0025           DO 201  I=1,NUMNUC
ISN 0026           DO 201  KP=1,MP
ISN 0027       201 READ (RDR,202) TIMEP(KP),FF(I,KP)
ISN 0028       202 FORMAT(E13.6,2X, E13.6)
          C
          C
          C        MATRIX CONTAINING BRANCHING RATIOS INITIALIZED TO ZERO
          C        ******************************************************
          C
          C
          C***
          C***     B        - MATRIX CONTAINING THE BRANCHING RATIOS.
          C***
ISN 0029           DO 40 I = 1,NUMNUC
ISN 0030                DO 40 J = 1,NUMNUC
ISN 0031                     B(I,J) = 0.0
ISN 0032        40 CONTINUE
          C
          C
          C        BRANCHING RATIOS FILLED IN MATRIX
          C        *********************************
          C
          C
          C***
          C***     PARNUC  - PARENT NUCLIDE
          C***     DAUNUC  - DAUGHTER NUCLIDE
          C***     BRATIO  - BRANCHING RATIO
          C***     PARNOD  - INDEX INTO MATRIX B
          C***               REPRESENTS PARENT NUCLIDE
          C***     DAUNOD  - INDEX INTO MATRIX B
          C***               REPRESENTS DAUGHTER NUCLIDE
          C***     NUMBRA  - NUMBER OF NONZERO BRANCHING RATIOS
          C***
ISN 0033           READ (RDR,10) NUMBRA
ISN 0034           IF (NUMBRA.EQ.0) GO TO 160
ISN 0036           DO 70 I = 1,NUMBRA
ISN 0037              READ (RDR,50) PARNUC,DAUNUC,BRATIO
ISN 0038        50    FORMAT (A8,5X,A8,5X,E13.6)
          C
          C
          C        LOOP TO SET APPROPRIATE INDICES INTO MATRIX B
          C        *********************************************
          C
          C
ISN 0039           DO 60 J = 1,NUMNUC
ISN 0040                     IF(PARNUC .EQ. NAMNUC(J))  PARNOD = J
ISN 0042                     IF(DAUNUC .EQ. NAMNUC(J))  DAUNOD = J
ISN 0044        60       CONTINUE
ISN 0045              B(DAUNOD,PARNOD) = BRATIO
ISN 0046        70 CONTINUE
ISN 0047        80 CONTINUE
          C***
          C***     NINTVL - NUMBER OF INTERVALS SPECIFYING OUTPUT TIMES
          C***     INCR(I) -  STEPSIZE FOR INTERVAL I
          C***     ENDTIM(I) -  RIGHT ENDPOINT OF INTERVAL I (DAY)
          C***     NOTE THAT ENDTIM(1) SHOULD BE AN INTEGRAL MULTIPLE OF INCR(1)
          C***     AND FOR I GREATER THAN 1, ENDTIM(I) - ENDTIM(I-1) SHOULD BE AN
          C***     INTEGRAL MULTIPLE OF INCR(I).
```

```
               C***
ISN 0048         160 READ (RDR,10) NINTVL
ISN 0049               DO  100  I=1,NINTVL
ISN 0050                   READ (RDR,90) INCR(I),ENDTIM(I)
ISN 0051          90       FORMAT (E13.6,I6)
ISN 0052         100 CONTINUE
ISN 0053         110 CONTINUE
               C
               C
               C**********************************************************************
               C***                                                                 ***
               C***                 RADIONUCLIDE DEPENDENT PARAMETERS               ***
               C***                                                                 ***
               C**********************************************************************
               C***
               C***
               C***
               C***  BSUBIV - CONCENTRATION OF NUCLIDE PER UNIT FRESH WEIGHT IN PLANT
               C***           (MICROCURIES PER KILOGRAM) DIVIDED BY CONCENTRATION OF
               C***           NUCLIDE PER UNIT DRY WEIGHT IN SOIL  (MICROCURIES PER
               C***           KILOGRAM)
               C***  FSUBF  - THE FRACTION OF THE ANIMAL'S DAILY INTAKE OF NUCLIDE(I)
               C***           WHICH APPEARS IN EACH KILOGRAM OF FLESH  (DAYS PER KILOGRAM)
               C***  FSUBM  - FRACTION OF THE DAILY INTAKE OF NUCLIDE I BY A COW
               C***           WHICH APPEARS PER LITER OF MILK AT EQUILIBRIUM
               C***           (DAYS PER LITER).
               C***  LAMRR  - RADIOACTIVE DECAY RATE OF THE NUCLIDE UNDER STUDY
               C***           (PER DAY)
               C***  TAUEXC - EXCRETION RATE OF A STABLE ISOTOPE OF THE NUCLIDE FROM
               C***           THE MUSCLE OF A STEER  (PER DAY)
               C***
               C
               C
               C
ISN 0054               DO 130 I = 1,NUMNUC
ISN 0055                   READ (RDR,120) LAMRR(I)
ISN 0056                   READ (RDR,120) FSUBM(I)
ISN 0057                   READ (RDR,120) FSUBF(I)
ISN 0058                   READ (RDR,120) BSUBIV(I)
ISN 0059                   READ (RDR,120) TAUEXC(I)
ISN 0060         120       FORMAT (10X,E13.7)
ISN 0061         130 CONTINUE
               C
               C
ISN 0062               IF (IFLAG .EQ. 1) GO TO 140
ISN 0064               IFLAG = 1
               C
               C
               C**********************************************************************
               C***                                                                 ***
               C***                RADIONUCLIDE INDEPENDENT PARAMETERS              ***
               C***                                                                 ***
               C**********************************************************************
               C***
               C***
               C***  A      - SOIL SURFACE AREA REQUIRED TO FURNISH FOOD CROPS FOR ONE
               C***           MAN (SQUARE METERS)
               C***  ASUBG  - PASTURE AREA PER COW  (SQUARE METERS)
```

```
C***  SMALLD - DEPTH OF THE PLOW LAYER  (CENTIMETERS).
C***  RHO    - DENSITY OF THE SOIL  (GRAMS PER CUBIC CENTIMETER).
C***  MSUBB  - MASS OF MUSCLE ON A STEER AT THE TIME OF SLAUGHTER
C***           (KILOGRAMS PER STEER)
C***  TAUBEF - FRACTION OF THE BEEF HERD SLAUGHTERED  (PER DAY)
C***  TAUMLK - TRANSFER RATE OF MILK FROM THE UDDER  (PER DAY)
C***  TAUES  - TRANSFER COEFFICIENT FROM E TO S  (PER DAY)
C***  TAUGR  - TRANSFER COEFFICIENT FROM G TO R  (PER DAY)
C***  TAUPH  - TRANSFER COEFFICIENT FROM P TO H  (PER DAY)
C***  TAURD  - TRANSFER COEFFICIENT FROM R TO D  (PER DAY)
C***  TAURG  - TRANSFER COEFFICIENT FROM R TO G  (PER DAY)
C***  TAUSP  - TRANSFER COEFFICIENT FROM S TO P  (PER DAY)
C***  U      - MILK CAPACITY OF THE UDDER  (LITERS)
C***  VSUBC  - DRY WEIGHT GRASS CONSUMPTION PER DAY BY A COW
C***           (KILOGRAMS PER DAY)
C***  TIMBH  - HOLDUP TIME (DAYS) FOR BEEF
C***  TIMCH  - HOLDUP TIME (DAYS) FOR MILK
C***
C
C
C
      READ (RDR,001) A
      READ (RDR,001) ASUBG
      READ (RDR,001) SMALLD
      READ (RDR,001) RHO
      READ (RDR,001) DSUBG
      READ (RDR,001) MSUBB
      READ (RDR,001) TAUBEF
      READ (RDR,001) TAUMLK
      READ (RDR,001) TAUES
      READ (RDR,001) TAUGR
      READ (RDR,001) TAUPH
      READ (RDR,001) TAURD
      READ (RDR,001) TAURG
      READ (RDR,001) TAUSP
      READ (RDR,001) U
      READ (RDR,001) VSUBC
      READ (RDR,001) TIMBH
      READ (RDR,001) TIMCH
C
  001 FORMAT (10X,E13.7)
C
C
C*****************************************************************
C***                                                           ***
C***                GEAP SUBROUTINE PARAMETERS                 ***
C***                                                           ***
C*****************************************************************
C
      READ (RDR,002) EPS
 002  FORMAT (10X,D13.6)
C
      READ (RDR,003) MF
  003 FORMAT (10X,I2)
C
  140 CONTINUE
      RETURN
      END
```

```
LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                SUBROUTINE OUTDAT
               C
               C
               C          SUBROUTINE OUTDAT ECHOS THE DATA INPUT IN SUBROUTINE INPUT
               C
               C
  ISN 0003                COMMON /INFLOW/ MP,TIMEP(30), FF(15,30)
  ISN 0004                COMMON /HOLTIM/ TIMBH,TIMCH
  ISN 0005                COMMON /BRANCH/ B(15,15)
  ISN 0006                COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0007                COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                         *               TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0008                COMMON /NAMES/ NAMNUC(15)
  ISN 0009                COMMON /NUMBRS/ NUMNUC
  ISN 0010                COMMON /TIME/ TIM(365),INCR(30),ENDTIM(30),NINTVL,NTIM
  ISN 0011                COMMON /SOURCE/ F0(15)
  ISN 0012                COMMON /GPARAM/ EPS,MF
  ISN 0013                COMMON /IODEV / PTR,RDR
               C
               C
               C
  ISN 0014                DOUBLE PRECISION  NAMNUC,PARNUC,DAUNUC,TIM,EPS
  ISN 0015                INTEGER  ENDTIM,PTR,RDR
  ISN 0016                REAL  MSUBB,INCR,LAMRR
               C
               C
               C
               C          NUCLIDE DEPENDENT PARAMETERS
               C          ****************************
               C
  ISN 0017                WRITE (PTR,40)
  ISN 0018          40    FORMAT ('1',53X,'NUCLIDE DEPENDENT PARAMETERS' /////
                         *         ' ',49X,'***  DEFINITION OF PARAMETERS  ***' ///
                         *         ' ',28X,'BSUBIV - CONCENTRATION OF NUCLIDE PER UNIT ',
                         *                 'FRESH WEIGHT IN PLANT  (MICRO- ' /
                         *         ' ',37X,'CURIES PER KILOGRAM)  DIVIDED BY CONCENTRATION ',
                         *                 'OF NUCLIDE PER UNIT' /
                         *         ' ',37X,'DRY WEIGHT IN SOIL  (MICROCURIES PER KILOGRAM)')
               C
  ISN 0019                WRITE (PTR,60)
  ISN 0020          60    FORMAT (' ',28X,'F0      - INITIAL GROUND DEPOSITION SOURCE ',
                         *                 ' (MICROCURIES PER SQUARE METER)' /
                         *         ' ',28X,'FSUBF  - THE FRACTION OF THE ANIMAL''S DAILY ',
                         *                 'INTAKE OF NUCLIDE WHICH APPEARS ' /
                         *         ' ',37X,'IN EACH KILOGRAM OF FLESH  (DAYS PER KILOGRAM)'/
                         *         ' ',T30,'FSUBM  - FRACTION OF THE DAILY INTAKE OF ',
                         *                 'NUCLIDE I BY A COW WHICH APPEARS' /
                         *         ' ',T39,'PER LITER OF MILK AT EQUILIBRIUM  ',
                         *                 '(DAYS PER LITER).' )
               C
  ISN 0021                WRITE (PTR,70)
  ISN 0022          70    FORMAT (' ',28X,'LAMRR  - RADIOACTIVE DECAY RATE OF THE NUCLIDE ',
                         *                 'UNDER STUDY  (PER DAY)' )
               C
  ISN 0023                WRITE (PTR,80)
  ISN 0024          80    FORMAT (' ',28X,'TAUEXC - EXCRETION RATE OF A STABLE ISOTOPE OF ',
```

```
                   *               'THE NUCLIDE FROM THE MUSCLE OF' /
                   *   ' ',37X,'A STEER  (PER DAY)' )
              C
ISN 0025             WRITE (PTR,90)
ISN 0026         90  FORMAT (////' ',51X,'***  VALUES OF PARAMETERS  ***' ///
                   *         ' ',28X,'BSUBIV',12X,'FO',12X,'FSUBF',11X,'FSUBM',11X,
                   *               'LAMPR',11X,'TAUEXC' /)
              C
ISN 0027             DO 110 I = 1,NUMNUC
ISN 0028             WRITE (PTR,100) NAMNUC(I),BSUBIV(I),FO(I),FSUBF(I),FSUBM(I),
                   *                 LAMPR(I),TAUEXC(I)
ISN 0029        100      FORMAT(17X,A8,6(E13.6,3X),/)
ISN 0030        110 CONTINUE
              C
              C      BRANCHING RATIOS
              C      ****************
              C
ISN 0031             IF (NUMNUC .EQ. 1) GO TO 35
              C
ISN 0033             WRITE (PTR,10)
ISN 0034         10  FORMAT ('1',54X,'BRANCHING RATIOS' ///
                   *         ' ',48X,'FROM',7X,'TO',9X,'FRACTION' //)
              C
ISN 0035             DO 30 I = 1,NUMNUC
ISN 0036                 DO 30 J = 1,NUMNUC
ISN 0037                     IF (B(I,J) .EQ. 0.0) GO TO 30
ISN 0039                     WRITE (PTR,20) NAMNUC(J),NAMNUC(I),B(I,J)
ISN 0040          20         FORMAT (49X,A8,2X,A8,2X,E13.6,/)
ISN 0041          30 CONTINUE
ISN 0042          35 CONTINUE
              C
              C
              C      NUCLIDE INDEPENDENT PARAMETERS
              C      ******************************
              C
ISN 0043             WRITE (PTR,140) A
ISN 0044        140  FORMAT ('1',52X,'NUCLIDE INDEPENDENT PARAMETERS' ////
                   *         ' ',27X,'A',6X,'- SOIL SURFACE AREA REQUIRED TO FURNISH ',
                   *               'FOOD CROPS FOR ONE ' /
                   *         ' ',36X,'MAN  (SQUARE METERS)',38X,E13.6)
              C
ISN 0045             WRITE (PTR,145) ASUBG
ISN 0046        145  FORMAT (' ',27X,'ASUBG  - PASTURE AREA PER COW  (SQUARE METERS)',
                   *            21X,E13.6)
              C
ISN 0047             WRITE (PTR,146) SMALLD
ISN 0048        146  FORMAT (' ',27X,'SMALLD - DEPTH OF THE PLOW LAYER  (CENTIMETERS)',
                   *            20X,E13.6 )
              C
ISN 0049             WRITE (PTR,147) RHO
ISN 0050        147  FORMAT (' ',27X,'RHO    - DENSITY OF THE SOIL  (GRAMS PER CUBIC',
                   *              ' CENTIMETER)',9X,E13.6 )
              C
ISN 0051             WRITE (PTR,150) DSUBG
ISN 0052        150  FORMAT (' ',27X,'DSUBG  - DRY WEIGHT AREAL GRASS DENSITY  (KILO',
                   *               'GRAMS PER SQUARE'/
                   *         ' ',36X,'METER)',52X,E13.6)
              C
```

```
ISN 0053           WRITE (PTR,165) MSUBB
ISN 0054      165  FORMAT (' ',27X,'MSUBB  - MASS OF MUSCLE ON A STEER AT THE TIME ',
                  *                   'OF SLAUGHTER' /
                  *          ' ',36X,'(KILOGRAMS PER STEER)',37X,E13.6)
              C
ISN 0055           WRITE (PTR,190) TAUBEF
ISN 0056      190  FORMAT (' ',27X,'TAUBEF - FRACTION OF THE BEEF HERD SLAUGHTERED ',
                  *                   ' (PER DAY)',10X,E13.6)
              C
ISN 0057           WRITE (PTR,195) TAUMLK
ISN 0058       195  FORMAT (' ',27X,'TAUMLK - TRANSFER RATE OF MILK FROM THE UDDER  ',
                  *                   '(PER DAY)',11X,E13.6)
              C
ISN 0059           WRITE (PTR,200) TAUES
ISN 0060      200  FORMAT (' ',27X,'TAUES  - TRANSFER COEFFICIENT FROM E TO S  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0061           WRITE (PTR,205) TAUGR
ISN 0062      205  FORMAT (' ',27X,'TAUGR  - TRANSFER COEFFICIENT FROM G TO R  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0063           WRITE (PTR,210) TAUPH
ISN 0064      210  FORMAT (' ',27X,'TAUPH  - TRANSFER COEFFICIENT FROM P TO H  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0065           WRITE (PTR,215) TAURD
ISN 0066      215  FORMAT (' ',27X,'TAURD  - TRANSFER COEFFICIENT FROM R TO D  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0067           WRITE (PTR,220) TAURG
ISN 0068      220  FORMAT (' ',27X,'TAURG  - TRANSFER COEFFICIENT FROM R TO G  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0069           WRITE (PTR,225) TAUSP
ISN 0070      225  FORMAT (' ',27X,'TAUSP  - TRANSFER COEFFICIENT FROM S TO P  ',
                  *                   '(PER DAY)',15X,E13.6)
              C
ISN 0071           WRITE (PTR,235) U
ISN 0072      235  FORMAT (' ',27X,'U',6X,'- MILK CAPACITY OF THE UDDER  (LITERS)',
                  *             22X,F13.6)
              C
ISN 0073           WRITE (PTR,240) VSUBC
ISN 0074      240  FORMAT (' ',27X,'VSUBC  - DRY WEIGHT GRASS CONSUMPTION PER ',
                  *                   'DAY BY A COW  (KILOGRAMS' /
                  *          ' ',36X,'PER DAY)',50X,E13.6)
              C
ISN 0075           WRITE (PTR,300) TIMBH
ISN 0076      300  FORMAT (' ',27X,'TIMBH  - HOLDUP TIME (DAYS) FOR BEEF',31X,E13.6)
              C
ISN 0077           WRITE (PTR,305) TIMCH
ISN 0078      305  FORMAT (' ',27X,'TIMCH  - HOLDUP TIME (DAYS) FOR MILK',31X,E13.6)
              C
              C    OUTPUT SPECIFICATION TIMES
              C    **************************
              C
ISN 0079           WRITE (PTR,260)
ISN 0080      260  FORMAT ('1',52X,'OUTPUT SPECIFICATION TIMES' ////
                  *          ' ',54X,'INCREMENT',4X,'END OF INTERVAL' /
```

```
     *         ' ',56X,'(DAY)',11X,'(DAY)' //)
C
      DO 280 I = 1,NINTVL
          WRITE (PTR,270) INCR(I),ENDTIM(I)
  270     FORMAT (53X,E13.6,6X,I6)
  280 CONTINUE
C
C***  INFLOW RATES FOR VARIOUS SPECIES
C
C*************************************************************
      WRITE (PTR,400)
 400  FORMAT ('1',20X,'INFLOW RATES FOR VARIOUS SPECIES')
C
      WRITE (PTR,401)
 401  FORMAT ('0',26X,'INITIAL TIME',22X,'RATE')
C
      WRITE (PTR,402)
 402  FORMAT (' ',8X,'NUCLIDE',14X,'(DAYS)',20X,'(UCI/SQ.M/DAY)')
C
      DO  406   I=1,  NUMNUC
      WRITE (PTR,407)
  407 FORMAT(' ')
      DO  406    KP=1, MP
      IF (KP .EQ. 1) WRITE (PTR,404) NAMNUC(I),TIMEP(KP),FF(I,KP)
      IF (KP .GT. 1) WRITE (PTR,405) TIMEP(KP),FF(I,KP)
  406 CONTINUE
 404  FORMAT (' '.8X,A8,9X,E10.3,18X,E10.3)
 405  FORMAT (' ',25X,E10.3,18X,E10.3)
C
C     GEAR SUBROUTINE PARAMETERS
C     **************************
C
      WRITE (PTR,410)
 410  FORMAT ('1',54X,'GEAR SUBROUTINE PARAMETERS')
C
      WRITE (PTR,420) EPS
 420  FORMAT ('0',55X,'EPS = ',D15.6)
C
      WRITE (PTR,421) MF
  421 FORMAT ('0',T57,'MF = ',I2 )
C
      RETURN
      END
```

```
LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                                SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                SUBROUTINE CALCIN
                    C
                    C
                    C
                    C CALCULATES THE VALUES OF CERTAIN PARAMETERS WHICH ARE USED IN
                    C DEFINING THE COEFFICIENTS OF THE SYSTEM OF DIFFERENTIAL EQUATIONS.
                    C
                    C
                    C
  ISN 0003                COMMON /TIME/ TIM(365),INCR(30),ENDTIM(30),NINTVL,NTIM
  ISN 0004                COMMON /CROPS/ MFO
  ISN 0005                COMMON/LMDA/LAMR(15),LAMC(15),LAMB(15),LAMA(15),
                         C  LAMS(15),LAMG(15)
  ISN 0006                COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                         *                 TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0007                COMMON /NUMBRS/ NUMNUC
  ISN 0008                COMMON /PARAM/ TAUGC(15),TAUGB(15)
  ISN 0009                COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
                    C
                    C
                    C
  ISN 0010                DOUBLE PRECISION  TIM
  ISN 0011                INTEGER  ENDTIM
  ISN 0012                REAL  MSUBB,LAMRR,INCR,LAMR,LAMC,LAMB,LAMA,LAMS,LAMG,MFO
                    C
                    C MFO = TOTAL MASS (GRAMS) OF CROP AT HARVEST TIME - USED IN SUBROUTINES
                    C CALC AND TIMDEP (BASED ON A SQUARE METERS OF LAND, 250 PLANTS PER
                    C SQUARE METER, 1 GRAM PER PLANT).
                    C
  ISN 0013                MFO = A * 250.0
                    C
                    C
  ISN 0014                DO  1   I=1,NUMNUC
  ISN 0015                TAUGC(I)= (TAUMLK*FSUBM(I)*VSUBC) / DSUBG
  ISN 0016                TAUGB(I)=  (VSUBC*FSUBF(I)*TAUEXC(I)) / DSUBG
                    C
                    C  DEFINE LAMDAS
  ISN 0017                LAMR(I)=  LAMRR(I) + TAURG + TAURD
  ISN 0018                LAMC(I)=  LAMRR(I) + TAUMLK
  ISN 0019                LAMB(I)=  LAMRR(I) + TAUBEF  + TAUEXC(I)
  ISN 0020                LAMA(I)=  LAMRR(I) + TAUES
  ISN 0021                LAMS(I)=  LAMRR(I) + TAUSP
  ISN 0022                LAMG(I)=  LAMRR(I) + TAUGR + VSUBC/(ASUBG*DSUBG)
  ISN 0023              1 CONTINUE
                    C
                    C
                    C
                    C
                    C DEFINE TIME ARRAY FROM THE FOLLOWING INPUT INFORMATION.
                    C
                    C     NINTVL     = NUMBER OF SUBINTERVALS.
                    C
                    C     ENDTIM(I) = THE RIGHT ENDPOINT OF SUBINTERVAL I.
                    C     INCR(I)    = THE TIME INCREMENT FOR SUBINTERVAL I.
  ISN 0024                NPREV = 0
  ISN 0025                NTIM = 0
```

```
                C
                C
ISN 0026              DO 2  I=1,NINTVL
ISN 0027              IM1 = I-1
ISN 0028              IF(I.EQ.1) START=0.0
ISN 0030              IF(I.NE.1) START= ENDTIM(IM1)
ISN 0032              NUMSUB = (ENDTIM(I)-START) / INCR(I)
ISN 0033              NTIM = NTIM + NUMSUB
                C
ISN 0034              DO 3     J=1,NUMSUB
ISN 0035              II = NPREV + J
ISN 0036            3 TIM(II) = START + J*INCR(I)
                C
ISN 0037              NPREV = NUMSUB + NPREV
ISN 0038            2 CONTINUE
                C
                C
ISN 0039              RETURN
ISN 0040              END
```

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LEVEL 21.8 ( JUN 74 )                                OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002             SUBROUTINE CALC
                 C
                 C
                 C
                 C CALLS GEAR SUBROUTINE TO CALCULATE AND PRINT VALUES OF STATE VARIABLES
                 C
                 C
                 C
  ISN 0003             EXTERNAL PEDERV,DIFFUN
  ISN 0004             DIMENSION TR(15),TB(15),PRORAT(15),QOBEF(15),QOMLK(15),
                     *   QBEF(15),QMLK(15),QWIGL(15)
  ISN 0005             COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0006             COMMON /BRANCH/ B(15,15)
  ISN 0007             COMMON /HOLTIM/ TIMBH,TIMCH
  ISN 0008             COMMON /GPARAM/ EPS,MF
  ISN 0009             COMMON /MCHECK/ TOTUCI(365,15)
  ISN 0010             COMMON /NUMBRS/ NUMNUC
  ISN 0011             COMMON /TIME/ TIM(365),INCR(30),ENDTIM(30),NINTVL,NTIM
  ISN 0012             COMMON /SOURCE/ FO(15)
  ISN 0013             COMMON /NAMES/ NAMNUC(15)
  ISN 0014             COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                     *                  TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0015             COMMON /HRVST/ HARTIM(30),NHARV
  ISN 0016             COMMON /CROPS/ MFO
  ISN 0017             COMMON /IODEV / PTR,RDR
                 C
                 C  THE DIMENSION OF THE ARRAY YO MUST BE AT LEAST 12*NUMNUC
                 C
  ISN 0018             DOUBLE PRECISION  LOG2,TIM,TOUT,YO(72),NAMNUC,TO,HO,EPS,TIME,
                     *                   HARTIM
  ISN 0019             INTEGER  ENDTIM,PTR,RDR
  ISN 0020             REAL  LAMRR,INCR,MFO,MSUBB
                 C
  ISN 0021             DATA IDIM /15/
                 C
                 C
  ISN 0022             WRITE (PTR,100)
  ISN 0023         100 FORMAT ('1',T55,'RAGTIME COMPARTMENTS' //// )
                 C
  ISN 0024             WRITE (PTR,105)
  ISN 0025        105  FORMAT (' ',28X,'E  -  RADIOACTIVITY PRESENT ON ABOVE-SURFACE ',
                     *                 'FOOD PER SQUARE METER OF SURFACE' /
                     *          ' ',34X,'ON WHICH FOOD CROP IS GROWN  (MICROCURIES PER ',
                     *                 'SQUARE METER).')
                 C
  ISN 0026             WRITE (PTR,107)
  ISN 0027        107  FORMAT ('0',28X,'S  -  RADIOACTIVITY PRESENT AT THE SOIL ',
                     *                 'SURFACE  (MICROCURIES PER SQUARE METER).')
                 C
  ISN 0028             WRITE (PTR,110)
  ISN 0029        110  FORMAT ('0',28X,'P  -  RADIOACTIVITY PRESENT IN THE SUBSURFACE ',
                     *                 'POOL ASSOCIATED WITH ONE MAN''S'/
                     *          ' ',34X,'FOOD SUPPLY  (MICROCURIES).')
                 C
  ISN 0030             WRITE (PTR,115)
  ISN 0031        115  FORMAT ('0',28X,'G  -  RADIOACTIVITY PRESENT IN THE GRASS COM',
```

```
                *                   'PARTMENT  (MICROCURIES PER SQUARE' /
                *          ' ',34X,' METER).')
              C
ISN 0032            WRITE (PTR,120)
ISN 0033         120  FORMAT ('0',28X,'R  -  RADIOACTIVITY PRESENT IN THE SOIL FROM ',
                *             'GROUND SURFACE TO THE ROOT DEPTH' /
                *             ' ',34X,'OF THE GRASS  (MICROCURIES PER SQUARE METER).')
              C
ISN 0034            WRITE (PTR,130)
ISN 0035         130  FORMAT ('0',28X,'C  -  CONCENTRATION OF RADIOACTIVITY IN THE ',
                *                   'MILK  (MICROCURIES PER LITER).')
              C
ISN 0036            WRITE (PTR,140)
ISN 0037         140  FORMAT ('0',28X,'B  -  CONCENTRATION OF RADIOACTIVITY IN THE ',
                *                 'BEEF  (MICROCURIES PER KILOGRAM).')
              C
ISN 0038            WRITE (PTR,150)
ISN 0039         150  FORMAT ('0',28X,'T  -  RADIOACTIVITY PRESENT IN THE INTERIOR ',
                *                   'OF PLANTS PRODUCED FOR HUMAN CON-'/
                *          ' ',34X,'SUMPTION  (MICROCURIES).')
              C
ISN 0040            WRITE (PTR,152)
ISN 0041         152  FORMAT ('0',28X,'EH -  CONCENTRATION OF RADIOACTIVITY IN FOOD ',
                *                   'WHICH IS STORED FOLLOWING' /
                *             ' ',34X,'HARVEST OF CROPS  (MICROCURIES PER KILOGRAM).')
              C
ISN 0042            WRITE (PTR,154)
ISN 0043         154  FORMAT ('0',28X,'BH -  CONCENTRATION OF RADIOACTIVITY IN BEEF ',
                *                   'HOLDUP COMPARTMENT  (MICROCURIES' /
                *           ' ',34X,'PER KILOGRAM).')
              C
ISN 0044            WRITE (PTR,156)
ISN 0045         156  FORMAT ('0',28X,'CH -  CONCENTRATION OF RADIOACTIVITY IN MILK ',
                *                   'HOLDUP COMPARTMENT  (MICROCURIES' /
                *          ' ',34X,'PER LITER).')
              C
              C
              C
              C
              C INITIALIZE STATE VARIABLES
              C Y(1)=E, Y(2)=S, Y(3)=P, Y(4)=G, Y(5)=R, Y(6)=D, Y(7)=C, Y(8)=B,
              C Y(9)=EH, Y(10)=T, Y(11)=H, Y(12)=MPRIME
              C
              C
              C
              C DETERMINE S VALUES AT TIME ZERO.
ISN 0046            TZERO = 0.0
ISN 0047            CALL SVAL(TZERO,S1,S2,S3,S4)
ISN 0048            DO  5  I=1,NUMNUC
              C NPREV= NO. OF PREVIOUS STATE VARIABLES. FO(I)=DEPOSITION SOURCE (NUCLIDE I).
ISN 0049            NPREV = (I-1)*12
ISN 0050            YO(NPREV+1)=S1*FO(I)
ISN 0051            YO(NPREV+2)=S2*FO(I)
ISN 0052            YO(NPREV+3)=0.0D0
ISN 0053            YO(NPREV+4)=S3*FO(I)
ISN 0054            YO(NPREV+5)=S4*FO(I)
ISN 0055            YO(NPREV+6)=0.0D0
ISN 0056            YO(NPREV+7)=0.0D0
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ISN 0057              YO(NPREV+8)=0.0D0
ISN 0058              YO(NPREV+9)=0.0D0
ISN 0059              YO(NPREV+10)=0.0D0
ISN 0060              YO(NPREV+11)=0.0D0
ISN 0061              YO(NPREV+12)=0.0D0
ISN 0062            5 CONTINUE
                C
                C INITIALIZE BEEF AND MILK HOLDUP COMPARTMENTS BH AND CH RESPECTIVELY
                C
                C     QBEF(I) = BURDEN OF NUCLIDE INUC IN COMPARTMENT BH (UCI / KG).
                C     QMLK(I) = BURDEN OF NUCLIDE INUC IN COMPARTMENT CH (UCI / L ).
                C
ISN 0063              DO  350  I=1,NUMNUC
ISN 0064                  QBEF(I) = 0.0
ISN 0065                  QMLK(I) = 0.0
ISN 0066          350 CONTINUE
                C
                C
                C DEFINE GEAR SUBROUTINE PARAMETERS
                C
                C
ISN 0067              INDEX = 1
                C TO= INITIAL TIME (DAY).
ISN 0068              TO = 0.0D0
                C HO= NEXT STEPSIZE IN T (DAYS), USED ONLY ON FIRST CALL.
ISN 0069              HO = 1.0D-6
                C
                C
                C CALCULATE AND PRINT VALUES OF E,S,P,G,R,C,B,T,EH,BH,CH AT TIMES
                C TIM(I), I=1,NTIM.
                C
                C
                C N=NUMBER OF EQUATIONS.
ISN 0070              N= NUMNUC*12
                C
                C
                C                             *** PAGING DESCRIPTION ***
                C
                C     KOUNT IS THE NUMBER OF OUTPUT SPECIFICATIONS TO BE PRINTED PER PAGE.
                C     ITS VALUE IS DETERMINED BY USING AN INTEGER FUNCTION OF THE
                C     NUMBER OF NUCLIDES IN THE CHAIN BEING STUDIED PLUS ONE FOR SPACING
                C     DIVIDED INTO THE TOTAL NUMBER OF AVAILABLE LINES PER PAGE AFTER
                C     HEADINGS HAVE BEEN PRINTED.  K IS INITIALLY SET EQUAL TO KOUNT,
                C     THUS ENABLING THE HEADINGS TO BE PRINTED THE FIRST TIME THROUGH
                C     THE LOOP.  ONCE THE HEADINGS ARE PRINTED K IS SET TO ZERO AND IS
                C     INCREMENTED BY ONE ON EACH PASS THROUGH THE LOOP UNTIL K IS EQUAL
                C     TO KOUNT.  THEN THE PROCESS OF PRINTING THE HEADINGS AND SETTING
                C     K EQUAL TO ZERO CONTINUES.
                C
                C
ISN 0071              KOUNT = 58 / (NUMNUC + 1)
ISN 0072              K = KOUNT
                C
                C
                C DEFINE PARAMETERS FOR CALL TO RESONS. THE FOLLOWING PARAMETERS
                C ARE NOT TIME-DEPENDENT AND ARE THEREFORE DEFINED BEFORE ENTERING THE
                C ITIM LOOP.
                C
```

```
C TR(INUC)=RAD. HALF-LIFE (DAY) OF NUCLIDE INUC.
C TB(INUC)=BIO. HALF-LIFE (DAY) OF NUCLIDE INUC. USE LARGE VALUE TO
C APPROXIMATE A BIO. REMOVAL FACTOR OF ZERO.
      LOG2=DLOG(2.000)
      DO  300  INUC=1,NUMNUC
      TR(INUC)=LOG2/DBLE(LAMBR(INUC))
      TB(INUC)=1.0E50
C PRORAT(INUC)=CONSTANT PRODUCTION RATE FOR NUCLIDE INUC.
      PRORAT(INUC)=0.0
  300 CONTINUE
C
      DO  4  I=1,NTIM
      IF (K .NE. KOUNT) GO TO 160
C PRINT HEADING
      WRITE (PTR,1) (NAMNUC(J),J=1,NUMNUC)
    1 FORMAT ('1CONTENTS OF COMPARTMENTS AT VARIOUS TIMES',//,
     *     ' NUCLIDES IN THE CHAIN... ',14A8)
      WRITE (PTR,2)
    2 FORMAT('0TIME',T17,'F',T28,'S',T39,'P',T50,'G',T61,'R',T72,'C',
     C  T83,'B',T94,'T',T105,'EH',T116,'BH',T125,'CH')
      WRITE (PTR,3)
    3 FORMAT(' (DAYS)',T13,'(UCI/SQ.M)',T24,'(UCI/SQ.M)',T37,'(UCI)',
     C  T46,'(UCI/SQ.M)',T57,'(UCI/SQ.M)',T68,'(UCI/L)',T80,'(UCI/KG)'
     C ,T91,'(UCI)',  T103,'(UCI/KG)' ,T114,'(UCI/KG)',T123,'(UCI/L)')
C IF I=1, PRINT VALUES OF COMPARTMENTS AT TIME ZERO.
      IF (I.NE.1) GO TO 200
      TIME = 0.000
C FIRST NUCLIDE IN CHAIN
      WRITE (PTR,11) TIME,YO(1),YO(2),YO(3),YO(4),YO(5),YO(7),
     *     YO(8),YO(10),YO(9),QBEF(1),QMLK(1)
      IF (NUMNUC.EQ.1) GO TO 200
C REMAINING NUCLIDES IN CHAIN
      DO 201 INUC=2,NUMNUC
      NPREV=12*(INUC-1)
      WRITE (PTR,12) YO(NPREV+1),YO(NPREV+2),YO(NPREV+3),
     C  YO(NPREV+4),YO(NPREV+5),YO(NPREV+7), YO(NPREV+8),
     *  YO(NPREV+10),YO(NPREV+9),QBEF(INUC),QMLK(INUC)
  201 CONTINUE
  200 K=0
C IF I=1, ADD 1 TO K TO ACCOUNT FOR PRINTING COMPARTMENT VALUES
C AT TIME ZERO.
      IF (I.EQ.1) K=K+1
  160 CONTINUE
      TOUT = TIM(I)
      TOWT = TOUT
      CALL GEAR(DIFFUN,PEDERV,N,TO,HO,YO,TOUT,EPS,MF,INDEX)
      IF (INDEX.EQ.0) GO TO 6
      WRITE (PTR,7) TOWT,INDEX
    7 FORMAT('0INTEG. WAS NOT COMPLETED TO TOWT=',E10.3,', INDEX= ',I3)
      GO TO 8
C
C
C     THE FOLLOWING STATEMENTS ARE USED TO CALCULATE THE TOTAL AMOUNT OF
C     RADIOACTIVITY (MICROCURIES) IN THE SYSTEM FOR EACH NUCLIDE IN THE
C     CHAIN.
C
C         TOTUCI(I,JNUC) = RADIOACTIVITY FOR NUCLIDE WITH INDEX JNUC
C
```

```
               C      THESE VALUES ARE COMPARED TO VALUES CALCULATED USING THE BATEMAN
               C      EQUATIONS IN SUBROUTINE CHECK.
               C
               C
ISN 0110            6 CONTINUE
ISN 0111              INDEX = 2
ISN 0112              DO  20 JNUC=1,NUMNUC
ISN 0113                 NPREV = 12 * (JNUC-1)
ISN 0114                 TOTUCI(I,JNUC) = YO(NPREV+1)*A + YO(NPREV+2)*A + YO(NPREV+3) +
                   *          YO(NPREV+4)*ASUBG + YO(NPREV+5)*ASUBG + YO(NPREV+6)*ASUBG
                   *          + YO(NPREV+7)*U + YO(NPREV+8)*MSUBB + YO(NPREV+12) +
                   *          YO(NPREV+10)*1. + YO(NPREV+11)*A + YO(NPREV+9)*(MFO*.001)
               C
ISN 0115        20   CONTINUE
               C
               C DEFINE TIME-DEPENDENT PARAMETERS FOR CALLS TO RESDNS.
               C
               C QOBEF(INUC)=INITIAL BURDEN OF NUCLIDE INUC IN BEEF COMPARTMENT.
               C QOMLK(INUC)=INITIAL BURDEN OF NUCLIDE INUC IN MILK COMPARTMENT.
ISN 0116              DO  301  INUC=1,NUMNUC
ISN 0117              NPREV=(INUC-1)*12
ISN 0118              QOBEF(INUC)=YO(NPREV+8)
ISN 0119              QOMLK(INUC)= YO(NPREV+7)
ISN 0120          301 CONTINUE
ISN 0121              CALL RESDNS (TIMBH,NUMNUC,TR,TB,B,PRORAT,QOBEF,QBEF,QWIGL,IDIM)
ISN 0122              CALL RESDNS (TIMCH,NUMNUC,TR,TB,B,PRORAT,QOMLK,QMLK,QWIGL,IDIM)
               C
               C      PRINT VALUES OF COMPARTMENTS AT TIME TIM(I)
               C
               C
ISN 0123              WRITE (PTR,11) TOUT,YO(1),YO(2),YO(3),YO(4),YO(5),YO(7),
                   *  YO(8),YO(10),YO(9),QBEF(1),QMLK(1)
ISN 0124           11 FORMAT('0',12 (D10.3,' '))
ISN 0125              IF (NUMNUC .EQ. 1) GO TO 170
               C
               C PRINT VALUES OF E,S,P,G,R,C,B,T,EH,BH, AND CH FOR REMAINING NUCLIDES.
               C
ISN 0127              DO 9  INUC =2,NUMNUC
ISN 0128              NPREV=12*(INUC-1)
ISN 0129              WRITE (PTR,12) YO(NPREV+1),YO(NPREV+2),YO(NPREV+3),
                   C  YO(NPREV+4),YO(NPREV+5),YO(NPREV+7), YO(NPREV+8),
                   *  YO(NPREV+10),YO(NPREV+9),QBEF(INUC),QMLK(INUC)
ISN 0130            9 CONTINUE
ISN 0131           12 FORMAT(' ', T13, 11 (D10.3,' '))
               C
ISN 0132          170 CONTINUE
               C IS TIM(I) A HARVEST TIME? QUERY RETURNS 1 IF YES, 0 IF NO.
ISN 0133              CALL QUERY(TIM(I),IANS)
ISN 0134              IF (IANS.EQ.0) GO TO 171
               C AT HARVEST TIME, REINITIALIZE STATE VARIABLES.
ISN 0136              TO = TIM(I)
ISN 0137              HO = 1.0D-5
ISN 0138              INDEX = 1
ISN 0139              DO  250  INUC=1,NUMNUC
ISN 0140              NPREV = (INUC-1)*12
               C
               C FOR THE PURPOSE OF MASS BALANCE CHECK, TRANSFER TOTAL ACTIVITY
               C FROM CROP HOLDUP COMPARTMENT (EH) TO COMPARTMENT MPRIME.
```

```
      YO(NPREV+12) = YO(NPREV+12) + (MFO * .001) * YO(NPREV+9)
C
C DIVIDE TOTAL ACTIVITY (UCI) TRANSFERRED TO CROP HOLDUP COMPARTMENT
C EH FROM E AND T BY TOTAL MASS (KG) OF CROP AT HARVEST.
      YO(NPREV+9) = (A*YO(NPREV+1) + YO(NPREV+10)) / (MFO * .001)
      YO(NPREV+1) = 0.000
      YO(NPREV+10)= 0.000
  250 CONTINUE
  171 K=K+1
    4 CONTINUE
C
C
C
C UPON COMPLETION OF I LOOP, RETURN.
      GO TO 10
C IF GEAR SUBROUTINE RETURNS INDEX OTHER THAN 0, STOP.
    8 STOP
C
C
   10 RETURN
      END
```

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LEVEL 21.8 ( JUN 74 )                                     OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002               FUNCTION F(I,T)
                  C F(I,T) =  SOURCE STRENGTH (UCI/SQ.M/DAY) FOR NUCLIDE I AT TIME T (DAYS).
                  C
                  C F IS DEFINED IN TERMS OF THE INFLOW RATE MATRIX,
                  C
                  C      FF(I,KP) , I=1,NUMNUC,     KP=1,MP
                  C
                  C WHICH IS DEFINED IN SUBROUTINE INPUT.
  ISN 0003               COMMON /INFLOW/ MP, TIMEP(30),FF(15,30)
  ISN 0004               COMMON /NAMES/ NAMNUC(15)
  ISN 0005               DOUBLE PRECISION NAMNUC
  ISN 0006               F = 0.0
  ISN 0007               IF  (T.GE. TIMEP(MP) .OR. MP.EQ.1) GO TO 3
  ISN 0009               MPM1 = MP-1
  ISN 0010               DO  1  KP=1,MPM1
  ISN 0011               IF (T.GE.TIMEP(KP) .AND. T .LT. TIMEP(KP+1)) GO TO 5
  ISN 0013             1 CONTINUE
  ISN 0014               WRITE(3,2) NAMNUC(I), T
  ISN 0015             2 FORMAT('OF(I,T) NOT DEFINED FOR NUCLIDE ', A8,' TIME ',E10.3,
                        C   ' (DAYS)' )
  ISN 0016               STOP
  ISN 0017             5 F=  FF(I,KP)
  ISN 0018               GO TO 4
  ISN 0019             3 F=FF(I,MP)
* ISN 0020             4 RETURN
  ISN 0021               END
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LEVEL 21.8 ( JUN 74 )                                  OS/360  FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                SUBROUTINE DIFFUN(N,T,Y,YDOT)
                    C
                    C
                    C
                    C COMPUTES THE RIGHT HAND SIDE OF YDOT=F(Y,T)
                    C
                    C
                    C
  ISN 0003                DIMENSION TAUPT(15)
  ISN 0004                COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUREF,TAUMLK,TAUES,TAUGR,
                         *               TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0005                COMMON/LMD1/LAMR(15),LAMC(15),LAMB(15),LAMA(15),
                         C  LAMS(15),LAMG(15)
  ISN 0006                COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0007                COMMON /PARAM/ TAUGC(15),TAUGB(15)
  ISN 0008                COMMON /NUMBRS/NUMNUC
  ISN 0009                COMMON /BRANCH/ B(15,15)
  ISN 0010                COMMON /IODEV / PTR,RDR
                    C
                    C
                    C
  ISN 0011                DOUBLE PRECISION T,Y(N),YDOT(N)
  ISN 0012                REAL  LAMBH,LAMCH,MSUBB,LAMRR,II,LAMR,LAMC,LAMB,LAMA,LAMS,
                         *      LAMG,IIPRIM,LAMPI
  ISN 0013                INTEGER  RDR,PTR
                    C
                    C
                    C
                    C THE STATE VARIABLES ARE
                    C      Y(NPREV+1) = E
                    C      Y(NPREV+2) = S
                    C      Y(NPREV+3) = P
                    C      Y(NPREV+4) = G
                    C      Y(NPREV+5) = R
                    C      Y(NPREV+6) = D
                    C      Y(NPREV+7) = C
                    C      Y(NPREV+8) = B
                    C      Y(NPREV+9) = EH
                    C      Y(NPREV+10) = T
                    C      Y(NPREV+11) = H
                    C      Y(NPREV+12) = MPRIME
                    C WHERE NPREV = 0,1,2,....,NUMNUC-1
                    C
                    C
                    C
                    C TIME (T) IS SOMETIMES REQUIRED TO BE IN SINGLE PRECISION (X).
  ISN 0014                X=T
  ISN 0015                CALL SVAL(X,S1,S2,S3,S4)
  ISN 0016                CALL TINDEP(X,TAUPT)
                    C
  ISN 0017                DO  1  I=1,NUMNUC
                    C NPREV = NO. OF PREVIOUS EQUATIONS
  ISN 0018                NPREV= (I-1)*12
                    C CALCULATE CONTRIBUTION FROM PREDECESSORS IN THE CHAIN.
  ISN 0019                SUM1 = 0.0
  ISN 0020                SUM2 = 0.0
```

```
ISN 0021                  SUM3 = 0.0
ISN 0022                  SUM4 = 0.0
ISN 0023                  SUM5 = 0.0
ISN 0024                  SUM6 = 0.0
ISN 0025                  SUM7 = 0.0
ISN 0026                  SUM8 = 0.0
ISN 0027                  SUM9 = 0.0
ISN 0028                  SUM10 = 0.0
ISN 0029                  SUM11 = 0.0
ISN 0030                  SUM12 = 0.0
ISN 0031                  IF (I.LE.1) GO TO 3
ISN 0033                  IM1= I-1
                  C
                  C
ISN 0034                  DO  2   J=1,IM1
ISN 0035                  JPREV=(J-1)*12
ISN 0036                  SUM1 = SUM1 + LAMRR(I)*B(I,J)*Y(JPREV+1)
ISN 0037                  SUM2 = SUM2 + LAMRR(I)*B(I,J)*Y(JPREV+2)
ISN 0038                  SUM3 = SUM3 + LAMRR(I)*B(I,J)*Y(JPREV+3)
ISN 0039                  SUM4 = SUM4 + LAMRR(I)*B(I,J)*Y(JPREV+4)
ISN 0040                  SUM5 = SUM5 + LAMRR(I)*B(I,J)*Y(JPREV+5)
ISN 0041                  SUM6 = SUM6 + LAMRR(I)*B(I,J)*Y(JPREV+6)
ISN 0042                  SUM7 = SUM7 + LAMRR(I)*B(I,J)*Y(JPREV+7)
ISN 0043                  SUM8 = SUM8 + LAMRR(I)*B(I,J)*Y(JPREV+8)
ISN 0044                  SUM9 = SUM9 + LAMRR(I)*B(I,J)*Y(JPREV+9)
ISN 0045                  SUM10 = SUM10 +LAMRR(I)*B(I,J)*Y(JPREV+10)
ISN 0046                  SUM11 = SUM11 +LAMRR(I)*B(I,J)*Y(JPREV+11)
ISN 0047                  SUM12 = SUM12 +LAMRR(I)*B(I,J)*Y(JPREV+12)
                  C
ISN 0048                2 CONTINUE
                  C
                  C CALCULATE YDOT
ISN 0049                3 YDOT(NPREV+1)=S1*F(I,X)-LAMA(I)*Y(NPREV+1) + SUM1
ISN 0050                  YDOT(NPREV+2)=TAUES*Y(NPREV+1)-LAMS(I)*Y(NPREV+2)+S2*F(I,X)+SUM2
                  C LAMPI IS TIME DEPENDENT.
ISN 0051                  LAMPI = LAMRR(I)+TAUPT(I) + TAUPH
ISN 0052                  YDOT(NPREV+3)=A*TAUSP*Y(NPREV+2)-LAMPI  *Y(NPREV+3)+SUM3
ISN 0053                  YDOT(NPREV+4)=S3*F(I,X)-LAMG(I)*Y(NPREV+4)+TAUFG*Y(NPREV+5)+SUM4
ISN 0054                  YDOT(NPREV+5)= S4*F(I,X) +
                         C                   TAUGR*Y(NPREV+4)-LAMR(I)*Y(NPREV+5)+SUM5
ISN 0055                  YDOT(NPREV+6)=TAURO*Y(NPREV+5)
                         C                   -LAMRR(I)*Y(NPREV+6)+SUM6
ISN 0056                  YDOT(NPREV+7)=TAUGC(I)
                         C                           *Y(NPREV+4)-LAMC(I)*Y(NPREV+7)+SUM7
ISN 0057                  YDOT(NPREV+8)=TAUGB(I)
                         C                           *Y(NPREV+4)-LAMB(I)*Y(NPREV+8) +SUM8
                  C
ISN 0058                  YDOT(NPREV+9) = -LAMRR(I) * Y(NPREV+9) + SUM9
                  C
ISN 0059                  YDOT(NPREV+10)=TAUPT(I) * Y(NPREV+3) - LAMRR(I) * Y(NPREV+10)
                         C  +SUM10
                  C
ISN 0060                  YDOT(NPREV+11) = (TAUPH/A)*Y(NPREV+3) - LAMRR(I)*Y(NPREV+11)
                         *  + SUM11
                  C
                  C       THE COMPARTMENT MPRIME (Y(NPREV+12)) RECEIVES ALL RADIOACTIVITY
                  C       FROM B AND C. THE TRANSFER COEFFICIENTS FROM B AND C TO MPRIME
                  C       ARE TOTBM AND TOTCM RESPECTIVELY AND ARE DEFINED AS FOLLOWS.
```

```
ISN 0061          TOTBM=TAUBEF*MSUBB
ISN 0062          TOTCM=TAUMLK*U
ISN 0063          IIPRIM = TOTBM * Y(NPREV+8) + TOTCM * Y(NPREV+7)
ISN 0064          YDOT(NPREV+12) = IIPRIM -LAMRR(I)*Y(NPREV+12) +
                C   (VSUBC/DSUBG - TAUGB(I)*MSUBB - TAUGC(I)*U) * Y(NPREV+4)
                C   + SUM12
            C
ISN 0065        1 CONTINUE
            C
            C
ISN 0066          RETURN
ISN 0067          END
```

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LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE PEDERV(N,T,Y,PD,NO)
              C
              C
  ISN 0003              DOUBLE PRECISION T, Y(NO,13), PD
              C
              C
  ISN 0004              RETURN
  ISN 0005              END
```

```
LEVEL 21.8 ( JUN 74 )                                OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                              SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE CHECK
                C CALCULATES AND PRINTS VALUES OF
                C
                C     TOTUCI(ITIM,INUC) = TOTAL ACTIVITY DUE TO NUCLIDE INUC AT TIME ITIM
                C                         AS CALCULATED BY SUBROUTINE CALC USING THE
                C                         GEAR SUBROUTINE
                C     ACT(INUC,ITIM)    = TOTAL ACTIVITY DUE TO NUCLIDE INUC AT TIME ITIM
                C                         AS CALCULATED BY SUBROUTINE TRAFUN, USING THE
                C                         BATEMAN EQUATIONS
                C AS WELL AS THE PERCENTAGE ERROR
                C
                C    (TOTUCI(ITIM,INUC) - ACT(INUC,ITIM))*100.  /  ACT(INUC,ITIM)
                C
                C FOR TIMES TIM(ITIM), ITIM=1 TO NTIM.
                C
  ISN 0003              DIMENSION TR(15),TB(15),ACT(15,365),P(15,30),RELER(15),RTIM(365),
                     *             AWIGL(15,365)
  ISN 0004              COMMON /INFLOW/ MP,TIMEP(30),FF(15,30)
  ISN 0005              COMMON /BRANCH/ B(15,15)
  ISN 0006              COMMON /MCHECK/ TOTUCI(365,15)
  ISN 0007              COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0008              COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                     *                  TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0009              COMMON /NUMBRS/ NUMNUC
  ISN 0010              COMMON /TIME/ TIM(365),INCR(30),ENDTIM(30),NINTVL,NTIM
  ISN 0011              COMMON /IODEV / PTR,RDR
                C
  ISN 0012              DOUBLE PRECISION TIM,LOG2
  ISN 0013              INTEGER ENDTIM,PTR,RDR
  ISN 0014              REAL  MSUBB,INCR,LAMRR
                C IDIM IS THE MAXIMUM FIRST DIMENSION FOR THE ARRAYS ACT, P, AND AWIGL.
                C IT CORRESPONDS TO THE MAXIMUM NUMBER OF NUCLIDES IN A CHAIN.
  ISN 0015              DATA IDIM /15/
                C
                C  PRINT HEADINGS FOR TIME, TOTAL ACTIVITY COMPUTED BY THE GEAR
                C  SUBROUTINE, TOTAL ACTIVITY COMPUTED USING BATEMAN EQUATIONS, AND
                C  RELATIVE ERROR.
                C
  ISN 0016              WRITE (PTR,100)
  ISN 0017         100  FORMAT ('1',52X,'COMPARISON OF TOTAL ACTIVITY' /
                     *          '0',10X,'TIME (DAYS)',12X,'TOTAL ACTIVITY (MICROCURIES)',
                     *              12X,'TOTAL ACTIVITY (MICROCURIES)',8X,'PERCENTAGE ',
                     *                  'ERROR' /
                     *          ' ',35X,'*** GEAR SUBROUTINE ***',17X,'*** BATEMAN ',
                     *                  'EQUATIONS ***')
                C
                C
                C DEFINE INPUT PARAMETERS FOR SUBROUTINE TRAFUN
                C
                C TR(INUC) =RADIOACTIVE HALF-LIFE (DAY) OF NUCLIDE I.
                C TB(INUC) =BIOLOGICAL HALF-LIFE (DAY) OF NUCLIDE I (USE LARGE VALUE
                C             TO APPROXIMATE A BIOLOGICAL REMOVAL FACTOR OF ZERO.)
                C P(INUC,KP)=SOURCE STRENGTH (MICROCURIES/DAY) FOR NUCLIDE I
                C FROM TIMEP(KP) TO TIMEP(KP+1) IF KP .LT. MP AND P(INUC,MP) =
                C SOURCE STRENGTH AT TIMES SUBSEQUENT TO TIMEP(MP).
                C BRANCH(I,J)
```

```
                 C           =BRANCHING RATIO FROM SPECIES J TO SPECIES I, J LESS THAN I.
                 C           =B(I,J)     (INPUT DATA - COMMON/BRANCH/ )
                 C
ISN 0018               LOG2= DLOG(2.0D0)
ISN 0019               DO  1 INUC=1,NUMNUC
ISN 0020               TR(INUC) =  LOG2 / DBLE(LAMRR(INUC))
ISN 0021               TB(INUC) =  1.0E50
ISN 0022               DO  6  KP=1,MP
ISN 0023               CALL  SVAL(TIMEP(KP),S1,S2,S3,S4)
ISN 0024             6 P(INUC,KP) = FF(INUC,KP) * ((S1+S2)*A + (S3+S4)*ASUBG)
ISN 0025             1 CONTINUE
                 C
                 C RTIM IS A REAL ARRAY WHOSE VALUES ARE THE SAME AS THOSE FOR TIM.
ISN 0026               DO  7  ITIM=1,NTIM
ISN 0027             7 RTIM(ITIM) = TIM(ITIM)
                 C THE CALL TO TRAFUN,
                 C CALL TRAFUN(N,TR,TB,BRANCH,MP,TIMEP,P,MA,TIMEA,AWIGL,ACT)
                 C BECOMES
ISN 0028               CALL  TRAFUN(NUMNUC,TP,TB,B,MP,TIMEP,P,NTIM,RTIM,AWIGL,ACT,IDIM)
                 C BEGIN ITIM LOOP TO CALCULATE PERCENTAGE ERRORS.
ISN 0029               DO  2  ITIM = 1,NTIM
ISN 0030               DO    4    INUC=1,NUMNUC
ISN 0031             4 RELER(INUC) = (TOTUCI(ITIM,INUC) - ACT(INUC,ITIM))*100./
                        C        ACT(INUC,ITIM)
ISN 0032             2 WRITE (PTR,3) TIM(ITIM),(TOTUCI(ITIM,INUC),ACT(INUC,ITIM),
                        C        RELER(INUC),INUC=1,NUMNUC)
ISN 0033          3     FORMAT (' ',9X,D13.6,18X,E13.6,26X,E13.6,20X,F12.3 / ' ',
                        *                     14(40X,E13.6,26X,E13.6,20X,F12.3 / ' '))
ISN 0034                RETURN
ISN 0035                END
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LEVEL 21.8 ( JUN 74 )                             OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE RESDNS(T,N,TR,TB,BRANCH,P,Q0,Q,QWIGL,IDIM)
                C THIS SUBROUTINE COMPUTES THE MICROCURIES Q AND THE
                C MICROCURIE-DAYS QWIGL OF N SPECIES OF A RADIONUCLIDE
                C CHAIN.  EVALUATION IS AT TIME T (DAYS) IN A COMPARTMENT
                C WITH FIRST-ORDER REMOVAL PROCESSES WITH HALF-TIME TB(I)
                C (DAYS) FOR THE I-TH NUCLIDE AND CONSTANT PRODUCTION
                C RATE P(I) (MICROCURIES/DAY).  TR(I) (DAYS) IS THE
                C RADIOACTIVE HALF-LIFE OF THE I-TH NUCLIDE.  THE INITIAL
                C BURDEN IS Q0(I) (MICROCURIES).  BRANCH(I,J) IS THE
                C FRACTION OF SPECIES J WHICH DISINTEGRATES TO SPECIES I,
                C WHERE J IS LESS THAN I.  THUS ALL NON-ZERO ENTRIES IN
                C BRANCH ARE BELOW THE MAIN DIAGONAL.
                C
                C ALL DIMENSIONS OF SIZE 20 CORRESPUND TO N, THE NUMBER OF
                C RADIOACTIVE SPECIES IN THE CHAIN.
                C
                C IDIM IS THE MAXIMUM FIRST DIMENSION FOR THE ARRAYS ACT, P, AND AWIGL.
                C IT CORRESPONDS TO THE MAXIMUM NUMBER OF NUCLIDES IN A CHAIN.
                C
  ISN 0003              REAL TR(N),TB(N),BRANCH(IDIM,IDIM),P(N),Q0(N),Q(N),QWIGL(N)
  ISN 0004              DOUBLE PRECISION LM(20),LMR(20),D(20),C(20,20),
                       $   LOG2,TEMPQ,TEMPQW,EXLI,EX1LI,EXPFUN,EXPF1
  ISN 0005              IF (T.GT.0.0) GO TO 10
  ISN 0007                DO 5 I=1,N
  ISN 0008                  Q(I)=Q0(I)
  ISN 0009                  QWIGL(I)=0.0
  ISN 0010             5 CONTINUE
  ISN 0011                GO TO 120
  ISN 0012            10 LOG2=DLOG(2.0D0)
                C COMPUTE DECAY AND REMOVAL CONSTANTS FROM HALF-TIMES.
  ISN 0013              DO 20 I=1,N
  ISN 0014                LMR(I)=LOG2/DBLE(TR(I))
  ISN 0015                LM(I)=LOG2/DBLE(TB(I)) + LMR(I)
  ISN 0016            20 CONTINUE
                C IF TWO LM(I) ARE NEARLY EQUAL, SEPARATE THEM.
                C
                C SKIP SEPARATION ROUTINE IF N=1.
  ISN 0017              IF(N.EQ.1) GO TO 45

                C BEGINNING OF SEPARATION ROUTINE..
                C
  ISN 0019              N1=N-1
                C KODE IS A SWITCH FOR WHICH THE VALUE 1 MEANS ANOTHER
                C PASS SHOULD BE MADE.
  ISN 0020              KODE=1
  ISN 0021            25 IF (KODE.NE.1) GO TO 45
  ISN 0023                KODE=0
                C BEGIN PASS.
  ISN 0024                DO 40 K=1,N1
  ISN 0025                  K1=K+1
  ISN 0026                  DO 35 L=K1,N
                C IF LM(L) AND LM(K) ARE NEARLY EQUAL, SEPARATE THEM.
  ISN 0027                    IF (DABS(LM(L)/LM(K)-1.0D0).GE.1.0D-6) GO TO 35
  ISN 0029                      LM(L)=LM(K)*1.00001D0
  ISN 0030                      KODE=1
  ISN 0031            35      CONTINUE
```

```
ISN 0032          40   CONTINUE
               C RETURN FOR POSSIBLY ANOTHER PASS.
ISN 0033             GO TO 25
               C END OF SEPARATION ROUTINE.
ISN 0034          45 CONTINUE
               C
               C COMPUTE COEFFICIENTS D(I), C(I,J).
ISN 0035             D(1)=P(1)/LM(1)
ISN 0036             IF (N.EQ.1) GO TO 60
ISN 0038             DO 55 I=2,N
ISN 0039               D(I)=0.0
ISN 0040               I1=I-1
ISN 0041               DO 50 J=1,I1
ISN 0042                 D(I)=D(I)+BRANCH(I,J)*D(J)
ISN 0043          50 CONTINUE
ISN 0044             D(I)=LMR(I)*D(I)/LM(I) + P(I)/LM(I)
ISN 0045          55 CONTINUE
ISN 0046          60 C(1,1)=Q0(1)-D(1)
ISN 0047             IF (N.EQ.1) GO TO 90
ISN 0049             DO 85 I=2,N
ISN 0050               I1=I-1
ISN 0051               DO 75 J=1,I1
ISN 0052                 C(I,J)=0.0
ISN 0053                 DO 70 K=J,I1
ISN 0054                   C(I,J)=C(I,J) + BRANCH(I,K)*C(K,J)
ISN 0055          70     CONTINUE
ISN 0056               C(I,J)=C(I,J)*(LMR(I)/(LM(I)-LM(J)))
ISN 0057          75   CONTINUE
ISN 0058               C(I,I)=Q0(I)-D(I)
ISN 0059               DO 80 J=1,I1
ISN 0060                 C(I,I)=C(I,I)-C(I,J)
ISN 0061          80   CONTINUE
ISN 0062          85 CONTINUE
               C END OF CALCULATION OF D(I), C(I,J).
ISN 0063          90 CONTINUE
               C COMPUTE Q(I), QWIGL(I), I=1,N
ISN 0064             DO 110 I=1,N
ISN 0065               TEMPQ=0.0
ISN 0066               TEMPQW=0.0
ISN 0067               EXLI=EXPFUN(-LM(I)*DBLE(T))
ISN 0068               EX1LI=EXPF1(LM(I),DBLE(T))
ISN 0069               I1=I-1
ISN 0070               DO 100 J=1,I1
ISN 0071                 TEMPQ=TEMPQ+C(I,J)*(EXPFUN(-LM(J)*DBLE(T))-EXLI)
ISN 0072                 TEMPQW=TEMPQW+C(I,J)*(EXPF1(LM(J),DBLE(T))-EX1LI)
ISN 0073         100   CONTINUE
ISN 0074               Q(I)=TEMPQ+D(I)*LM(I)*EX1LI+Q0(I)*EXLI
ISN 0075               QWIGL(I)=TEMPQW+D(I)*(DBLE(T)-EX1LI)+Q0(I)*EX1LI
ISN 0076         110 CONTINUE
ISN 0077         120 RETURN
ISN 0078             END
```

```
LEVEL 21.8 ( JUN 74 )                                OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              DOUBLE PRECISION FUNCTION EXPFUN(T)
  ISN 0003              DOUBLE PRECISION T
  ISN 0004              EXPFUN=0.0D0
  ISN 0005              IF(T.LT.-180.0D0) GO TO 10
  ISN 0007                EXPFUN=DEXP(T)
  ISN 0008           10 RETURN
  ISN 0009              END
```

```
LEVEL 21.8 ( JUN 74 )                                   OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002            DOUBLE PRECISION FUNCTION EXPF1(LM,T)
  ISN 0003            DOUBLE PRECISION LM,T,LMT,EXPFUN
  ISN 0004            LMT=LM*T
  ISN 0005            IF(LMT.LT.0.03D0) GO TO 10
  ISN 0007            GO TO 20
  ISN 0008         10  EXPF1=T*((((((LMT/7.0D0-1.0D0)*LMT/6.0D0+1.0D0)
                     *LMT/5.0D0-1.0D0)*LMT/4.0D0+1.0D0)*LMT/3.0D0-1.0D0)
                   $  *LMT/2.0D0+1.0D0)
  ISN 0009            GO TO 30
  ISN 0010         20 EXPF1=(1.0D0-EXPFUN(-LMT))/LM
  ISN 0011         30 RETURN
  ISN 0012            END
```

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LEVEL 21.8 ( JUN 74 )                                    OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE TRAFUN(N,TR,TB,BRANCH,MP,TIMEP,P,MA,TIMEA,AWIGL,ACT,
                     *                         IDIM)
                C TRAFUN SUGGESTS TRANSFER FUNCTION.
                C WE ARE CONSIDERING N RADIOACTIVE SPECIES IN A CHAIN IN A BIOLOGICAL
                C COMPARTMENT.  TR(I) AND TB(I) ARE THE RADIOACTIVE HALF-LIFE (DAYS)
                C AND BIOLOGICAL HALF-TIME (DAYS), RESPECTIVELY, OF THE I-TH SPECIES
                C IN THE COMPARTMENT.  BRANCH(I,J) IS THE BRANCHING RATIO OF SPECIES
                C J TO SPECIES I, WHERE J IS LESS THAN I.  THE INFLOW RATE OF EACH
                C SPECIES IS GIVEN AS A DISCRETE FUNCTION OF TIME BY THE ARRAYS
                C TIMEP (DAYS) AND P (MICROCURIES/DAY).  P(I,KP) IS THE INFLOW RATE
                C OF SPECIES I FROM TIMEP(KP) TO TIMEP(KP+1), AND P(I,MP) IS THE
                C RATE AT TIMES SUBSEQUENT TO TIMEP(MP).  AWIGL(I,KA) IS THE
                C CUMULATED ACTIVITY (MICROCURIE-DAYS) IN THE COMPARTMENT UP TO
                C TIMEA(KA).  THE TIME ARRAYS MUST BE ARRANGED IN INCREASING ORDER.
                C ACT(I,KA) IS THE ACTIVITY FOR NUCLIDE I (MICROCURIES) IN THE
                C COMPARTMENT AT TIMEA(KA).
                C
                C IDIM IS THE MAXIMUM FIRST DIMENSION FOR THE ARRAYS ACT, P, AND AWIGL.
                C IT CORRESPONDS TO THE MAXIMUM NUMBER OF NUCLIDES IN A CHAIN.
                C  THE MAXIMUM DIMENSION 20 FOR THE ARRAYS PTEMP,ATEMP AND AWTEMP CORRES-
                C  PONDS TO N (THE NUMBER OF RADIOACTIVE NUCLIDES IN THE CHAIN).
  ISN 0003              REAL TR(N),TB(N),BRANCH(IDIM,IDIM),ACT(IDIM,365)
  ISN 0004              REAL TIMEP(30),P(IDIM,30),TIMEA(MA),AWIGL(IDIM,365)
  ISN 0005              REAL PTEMP(20),ATEMP(20),AWTEMP(20)
                C
                C
                C FOR EACH TIMEP(KP) AND THE CORRESPONDING COLUMN P(*,KP) OF
                C RATES, USE RESID ITERATIVELY TO CALCULATE THE CONTRIBUTION
                C TO AWIGL(*,KA) AT TIME TIMEA(KA).  FIRST INITIALIZE AWIGL AND ACT
                C TO ZERO.
  ISN 0006              COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                     *                 TAUPH,TAURO,TAUFS,TAUSP,U,VSUBC,SMALLD,RHO
  ISN 0007              COMMON /SOURCE/ FO(15)
  ISN 0008              CALL ZEROM(IDIM,MA,AWIGL)
  ISN 0009              CALL ZEROM(IDIM,MA,ACT)
  ISN 0010              DO 25 KP=1,MP
  ISN 0011                DO 10 I=1,N
  ISN 0012                  PTEMP(I)=P(I,KP)
  ISN 0013          10    CONTINUE
  ISN 0014                DO 20 KA=1,MA
  ISN 0015                  CALL ZEROV(N,ATEMP)
                C IF KP=1, SET INITIAL TOTAL ACTIVITY IN THE SYSTEM EQUAL TO THAT
                C DETERMINED BY FO(I), I=1 TO N AND S1,S2,S3,S4.
  ISN 0016              IF (KP .NE. 1) GO TO 40
                C
                C CALCULATE TOTAL INITIAL ACTIVITY (MICROCURIES) IN RAGTIME COMPARTMENTS
                C E,S,G AND R.
  ISN 0018              TZERO = 0.0
  ISN 0019              CALL SVAL(TZERO,S1,S2,S3,S4)
  ISN 0020              DO  41  I=1,N
  ISN 0021          41 ATEMP(I) = ((S1+S2)*A + (S3+S4)*ASUBG) * FO(I)
  ISN 0022          40      CALL ZEROV(N,AWTEMP)
  ISN 0023                  T1=TIMEP(KP)
  ISN 0024                  IF (T1.GT.TIMEA(KA)) GO TO 20
  ISN 0026                  IF (KP.LT.MP) T2=TIMEP(KP+1)
  ISN 0028                  IF (KP.EQ.MP) T2=TIMEA(KA)
```

```
ISN 0030               CALL RESID(N,TR,TB,BRANCH,ATEMP,PTEMP,T1,T2,
                  $       AWTEMP,TIMEA(KA),IDIM)
ISN 0031               DO 15 I=1,N
ISN 0032                 AWIGL(I,KA)=AWIGL(I,KA)+AWTEMP(I)
ISN 0033           ACT(I,KA) = ATEMP(I) + ACT(I,KA)
ISN 0034        15     CONTINUE
ISN 0035        20   CONTINUE
ISN 0036        25 CONTINUE
ISN 0037           RETURN
ISN 0038           END
```

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LEVEL 21.8 ( JUN 74 )                                  OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE ZEROM(N,M,A)
  ISN 0003              DIMENSION A(N,M)
  ISN 0004              DO 10 I=1,N
  ISN 0005                DO 10 J=1,M
  ISN 0006                  A(I,J)=0.0
  ISN 0007           10 CONTINUE
  ISN 0008              RETURN
  ISN 0009              END
```

```
LEVEL 21.8 ( JUN 74 )                                   OS/360  FORTRAN H

           COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                              SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE ZEROV(N,V)
  ISN 0003              DIMENSION V(N)
  ISN 0004              DO 10 I=1,N
  ISN 0005           10 V(I)=0.0
  ISN 0006              RETURN
  ISN 0007              END
```

```
LEVEL 21.8 ( JUN 74 )                                 OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE RESID(N,TR,TB,BRANCH,A,P,T1,T2,AW,T,IDIM)
                  C COMPUTES MICROCURIE-DAYS RESIDENCE AW(I) OF THE I-TH RADIOACTIVE
                  C SPECIES IN A CHAIN OF N NUCLIDES.  PARAMETERS TR,TB,AND
                  C BRANCH ARE AS IN SUBROUTINE TRAFUN.  INPUT IS A PULSE VECTOR
                  C P (MICROCURIES/DAY) FROM TIME T1 TO T2 (DAYS).  INITIAL VECTOR
                  C OF ACTIVITIES IS A (MICROCURIES), AND A IS UPDATED TO SHOW
                  C FINAL ACTIVITIES.  AW IS EVALUATED AT TIME T.  IN CASE T IS
                  C LESS THAN T1, S IS UNCHANGED AND AW IS ZERO.
                  C IDIM IS THE MAXIMUM FIRST DIMENSION OF THE ARRAY BRANCH.
                  C  THE MAXIMUM DIMENSION 20 FOR THE ARRAYS A1,P1 AND AW1 CORRESPONDS TO
                  C  N (THE NUMBER OF NUCLIDES IN THE CHAIN).
  ISN 0003              REAL TR(N),TB(N),A(N),P(N),AW(N),BRANCH(IDIM,IDIM)
  ISN 0004              REAL A1(20),P1(20),AW1(20)
  ISN 0005              CALL ZEROV(N,P1)
  ISN 0006              IF (T1.GT.T2) GO TO 20
  ISN 0008                TTEMP=AMAX1(0.0,AMIN1(T,T2)-T1)
  ISN 0009                CALL RESDNS(TTEMP,N,TR,TB,BRANCH,P,A,A1,AW,IDIM)
  ISN 0010                DO 10 I=1,N
  ISN 0011          10      A(I)=A1(I)
  ISN 0012                IF (T.LE.T2) GO TO 30
  ISN 0014                  TTEMP=T-T2
  ISN 0015                  CALL RESDNS(TTEMP,N,TR,TB,BRANCH,P1,A,A1,AW1,IDIM)
  ISN 0016                  DO 15 I=1,N
  ISN 0017                    A(I)=A1(I)
  ISN 0018                    AW(I)=AW(I)+AW1(I)
  ISN 0019          15      CONTINUE
  ISN 0020          20    CONTINUE
  ISN 0021              TTEMP=AMAX1(0.0,T-T1)
  ISN 0022              CALL RESDNS(TTEMP,N,TR,TB,BRANCH,P1,A,A1,AW)
  ISN 0023              DO 25 I=I,N
  ISN 0024          25    A(I)=A1(I)
  ISN 0025          30 RETURN
  ISN 0026              END
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LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                SUBROUTINE SVAL(T,S1,S2,S3,S4)
                C
                C RETURNS VALUES OF INTERCEPTION FRACTIONS S1,S2,S3,S4 AT TIME T (DAYS).
                C
  ISN 0003                COMMON /HRVST / HARTIM(30),NHARV
  ISN 0004                COMMON /EMERG/ EMERGE(30)
  ISN 0005                DOUBLE PRECISION HARTIM
  ISN 0006                REAL  M,MFOS1
  ISN 0007                MFOS1 = 1.0
  ISN 0008                SLO=0.00075
  ISN 0009                ATAU=1.24E-4
  ISN 0010                S1=0.0
  ISN 0011                DO  1  I=1,NHARV
  ISN 0012                IF(T.GE.EMERGE(I).AND.T.LT.HARTIM(I))  GO TO 2
  ISN 0014              1 CONTINUE
                C IF T DOES NOT LIE BETWEEN EMERGE(I) AND HARTIM(I) FOR ANY I=1 TO
                C NHARV, THEN S1=0.
  ISN 0015                GO TO 3
  ISN 0016              2 TO=EMERGE(I)
  ISN 0017                M = MFOS1*(1.0-EXP(-ATAU*(T**2-TO**2)))
  ISN 0018                S1=     SLO*(M**0.545)*250.0
  ISN 0019              3 CONTINUE
  ISN 0020                IF(S1.LE.1.0) GO TO 4
                C S1 SHOULD NOT EXCEED 1.
  ISN 0022                WRITE(3,5)  S1
  ISN 0023              5 FORMAT('0S1 VALUE (',F10.3,') TOO LARGE')
  ISN 0024                STOP
  ISN 0025              4 S2= 1.0  -S1
  ISN 0026                S3=  0.25
  ISN 0027                S4= 0.75
  ISN 0028                RETURN
  ISN 0029                END
```

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LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE HARVST
                C
                C DEFINES HARVEST TIMES (DAYS)
                C
                C       HARTIM(I), I=1 TO NHARV
                C
                C AND COMMUNICATES THESE VALUES TO SUBROUTINE CALC VIA
                C COMMON BLOCK /HRVST/.
                C
  ISN 0003              DOUBLE PRECISION HARTIM
  ISN 0004              COMMON /EMERG/ EMERGE(30)
  ISN 0005              COMMON /HRVST/ HARTIM(30),NHARV
  ISN 0006              NHARV = 1
  ISN 0007              EMERGE(1) = 70.
  ISN 0008              HARTIM(1) = 175.0D0
  ISN 0009              RETURN
  ISN 0010              END
```

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LEVEL 21.8 ( JUN 74 )                                  OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE TIMDEP (T,TAUPT)
                  C
                  C ****************************
                  C * SUBROUTINE  T I M D E P *
                  C ****************************
                  C
                  C  TIMDEP RETURNS TAUPT(I) = TRANSFER COEFFICIENT FROM P TP T (SUBSUR-
                  C  FACE SOIL POOL TO PLANT INTERIOR) FOR NUCLIDES NAMNUC(I),I=1,NUMNUC.
                  C  TAUPT IS BASED ON THE TIME INTERVAL CONTAINING T.
                  C
  ISN 0003              DIMENSION  TAUPT(15)
                  C
  ISN 0004              COMMON /HRVST/ HARTIM(30),NHARV
  ISN 0005              COMMON /EMERG/ EMERGE(30)
  ISN 0006              COMMON /CROPS/ MFO
  ISN 0007              COMMON /NAMES/ NAMNUC(15)
  ISN 0008              COMMON /NUMBRS/NUMNUC
  ISN 0009              COMMON /DEP/ LAMRR(15),FSUBM(15),TAUEXC(15),FSUBF(15),BSUBIV(15)
  ISN 0010              COMMON /INDEP/ A,ASUBG,DSUBG,MSUBB,TAUBEF,TAUMLK,TAUES,TAUGR,
                       *               TAUPH,TAURD,TAURG,TAUSP,U,VSUBC,SMALLD,RHO
                  C
  ISN 0011              DOUBLE PRECISION  NAMNUC,HARTIM
  ISN 0012              REAL  LAMRR,MSUBB,MFO
                  C
  ISN 0013              ATAU = 1.24E-4
                  C
                  C  FIND THE TIME INTERVAL (EMERGE(J) TO HARTIM(J) ) CONTAINING T.
  ISN 0014              DO 10  J=1,NHARV
  ISN 0015                IF (T .GE. EMERGE(J) .AND. T .LT. HARTIM(J))  GO TO 20
  ISN 0017         10   CONTINUE
                  C
                  C  T IS NOT IN ANY OF THE GIVEN TIME INTERVALS (EMERGE(J) TO HARTIM(J) )
  ISN 0018              DO 15  I=1,NUMNUC
  ISN 0019                TAUPT(I) = 0.0
  ISN 0020         15   CONTINUE
                  C
                  C  END OF PROCESS IF T IS OUTSIDE OF THE GIVEN TIME INTERVALS.
  ISN 0021              GO TO 30
                  C
                  C  T IS IN THE TIME INTERVAL EMERGE(J) TO HARTIM(J). TO IS EQUAL
                  C  TO THE EMERGENCE TIME FOR THE CROP INTERVAL.
  ISN 0022         20   TO = EMERGE(J)
                  C
                  C  CALCULATE TAUPT FOR EACH NUCLIDE IN THE CHAIN.
  ISN 0023              DO 25  I=1,NUMNUC
  ISN 0024                UDOT = 2.0 * ATAU * T * EXP(-ATAU * (T**2 - TO**2))
  ISN 0025                TAUPT(I) = (MFO * UDOT * BSUBIV(I)) / (10000.0 * A * SMALLD*RHO)
  ISN 0026         25   CONTINUE
                  C
  ISN 0027         30   RETURN
  ISN 0028              END
```

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LEVEL 21.8 ( JUN 74 )                              OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002             SUBROUTINE QUERY(T, IANS)
                 C
                 C IS CALLED BY SUBROUTINE CALC TO DETERMINE WHETHER OR NOT TIME T (DAYS) IS
                 C A HARVEST TIME. THE VALUE OF IANS IS SET TO
                 C
                 C      1 IF T IS A HARVEST TIME,
                 C      0 IF NOT.
                 C
                 C QUERY SEARCHES THE ARRAY HARTIM, WHICH IS DEFINED BY SUBROUTINE HARVST,
                 C IN ORDER TO DETERMINE WHETHER OR NOT T IS A HARVEST TIME, I.E. WHETHER
                 C OR NOT  T= HARTIM(J) FOR SOME J=1 TO NHARV.
  ISN 0003             COMMON /HRVST/ HARTIM(30),NHARV
  ISN 0004             DOUBLE PRECISION HARTIM,T
  ISN 0005             IANS = 0
  ISN 0006             DO  1  J=1,NHARV
  ISN 0007             IF (T.EQ.HARTIM(J)) IANS=1
  ISN 0009             IF(IANS.EQ.1) GO TO 2
  ISN 0011           1 CONTINUE
  ISN 0012           2 RETURN
  ISN 0013             END
```

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LEVEL 21.8 ( JUN 74 )                                   OS/360  FORTRAN H

           COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
               C
               C RAGTIME
               C-----------------------------------------------------------------------
               C
               C PROGRAM AUTHORS : J.C.PLEASANT, L.M.MCDOWELL-BOYER, AND G.G.KILLOUGH
               C                   HEALTH AND SAFETY RESEARCH DIVISION
               C                   OAK RIDGE NATIONAL LABORATORY
               C                   OAK RIDGE, TENNESSEE   37830
               C
               C-----------------------------------------------------------------------
               C
               C  PTR IS USED TO REPRESENT THE UNIT NUMBER ASSOCIATED WITH THE LINE
               C  PRINTER, RDR IS USED TO REPRESENT THE UNIT NUMBER ASSOCIATED WITH
               C  THE CARD READER.
               C
 ISN 0002            COMMON /IODEV / PTR,RDR
 ISN 0003            INTEGER  PTR,RDR
 ISN 0004            RDR = 5
 ISN 0005            PTR = 6
               C
 ISN 0006            IFLAG = 0
               C
               C     IFLAG IS A PARAMETER PASSED IN SUBROUTINE INPUT WHICH DIRECTS
               C     THE FLOW OF THE PROGRAM.  IF IFLAG IS SET TO ZERO, THE ENTIRE
               C     SUBROUTINE IS EXECUTED AND IFLAG IS SET EQUAL TO ONE.  THIS
               C     ENABLES A BRANCH TO BE MADE AROUND THE PORTION OF CODE THAT INPUTS
               C     THE NUCLIDE INDEPENDENT PARAMETERS ON SUCCESSIVE CALLS FOR THE
               C     VARIOUS CHAINS BEING STUDIED.
               C
 ISN 0007            READ (RDR,10) NCHAIN
 ISN 0008         10 FORMAT (10X,I2)
               C
 ISN 0009            DO 20 I = 1,NCHAIN
 ISN 0010            CALL INPUT (IFLAG)
 ISN 0011            CALL OUTDAT
 ISN 0012            CALL CALCIN
 ISN 0013            CALL HARVST
 ISN 0014            CALL CALC
 ISN 0015            CALL CHECK
 ISN 0016         20 CONTINUE
               C
 ISN 0017            STOP
 ISN 0018            END
```

Job Control Language (JCL) for RAGTIME

Job control language varies from one computer installation to another. For execution of RAGTIME on the IBM 360/91 at Oak Ridge National Laboratory, the following JCL arrangement has been used:

```
//jobname_JØB_(charge no.),'X-10 7509 PLEASANT'
//*CLASS_CPU91=44S,IØ=2.8,REGIØN=270K
/*RØUTE_XEQ_CPU91
//_EXEC_FØRTHCLG,REGION.GØ=270K,PARM.GØ='EU=-1'
//FØRT.SYSIN_DD_*

source decks (RAGTIME MAIN and subroutines)

/*
//LKED.GEAR_DD_DSN=T.GGK05716.GEAR,DISP=SHR,UNIT=SPDA,
//   _DCB=(RECFM=FB,LRECL=80,BLKSIZE=800)
//LKED.SYSIN_DD_*
  INCLUDE_GEAR
/*
//GØ.FT03F001_DD_SYSØUT=A,DCB=(RECFM=VBA,LRECL=137,BLKSIZE=1000)
//GØ.FT01F001_DD_*

data deck

/*
//
```

The underline (_) is used to indicate a space. The JCL shown above makes use of compiled code for GEAR stored in the system as a catalogued data set and made available to the Linkage Editor through the JCL statements comprehended by the brace. If the subroutines of the GEAR package are to be compiled along with RAGTIME, they should be included with the source decks and the JCL statements in the brace deleted. The additional compilation time would require that the limits on the CLASS card be revised. We note also that other sets of input data (e.g., radionuclide chains with more than two species or multiple problems within one job) will require longer running times. Moreover, the running times will vary greatly with the model of IBM system and other local factors.

APPENDIX B

SAMPLE RUN OF THE RAGTIME CODE

APPENDIX B

Output from a sample run of the currently implemented version of RAGTIME is provided in this appendix. Values for all state variables are listed, and concentrations in grains, milk, and beef are plotted versus time in Fig. B.1, B.2, and B.3. A number of parametric values had to be specified and options chosen to complete this run (see Table B.1). Table B.2 exhibits a listing of the data cards used for the sample run.

Following is a brief description of values and options specified for the sample run conducted, which considers a chronic deposition term (F_i) of 1 μCi ^{90}Sr per m^2 per day, beginning 70 days prior to emergence of the grain. Compartment E_i, representing direct contamination of the surface of above-ground food crops through interception of depositing radionuclides, was considered to consist only of grain crops. In doing so, the time-dependent intercepting efficiency of the edible portion of the crop, the grain, was modeled using empirical values describing projected surface area as a function of plant mass, rather than using the geometric approach (see Sect. 3 discussion). Both empirical values and plant growth curves were obtained mainly from work documented by Miller[1] of the Stanford Research Institute. An equation describing the mass m of the grain per plant (grams/plant) was adopted from Miller; at any time $t \geq t_0$,

$$m = m_f^0 \left[1 - e^{-a_\tau(t^2 - t_0^2)}\right] , \qquad (B.1)$$

where m_f^0 = final mass of grain at harvest (grams/plant); t_0 = time of emergence of grain (days), and a_τ = growth coefficient (day^{-2}). All of these input parameters represent averages for a number of grain varieties. For the sample run of RAGTIME, the following values were used:

m_f^0 = 1 gram/plant

t_0 = 70 days

a_τ = 1.24×10^{-4} day^{-2}

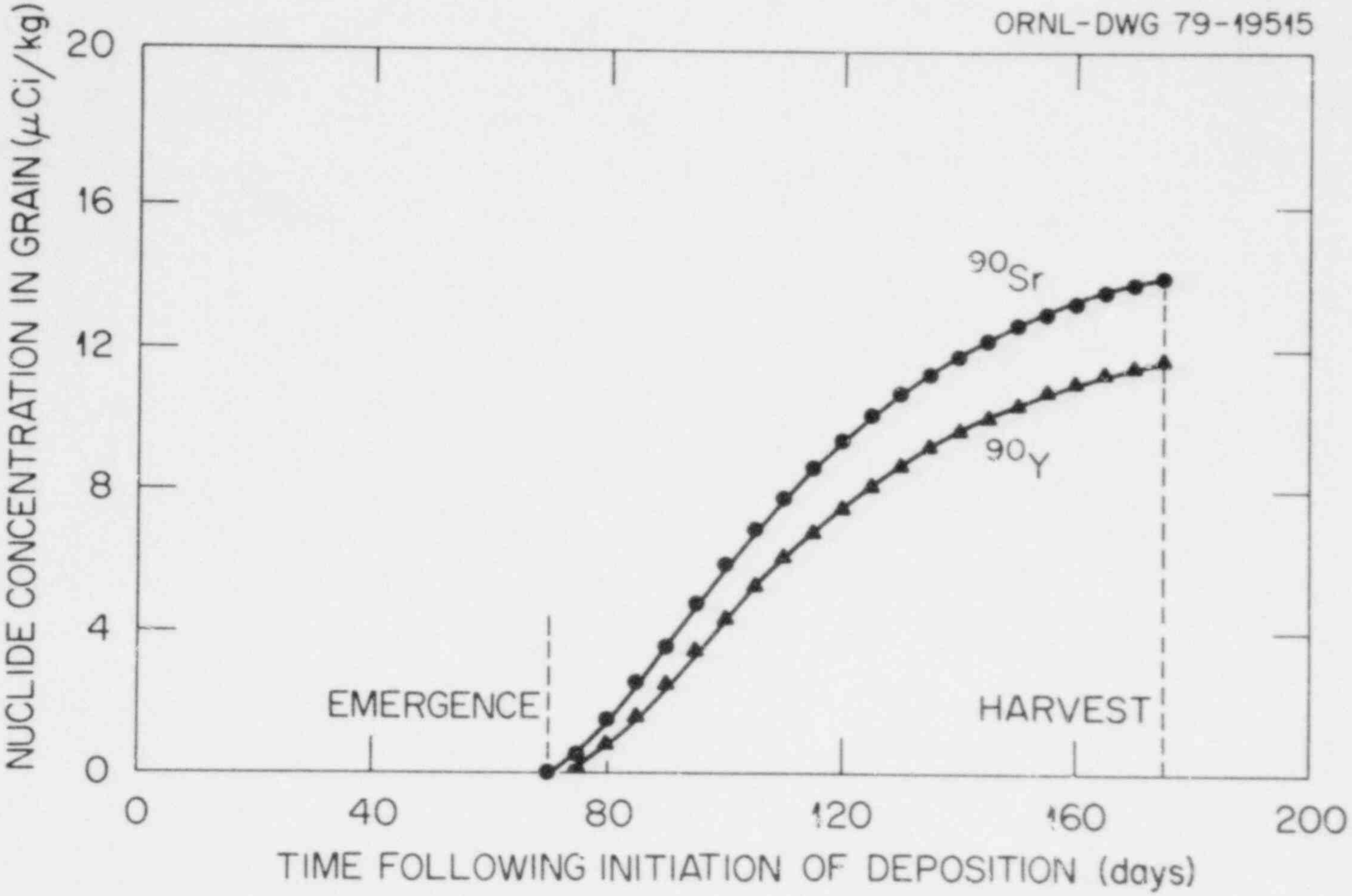

Fig. B.1. Predicted concentrations of ^{90}Sr and ^{90}Y in grain vs time (1 μCi m^{-2} day^{-1} deposition of ^{90}Sr).

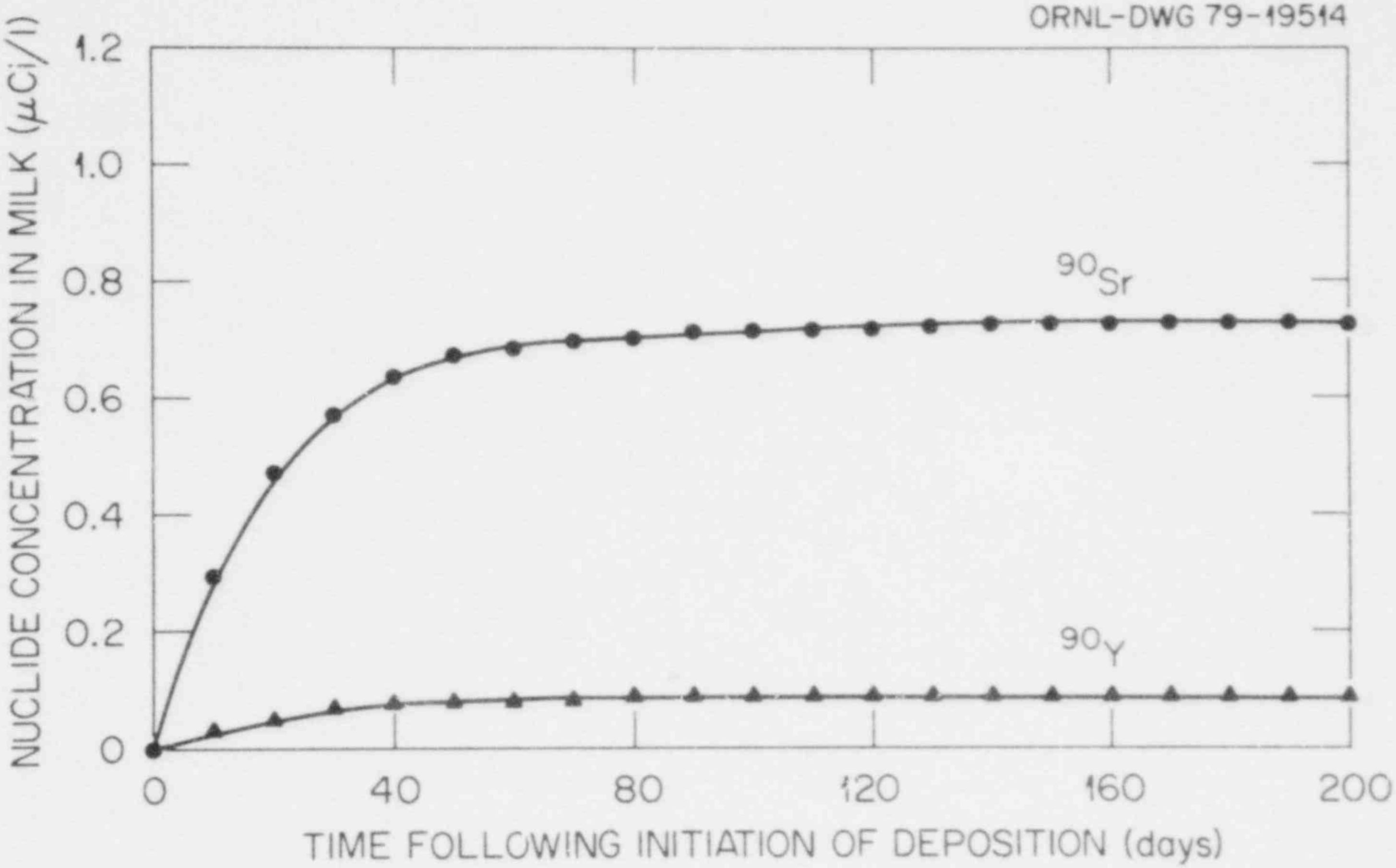

Fig. B.2. Predicted concentrations of ^{90}Sr and ^{90}Y in milk vs time (1 μCi m^{-2} day^{-1} deposition of ^{90}Sr).

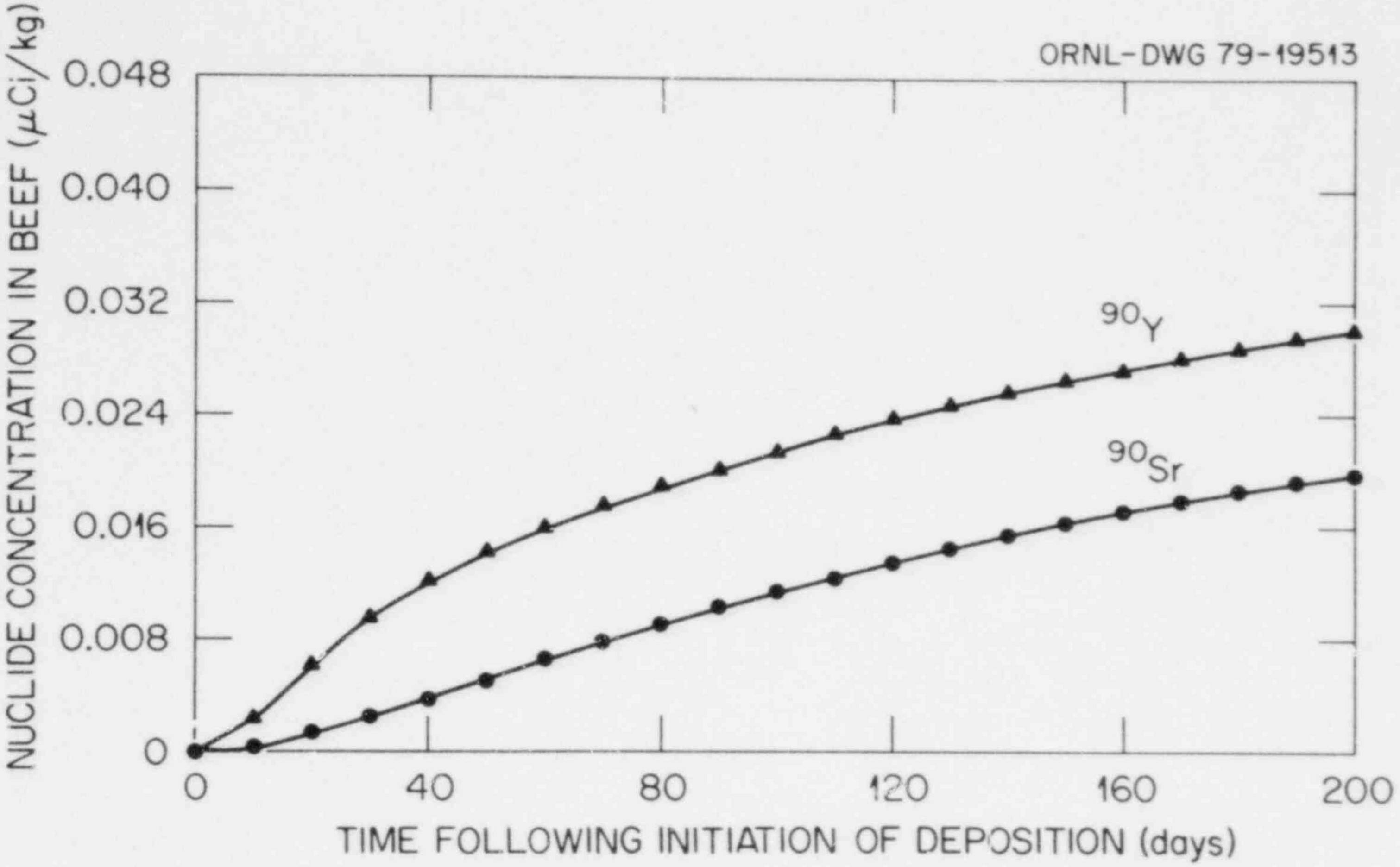

Fig. B.3. Predicted concentrations of ^{90}Sr and ^{90}Y in beef vs time (1 μCi m^{-2} day^{-1} deposition of ^{90}Sr).

Table B.1. Values of parameters and other quantities used in sample run of RAGTIME for the ^{90}Sr, ^{90}Y decay chain[a]

Parameter	FORTRAN name	Specific for	Value used	Reference or section of report containing discussion
A	A		1,000 m^2	4
A_g	ASUBG		10,000 m^2	4
a_τ	ATAU	grains	1.24×10^{-4} day^{-2}	App. B
B_{21}	B(2,1)		1 (= radioactive branching radio from ^{90}Sr to ^{90}Y)	Sect. 6.1
B_{iv}	BSUBIV(I)		0.290 for ^{90}Sr, 0.00430 for ^{90}Y	2, 3
d	SMALLD		20 cm	4
D_g	DSUBG		0.15 kg m^{-2}	4
$F_i(t)$	F(I,T)		$F_1(t) = 1$ μCi m^{-2} day^{-1} $F_2(t) = 0$ μCi m^{-2} day^{-1}	App. B
$(F_f)_i$	FSUBF(I)		3.0×10^{-4} for ^{90}Sr 5.8×10^{-3} for ^{90}Y	2
$(F_m)_i$	FSUBM(I)		2.4×10^{-3} for ^{90}Sr 2.0×10^{-5} for ^{90}Y	2

Table B.1 (continued)

Parameter	FORTRAN name	Specific for	Value used	Reference or section of report containing discussion
λ_i^R	LAMRR(I)		$\lambda_1 = 6.66 \times 10^{-5}$ day^{-1} $\lambda_2 = 0.26$ day^{-1}	6
m	M	grains	$m_f^o \left[1 - e^{-a_T(t^2 - t_0^2)}\right]$, $t \geq t_0$, where t represents time (days)	1
M_b	MSUBB		200 kg	4
M_f^o	MFOS1	grains	1 g/plant	App. B
M_f^o	MFO	grains	250,000 g	App. B
n_L	NSUBL	grains	0.455	1
ρ	RHØ	soil	1.4 g/cm^{-3}	4
$\mathcal{S}_1$	S1	grains	$0.00075\ m^{0.545}{}_w$	1
$\mathcal{S}_2$	S2	grains	$1 - \mathcal{S}_1$	Sect. 3.1
$\mathcal{S}_3$	S3	pasture	0.25	Sect. 4.1
$\mathcal{S}_4$	S4	pasture	0.75	Sect. 4.1
S_L	SL	grains	$0.00075m^{-0.455}$	1
S_L^o	SLO	grains	0.00075	1

Table B.1 (continued)

Parameter	FORTRAN name	Specific for	Value used	Reference or section of report containing discussion
τ_{beef}	TAUBEF		3.81×10^{-3} day^{-1}	4
$\tau_{e,s}$	TAUES		0.0495 day^{-1}	4, 7
τ_{exc}	TAUEXC(I)		2.0×10^{-3} day^{-1} for ^{90}Sr, 2.0×10^{-3} day^{-1} for ^{90}Y	4
$\tau_{g,*}$			$V_c/(A_g D_g) = 6.67 \times 10^{-3}$ day^{-1}	Sect. 4.1
$(\tau_{g,b})_i$	TAUGB(I)		$[(F_f)_i(\tau_{exc})_i V_c]/D_g$	Sect. 4.2
$(\tau_{g,c})_i$	TAUGC(I)		$[(F_m)_i\ \tau_{milk} V_c]/D_g$	Sect. 4.2
$\tau_{g,r}$	TAUGR		0.0495 day^{-1}	4, 7
τ_{milk}	TAUMLK		2 day^{-1}	4
$\tau_{p,h}$	TAUPH		1.096×10^{-4} day^{-1}	4, 8
$(\tau_{p,t})_i$	TAUPT(I)	grains	$[M_f^o \dot{U}(t) B_{iv}]/(10{,}000 \times Ad\rho)$	App. B
$\tau_{r,d}$	TAURD		1.096×10^{-4} day^{-1}	4, 8
$\tau_{r,g}$	TAURG		2.74×10^{-5} day^{-1}	Sect. 4.1
$\tau_{s,p}$	TAUSP		6.93×10^{-4} day^{-1}	Sect. 2.1
t_b^h	TIMBH		20 days	5

Table B.1 (continued)

Parameter	FORTRAN name	Specific for	Value used	Reference or section of report containing discussion
t_c^h	TIMCH		2 days	App. B
t_0	TO	grains	70 days	App. B
U	U		5.5 liters	4
$\dot{U}(t)$	UDØT	grains	$2a_\tau t e^{-a_\tau(t^2 - t_0^2)}$, $t \geq t_0$, where t represents time (days)	1
V_c	VSUBC		10 kg day^{-1}	4
w	W	grains	250 plants m^{-2}	App. B

---

[a] The subscript i used with parameter names refers to the *ith* nuclide (i = 1 for ^{90}Sr, i = 2 for ^{90}Y).

Table B.2. Format of input parameters for RAGTIME

```
NCHAIN     1
  2
SR90    0.0
Y90     0.0
    1
        0.0E0         1.0E0
        0.0E0         0.0E0
  1
SR90        Y90          1.0
  1
1.             365
LAMRR SR906.66    E-05
FSUBM SR902.4     E-03
FSUBF SR903.0     E-04
BSUBTVSR902.9     E-01
TAUEXCSR900.002
LAMRR Y90 2.60    E-01
FSUBM Y90 2.0     E-05
FSUBF Y90 5.8     E-03
BSUBTVY90 4.3     E-03
TAUEXCY90 0.002
A         1000.0
ASUBG     10000.0
DSUBF     0.1
DSUBG     0.15
SMALLD    20.0
D1        0.25
D2        0.25
D3        1.0
D4        1.0
MSUBB     200.
RHO       1.4
TAUBFF    0.00381
TAUMLK    2.0
TAUBM     0.3
TAUCM     1.0
TAUES     0.0495
TAUGR     0.0495
TAUPD     0.0001096
TAURD     0.0001096
TAURG     0.0000274
TAUSP     0.000693
TAUTM     .00
U         5.5
V         0.25
VSUBC     10.0
VSUBS     280000000.0
LAMEH           1.0E+01
LAMTH           1.0E+01
LAMBH           5.0E-02
LAMCH           5.0E-01
```

The specified values were derived from a minimum of data, for the grain of one variety of wheat, and thus may not be the best values to use for other simulations.

We have made use of Eq. (B.1) in deriving time-dependent values for the interception fraction S_1 and a normalized version of this equation in the derivation of values for the transfer coefficient $(\tau_{p,t})_i$. The fraction S_1 may be viewed as the ratio of the projected surface area (m²) of the grain to the area (m²) of the land on which the crop is grown. Thus, S_1 is related to the specific area,

$$S_L = \frac{\text{projected surface area of grain (m}^2\text{)}}{\text{mass of grain (grams)}}$$

by the equation

$$S_1 = S_L mw \tag{B.2}$$

where m = mass of grain per plant (grams), and w = number of plants per square meter of land. The specific area, S_L, may be fitted to an equation of the form

$$S_L = S_L^0 m^{-n_L} \tag{B.3}$$

in which S_L^0 and n_L are empirical constants and m is the time-dependent mass of the grain per plant as given in Eq. (B.1). This model is adopted from ref. 1 (p. 177). Using the values $S_L^0 = 0.00075$ and $n_L = 0.455$ from this document, the value of S_1 is calculated from Eqs. (B.2) and (B.3) to be

$$S_1 = 0.00075\ m^{0.545}\ w$$

For the root uptake compartment T_i, again only grains were considered in the sample run. The rate (microcuries day⁻¹) at which radioactivity is absorbed by plant roots is represented in Eq. (2.9) by the term $(\tau_{p,t})_i P_i$, where P_i represents the radioactivity (μCi) present in the subsurface soil pool associated with one man's food supply. As in our discussion of Eq. (B.1), it follows that the total mass (grams), as time $t \geq t_0$, of grain in compartment T_i is given by $M_f^0 U(t)$, where

$$U(t) = 1 - e^{-a_\tau(t^2 - t_0^2)} \qquad (B.4)$$

and M_f^0 = total mass (grams) of crop at harvest time grown on land associated with one man's food supply. The rate of root absorption of radioactivity, $(\tau_{p,t})_i P_i$ (microcuries day^{-1}) is assumed to be the product of the rate of increase of grain mass $M_f^0 U(t)$(grams day^{-1}) and the radioactivity concentration in grain (microcuries gram^{-1}), the latter quantity being approximated by

$$\frac{B_{iv} P_i}{\text{mass (grams) of soil in compartment } P_i} = \frac{B_{iv} P_i}{10{,}000 \times Ad\rho} \qquad (B.5)$$

where B_{iv} = concentration of nuclide i per unit fresh weight in plant (μCi kg^{-1}) divided by concentration of nuclide per unit dry weight in soil (μCi kg^{-1}); A = soil area used for crop production, chosen as 10^3 m^2 here; d = plow depth, assumed to be 20 cm; and ρ = soil density, assumed to be 1.4 g cm^{-3} (dry weight). This derivation then leads to the equation

$$(\tau_{p,t})_i = \frac{M_f^0 \, \dot{U}(t) \, B_{iv}}{10{,}000 \times Ad\rho} , \qquad (B.6)$$

where

$$\dot{U}(t) = 2a_\tau t \cdot e^{-a_\tau(t^2 - t_0^2)} \qquad (B.7)$$

Factors describing growth rate [i.e., $\dot{U}(t)$ and a_τ] were again derived from empirical data available for grains[1] and are consistent with those used in estimating interception of airborne radionuclides by grains. Values of B_{iv} (see Table B.1) were derived from empirically obtained data for the elements Sr and Y.[2,3]

For compartments B_i and C_i, respectively representing beef and milk concentrations of ^{90}Sr and ^{90}Y, all parameters were defined and assigned values in Sect. 4 of this document, with the exception of $(\tau_{exc})_i$, $(F_f)_i$, $(F_m)_i$, t_b^h, and t_c^h. A constant value of 0.002 day^{-1}, adopted from TERMOD,[4] has temporarily been assigned to $(\tau_{exc})_i$. This value for $(\tau_{exc})_i$ represents the fractional weight gain per day for a mature steer, and thus implies that dilution of the elemental concentration is due only to growth. In this sense, it represents the lower limit for $(\tau_{exc})_i$, and thus may underestimate loss from the beef compartment because metabolic turnover, which may be element-specific, is neglected. Values for F_f and F_m (Table B.1) were taken from a review of literature concerning uptake of these elements by cattle and subsequent transfer to meat and milk, respectively.

The holdup times for compartments B_i and C_i were specified using values either given in, or derived from, the U. S. Nuclear Regulatory Commission's (USNRC) Regulatory Guide 1.109 (October, 1977).[5] The assumed time between slaughter and consumption of beef (t_b^h) was 20 days, and between milking and milk consumption (t_c^h) was 2 days, the latter representing one-half of the total time given for transfer from feed, through milk, to man. For compartments E_i and T_i, holdup times were not specified, but rather the concentrations after harvest are printed at each output time so that the value of this parameter is left to the user's discretion.

REFERENCES - APPENDIX B

1. C. F. Miller, *Operation Ceniza-Arena: Retention of Fallout Particles from Volcan Irazu (Costa Rica) by Plants and People,* Part Three, SRI-MU-4890, Stanford Research Institute, Menlo Park, California (December 1967).

2. R. E. Moore, C. F. Baes III, L. M. McDowell-Boyer, A. P. Watson, F. O. Hoffman, J. C. Pleasant, and C. W. Miller, *AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides,* ORNL-5532, Oak Ridge National Laboratory, Oak Ridge, Tennessee (June 1979).

3. E. M. Romney, J. W. Neal, H. Nishita, J. H. Olafson, and K. H. Larson, "Plant Uptake of Sr90, Y91, Ru106, CS137, and Ce144 from Soils," *Soil Sci.* 83, 369-376 (1957).

4. R. S. Booth and S. V. Kaye, *A Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment,* ORNL/TM-3135, Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1971).

5. U. S. Nuclear Regulatory Commission, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I,* Regulatory Guide 1.109, Revision 1, USNRC, Washington, D. C. (October 1977).

6. D. C. Kocher, *Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities,* ORNL/NUREG/TM-102, Oak Ridge National Laboratory, Oak Ridge, Tennessee (August 1977).

7. J. D. Zimbrick and P. G. Voillequé, ed., *1967 CERT Progress Report, Controlled Environmental Radioiodine Tests at the National Reactor Testing Station,* Progress Report Number Four, IDO-12065, Idaho Falls, Idaho (December 1968).

8. R. G. Menzel, "Factors Influencing the Biological Availability of Radionuclides for Plants," *Fed. Am. Soc. Exptl. Biol. Proc.* 22, 1398-1401 (1963).

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