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SPARTAN--A SIMPLE PERFORMANCE ASSESSMENT CODE FOR THE NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS PROJECT

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ABSTRACT

SPARTAN is a simple computer model designed for the Nevada Nuclear Waste Storage Investigations Project to calculate radionuclide transport in geologic media. The physical processes considered are limited to Darcy's flow, radionuclide decay, and convective transport with constant retardation of radionuclides relative to water flow. Inputs for the model must be provided for the geometry, repository area, flow path, water flux, effective porosity, initial inventory, waste solubility, canister lifetime, and retardation factors. Results from the model consist of radionuclide release rates from the prospective Yucca Mountain repository for radioactive waste and cumulative curies released across the flow boundaries at the end of the flow path. The rates of release from the repository relative to NRC performance objectives and releases to the accessible environment relative to EPA requirements are also calculated. Two test problems compare the results of simulations from SPARTAN with analytical solutions. The comparisons show that the SPARTAN solution closely matches the analytical solutions across a range of conditions that approximate those that might occur at Yucca Mountain.

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1.0 INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is investigating the possibility of locating a repository for high-level radioactive waste at Yucca Mountain in southern Nevada. Yucca Mountain is located along the southwest corner of the Nevada Test Site (NTS) and on adjacent federal property in southern Nevada. The conceptual design and assessment of performance for the repository are being performed by Sandia National Laboratories (SNL) under the direction of the Department of Energy's (DOE's) Nevada Operations Office, which manages the NNWSI Project. SNL is conducting this effort in cooperation with Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and the U.S. Geological Survey (USGS).

One of the principal programmatic emphases of the NNWSI Project is assessment of repository performance, that is, the ability of the repository to isolate high-level radioactive wastes for tens to hundreds of thousands of years. One of the objectives of performance assessment is to predict as accurately as possible the rate at which radionuclides would be released to the accessible environment (in this report, the water table) in the event of a breach in waste containment. A computer model that provides Simple Performance Assessment of Radionuclide Transport at Nevada (SPARTAN) has been developed to make these predictions.

This report describes the SPARTAN model and its use in solving problems involving water flow through the waste disposal area and transport of soluble radionuclides to the water table. The SPARTAN model was developed to support the environmental assessment document for the potential Yucca Mountain repository (DOE, 1984). The SPARTAN model simulates one-dimensional, dispersionless transport of radionuclides in a multiple-flow-path, homogeneous, geologic medium with sorption in a constant-velocity field. It was initially designed for system studies and found to be an effective tool for simulation of the performance of the repository systems at Yucca Mountain (Sinnock et al., 1984).

The physical processes considered in SPARTAN are limited to Darcy's flow, congruent leaching, radionuclide decay, and convective transport with retardation of radionuclides relative to water flow. This simple approach has been taken to estimate radionuclide migration in geologic media because many of the data and parameters needed to simulate a more detailed physical process are not available at this time. SPARTAN can be used to simulate the problems both in a porous matrix and in fractured media. Water flow, the rate of decay of each radionuclide, and radionuclide transport are simulated directly to calculate the number of curies released to the accessible environment over a time of interest, taking all three of these processes into account. The performance of the repository is measured by the rates of release from the repository relative to NRC performance objectives (NRC, 1983) and the cumulative curies released to the accessible environment relative to EPA standards (EPA, 1984).

It is not the intent of this report to establish the conceptual model of the Yucca Mountain repository site or to formally document and verify SPARTAN. Rather, this report provides some insight into the mathematical basis of SPARTAN and substantiates the accuracy of the code in a preliminary manner. Two problems are simulated to demonstrate SPARTAN's capabilities. The problems selected represent the range of groundwater recharge fluxes at Yucca Mountain. The first problem consists of a 0.5-mm/yr flux in the matrix of the unsaturated zone. This problem represents the flux expected at Yucca Mountain, given the existing climatic and subsurface conditions. In the second problem, a groundwater recharge flux of 5 mm/yr involves flow in both matrix and fractures. This rate of recharge will probably not occur because the unsaturated zone would have to become sufficiently saturated to cause water to flow through the fractures, which is unlikely under the existing climatic and subsurface conditions at Yucca Mountain (Sinnock et al., 1984). Radionuclide transport to the water table is calculated for both circumstances. The accuracy of the results is examined by means of comparisons with analytical solutions. Details of test problems with relevant data and assumptions are taken directly from Sinnock et al. (1984).

Section 2 of this report contains a description of the SPARTAN model. Section 3 contains descriptions of the two scenarios, discusses SPARTAN's solutions and the analytical solutions, and compares the results of the SPARTAN and analytical solutions. Section 4 provides conclusions. Two appendices are provided: Appendix A contains a computer listing for SPARTAN, and Appendix B contains the computer program and input data used to calculate the analytical solution.

2.0 MATHEMATICAL BASIS OF THE SPARTAN MODEL

The following mathematical principles and assumptions served as the basis for formulation of the series of computer algorithms that make up the SPARTAN model. The computer program used to calculate the test problems in Section 3 is provided in Appendix A.

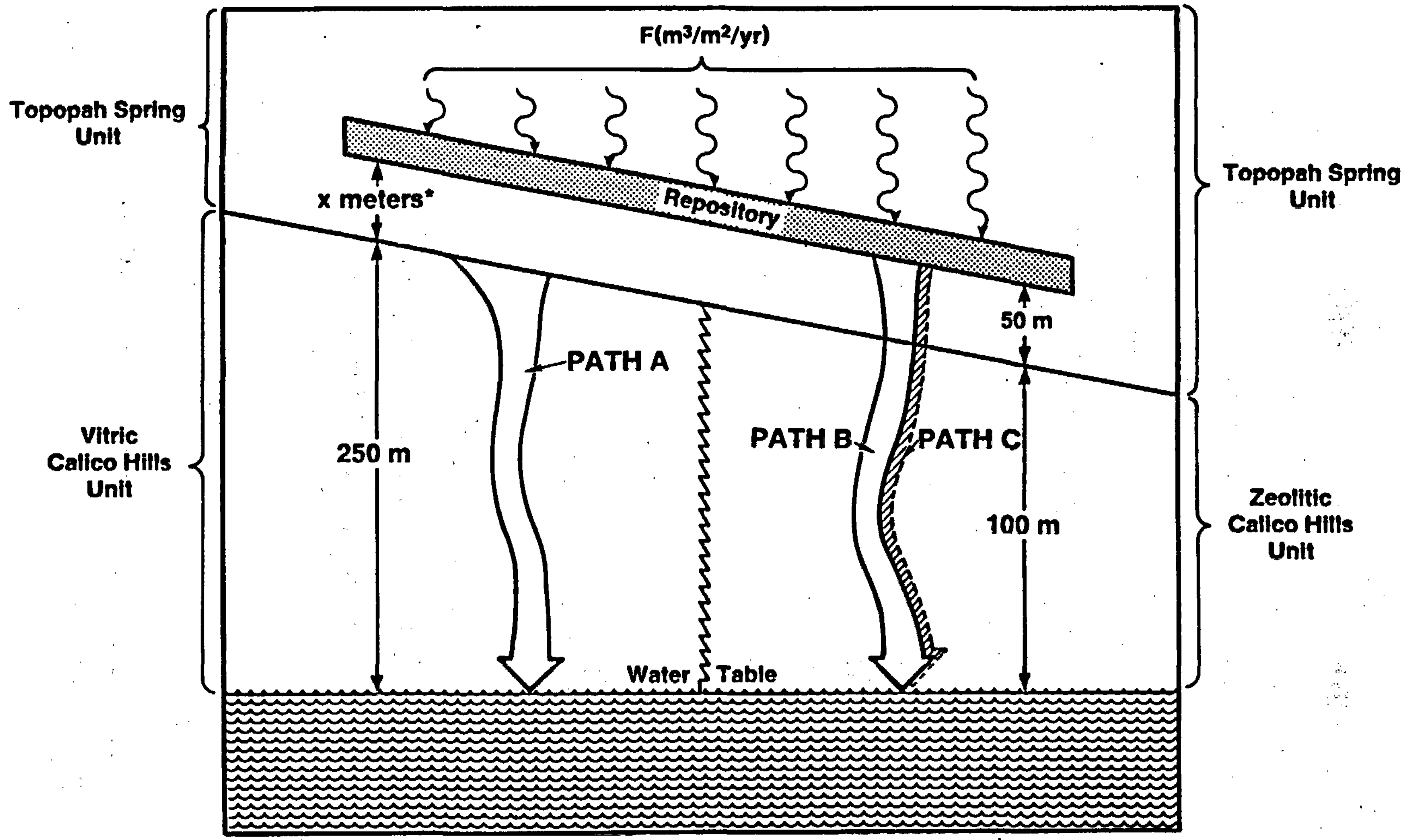
A repository, as depicted in Figure 1, is assumed to contain M(t) metric tons of heavy metal radioactive waste in a planar horizon distributed over an area expressed in square meters. The repository is assumed to be at a height, H, in meters above the water table. The volume of groundwater that flows vertically downward through the unsaturated zone from a unit area at the disposal horizon per unit of time is called the flux and is assumed to be a parameter, F, given in $m^3/m^2/yr$. Flow in the unsaturated zone is assumed to obey Darcy's law. The boundary of the accessible environment is assumed to occur in the saturated zone a distance 2 to 10 km downgradient of the repository. Though not considered in the test problems presented later, water flow time through the saturated zone is treated in SPARTAN as a constant parameter, T^s.

2.1 Water Flow

The subscript, j, identifies the two components of the medium (porous matrix and fractures); j=1 denotes the matrix and j=2 denotes the fractures. Darcy's law for the steady state of flow in both the matrix and fractures is expressed by

$$F_j = -K_j \frac{dh_j}{dl} \qquad (m^3/m^2/yr) \tag{1}$$

where h_j is hydraulic head, $\frac{dh_j}{dl}$ is the hydraulic gradient, K_j is the hydraulic conductivity, and F_j is called "Darcy velocity" or "Darcy flux." For water percolating vertically downward through a uniform profile to a



PATH A: Matrix flow for all values of flux.
PATH B: Matrix flow for flux up to 1 mm/yr.
PATH C: Fracture flow for flux in excess of 1 mm/yr; identical properties assumed for Topopah Spring and Calico Hills units.

***Undefined thickness of Topopah Spring unit ignored in calculations**

Figure 1. Schematic Representation of Conceptual Geometric Model Used in Calculating Releases of Radionuclides from a Repository at Yucca Mountain

stationary water table, $\frac{dh_j}{dl}$ is assumed to be -1. The flux through the j^{th} medium cannot exceed the maximum hydraulic conductivity of the j^{th} medium. Thus, if the flux is less than the saturated conductivity of the matrix, $K^s_{j=1}$, it is assumed that the flux flows through the porous matrix, and the effective hydraulic conductivity and the gradient will adjust to satisfy Equation 1. If the flux is greater than $K^s_{j=1}$, the excess flux, $F_{j=2}$, will flow through fractures of sufficient conductivity to satisfy Equation 1.

The average particle velocity of water, V_j, is

$$V_j = \frac{F_j}{n_j} \qquad \text{(m/yr)} \tag{2}$$

where n_j is the effective porosity of the j^{th} medium. The water travel time, T^u_j, through H_j thickness of the unsaturated zone in meters is

$$T^u_j = \frac{H_j n_j}{F_j} \qquad \text{(yr)} \quad . \tag{3}$$

Saturated flow time is treated as a parameter, T^s. The total water travel time, T^w_j, from the repository to the accessible environment is the sum of travel time in the saturated zone, T^s, and the travel time in the unsaturated zone and is

$$T^w_j = T^u_j + T^s \qquad \text{(yr)} \quad . \tag{4}$$

Assigning a value of zero to T^s, as done for this report, allows a consideration of flow only to the water table.

2.2 Waste Dissolution

The flux that passes through the repository level may intercept the radioactive waste. The maximum volume of water that could interact annually with the waste, for either matrix or fracture flow, is the total flow through the repository area and is given by

$$Q_j = F_j \cdot A \qquad (m^3/yr) \tag{5}$$

where Q_j is the annual flow rate through j^{th} medium, F_j is the annual flux through j^{th} medium, and A is the total area of the repository. Assuming only one-dimensional vertical flow, the annual amount of water in cubic meters actually intercepting the waste emplacement area, q_j, is less than Q_j and is given by

$$q_j = F_j \cdot A \cdot \alpha_j \qquad (m^3/yr) \tag{6}$$

where α_j is the ratio of the area occupied by the waste (i.e., the effective cross-sectional area for water flow intercepted by emplaced waste canisters or their emplacement holes) to the total repository area.

The water intercepting the actual waste emplacement area will not contact radioactive waste unless a canister fails. Canister failure is treated in two simple ways: (1) a constant lifetime of either 300 or 1,000 yr represents the time of immediate and simultaneous failure of all canisters, i.e., having a step function at the constant lifetime, T_f

$$G(t) = U(t - T_f) \tag{7}$$

where

$$U(t - T_f) = 0 \text{ if } t \leq T_f$$

$$U(t - T_f) = 1 \text{ if } t > T_f$$

and (2) a variable lifetime represents the exponential lifetime distribution of the canister failure, i.e., having a probability density function of

$$g(t) = \begin{cases} \frac{1}{\mu} \exp(-t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{8}$$

for which the cumulative distribution is

$$G(t) = \int_{-\infty}^{t} g(y)dy = \begin{cases} 1 - \exp(-t/\mu) & t \geq 0 \\ 0 & t < 0 \end{cases} . \tag{9}$$

The parameter μ is the mean time-to-failure of the waste canisters. Though SPARTAN has the capability to use variable lifetimes, only a constant lifetime of 300 yr is used in the sample problems.

It is assumed that wastes contacted by water dissolve congruently with uranium on a mass basis. Thus, given a solubility limit of uranium, $S_{i=u}$(kg/m^3), the expected annual dissolution rate for uranium is given by

$$D_{i=u,j}(t) = q_j \cdot S_{i=u} \cdot G(t) \qquad \text{(kg/yr)}. \tag{10}$$

For the i^{th} radionuclide, the annual dissolution rate is given by

$$D_{i,j}(t) = D_{i=u,j}(t) \cdot \frac{m_i(t)}{m_{i=u}(t)} \qquad \text{(kg/yr)} \tag{11}$$

where $m_i(t)$ is the inventory of i^{th} radionuclide in kilograms at time, t, and i=u represents uranium. Because it is assumed that radionuclides dissolve instantaneously when they come in contact with water, the mass release rate to water is the same as the dissolution rate. The total amount of waste released, $\sum_{i=1}^{N} \Delta m_i(t)$, is simply the sum of dissolved amounts for all radionuclides.

$$\sum_{i=1}^{N} \Delta m_i(t) = \sum_{i=1}^{N} \sum_{j=1}^{M} D_{i,j}(t) \qquad \text{(kg/yr)} \qquad (12)$$

where N is the number of radionuclide species, and M is the number of pathway types.

The annual fractional release rate is defined as

$$R = \frac{\sum_{i=1}^{N} \Delta m_i(t)}{\sum_{i=1}^{N} m_i(t)} \qquad (yr^{-1}). \qquad (13)$$

Allowing water to dissolve the wastes and assuming releases based on a high solubility for uranium results in an overestimation of waste dissolution in the repository. A more realistic approach is to use mass-transfer theories to estimate the time-dependent dissolution rate of waste material in a geological repository (Chambré et al., 1982). However, the first approach, which is used in SPARTAN, can reveal the unique natural qualities of the site, which will contribute to waste containment independently of engineered features.

Given an initial inventory of radionuclides, the mass of any radionuclide $m_i(t)$, and $\Delta m_i(t)$ that is present at some time (t) after the initial time, t_o, can be computed analytically by solving a system of ordinary differential equations that describe radiocative decay (Bateman, 1910).

The rate of curies released annually for the i^{th} species to the water flowing through the j^{th} medium, $C_{i,j}$, is the product of specific activity, a_i, and annual dissolution rate, $D_{i,j}$

$$C_{i,j}(t) = a_i \, D_{i,j}(t) \qquad \text{(Ci/yr)} \quad . \tag{14}$$

Though not used in the test problems presented later, SPARTAN has the capability to assess the annual release rate for each radionuclide in terms of the NRC performance objectives (NRC, 1983). An "NRC Ratio," NR_i, can be calculated from

$$NR_i = \frac{\sum_{j=1}^{2} C_{i,j}(t)}{NL_i} \tag{15}$$

where NL_i is the NRC release limit for the i^{th} radionuclide defined in Table 1. Similarly, a total NRC ratio for all radionuclides can be computed with

$$NR = \sum_{i=1}^{N} NR_i . \tag{16}$$

2.3 Radionuclide Transport

The transport time for the i^{th} radionuclide, $T^r_{i,j}$, is related to the water travel time by

$$T^r_{i,j} = Rd_{i,j} \, T^w_j \qquad \text{(yr)} \tag{17}$$

TABLE 1

RADIONUCLIDE INVENTORY OF SPENT FUEL AND ALLOWABLE RELEASE LIMITS OF THE NRC AND EPA

Isotope	Half-Life (yr)	Specific Activity (Ci/g)	Inventory (Ci/1,000 MTHM) t = 10 yr[a]	Annual NRC Release Limits from Repository (Ci/1,000 MTHM)[b]		EPA Cumulative Release Limits at Accessible Environment (Ci/1,000 MTHM)[d]
^{246}Cm	5.5×10^3	2.64×10^{-1}	3.5×10^1	3.1×10^{-4}	(NA)[c]	100
^{245}Cm	9.3×10^3	1.57×10^{-1}	1.8×10^2	1.7×10^{-3}	(NA)	100
^{244}Cm	1.76×10^1	8.32×10^1	9.0×10^5	0	(NA)	100
^{242}Cm	4.5×10^{-1}	3.32×10^3	8.5×10^3	1.1×10^{-3}	(NA)	100
^{243}Am	7.95×10^3	1.85×10^{-1}	1.4×10^4	1.3×10^{-1}		100
^{242}Am	1.52×10^2	9.72	1.0×10^4	1.1×10^{-3}	(NA)	1,000
^{241}Am	4.58×10^2	3.24	1.6×10^6	3.5		100
^{242}Pu	3.79×10^5	3.90×10^3	1.6×10^3	1.6×10^{-2}		100
^{241}Pu	1.32×10^1	1.12×10^2	6.9×10^7	1.7×10^{-3}	(NA)	100
^{240}Pu	6.58×10^3	2.26×10^{-1}	4.5×10^5	4.1		100
^{239}Pu	2.44×10^4	6.13×10^{-2}	2.9×10^5	2.8		100
^{238}Pu	8.6×10^1	1.75×10^1	2.0×10^6	9.3×10^{-3}	(NA)	100
^{239}Np	6.4×10^{-3}	2.33×10^5	1.4×10^4	1.3×10^{-1}		1,000
^{237}Np	2.14×10^6	7.05×10^{-4}	3.1×10^2	5.8×10^{-3}	(NA)	100
^{238}U	4.51×10^9	3.33×10^{-7}	3.2×10^2	3.2×10^{-3}	(NA)	100
^{236}U	2.39×10^7	6.34×10^{-5}	2.2×10^2	2.3×10^{-3}	(NA)	100
^{235}U	7.1×10^8	2.14×10^{-6}	1.6×10^1	1.6×10^{-4}	(NA)	100
^{234}U	2.47×10^5	6.18×10^{-3}	7.4×10^1	7.8×10^{-3}	(NA)	100
^{233}U	1.62×10^5	9.47×10^{-3}	3.8×10^{-2}	2.1×10^{-5}	(NA)	100
^{231}Pa	3.25×10^4	4.51×10^{-2}	5.3×10^{-3}	3.7×10^{-6}	(NA)	100
^{232}Th	1.4×10^{10}	1.10×10^{-7}	1.1×10^{-7}	1.2×10^{-10}	(NA)	100
^{230}Th	8.0×10^4	1.94×10^{-2}	4.1×10^{-3}	9.0×10^{-5}	(NA)	100
^{229}Th	7.34×10^3	2.13×10^{-1}	2.8×10^{-5}	9.2×10^{-7}	(NA)	100
^{226}Ra	1.60×10^3	9.88×10^{-1}	7.4×10^{-6}	1.5×10^{-5}	(NA)	100
^{225}Ra	4.05×10^{-2}	3.92×10^4	8.1×10^{-5}	9.4×10^{-7}	(NA)	1,000
^{210}Pb	2.23×10^1	7.63×10^1	7.0×10^{-7}	1.7×10^{-5}	(NA)	1,000
^{137}Cs	3.0×10^1	8.70×10^1	7.5×10^7	2.2×10^{-8}	(NA)	1,000
^{135}Cs	3.0×10^6	8.82×10^{-4}	2.7×10^2	2.7×10^{-3}	(NA)	1,000
^{129}I	1.59×10^7	1.74×10^{-4}	3.3×10^1	3.3×10^{-4}	(NA)	1,000
^{126}Sn	1.0×10^5	2.84×10^{-2}	4.8×10^2	4.8×10^{-3}	(NA)	1,000
^{99}Tc	2.15×10^5	1.70×10^{-2}	1.3×10^4	1.3×10^{-1}		10,000
^{93}Zr	9.5×10^5	4.04×10^{-3}	1.7×10^3	1.7×10^{-2}		1,000
^{90}Sr	2.9×10^1	1.37×10^2	5.2×10^7	6.5×10^{-9}	(NA)	1,000
^{59}Ni	8.0×10^4	7.57×10^{-2}	3.0×10^1	3.0×10^{-4}	(NA)	1,000
^{14}C	5.73×10^3	4.45	1.4×10^3	1.2×10^{-2}	(NA)	100
				$\Sigma = 1.1\times10^1$		

a. 10 yr out of the reactor, i.e., the assumed time of emplacement (DOE, 1979).
b. 1×10^{-5} times inventory at 1,060 yr (NRC, 1983).
c. NA means not applicable; curies remaining at 1,060 yr are less than about 1.1×10^{-2} Ci, i.e., less than 0.1% of the total release rate limit of about 11 Ci/yr; each of these nuclides thus has a release rate limit of 1.1×10^{-2} Ci/yr.
d. Applied 10,000 yr after repository closure (EPA, 1984).

where $Rd_{i,j}$ is a dimensionless retardation factor for the i^{th} radionuclide through the j^{th} medium. For porous flow, i.e., j=1, the retardation factor is defined as

$$Rd_{i,1} = 1 + \frac{\gamma Kd_i}{n_1} \tag{18}$$

where the γ is the bulk rock density (kg/m^3), Kd_i is the distribution coefficient (m^3/kg) or sorption ratio for the i^{th} radionuclide in porous matrix blocks, and n_1 is the effective porosity of the blocks.

In the case of water flow through fractures, i.e., j=2, it is more appropriate, as suggested by Burkholder (1976), to relate the retardation factor to a distribution coefficient, Ka_i, by the equation

$$Rd_{i,2} = 1 + Rf\ Ka_i \tag{19}$$

where Rf is the ratio of surface area to void space (volume) for the fracture opening through which the radionuclide is being transported. Ka_i is a measure of moles of the i^{th} radionuclide in the sorbed state per unit of surface area divided by the moles of the i^{th} nuclide in the dissolved state per unit volume of groundwater when the groundwater and sorbing medium are in equilibrium. Because the fracture surfaces are generally irregular, the actual surface area with which the radionuclide reacts is unknown. A simple approach is to express Ka_i in terms of the area of an assumed planar fracture surface (Freeze and Cherry, 1979; p. 410). In this case, retardation factors for fracture flow may be computed as

$$Rd_{i,2} = 1 + \frac{2Ka_i}{b} \tag{20}$$

where b is the width of the fracture aperture.

The differential equation describing the one-dimensional transport of radionuclides and their decay products through geologic media with sorption is listed below.

$$Rd_{\ell,j} \frac{\partial N_{\ell,j}}{\partial t} + V_j \frac{\partial N_{\ell,j}}{\partial z} + Rd_{\ell,j} \lambda_\ell N_{\ell,j} = Rd_{\ell-1,j} \lambda_{\ell-1} N_{\ell-1,j} \qquad (21)$$

where

$N_{\ell,j}$ = radionuclide concentration for the ℓ^{th} member of the decay chain through the j^{th} medium,

$Rd_{\ell,j}$ = retardation factor for the ℓ^{th} member of the decay chain through the j^{th} medium,

λ_ℓ = decay constant for the ℓ^{th} member of the decay chain

V_j = where $\lambda_0 = 0$, and groundwater velocity through the j^{th} medium.

Hydrodynamic dispersion and diffusion are not considered in these equations.

2.4 Release to the Accessible Environment

The amount of curies released to the accessible environment may be expressed in curies as $C^a_{i,j}$. This quantity is obtained by decaying the curies of each radionuclide dissolved (Equation 11) for the time period represented by the retarded radionuclide transport time (Equation 17) from the repository to the accessible environment.

$C^a_{i,j}$ is computed by a direct-simulation approach that defines numerical matrices that represent the material balances of the ℓ^{th} members of decay chains and all preceding chain members (Equation 21) over a differential length of flow path and a differential time. The annual amount of curies at any time after dissolution from the repository, $C_{i,j}(t)$, is modeled during transport as a set of discrete lumped slugs. Each slug, by definition, consists of a discrete quantity of curies, $(C_p)_{i,j}$, approximated by

$$(C_p)_{i,j} = (C^k_{i,j} + C^{k+1}_{i,j}) \frac{\Delta t_k}{2} \qquad (Ci) \tag{22}$$

where

Δt_k = the time increment for the k^{th} time step

$C^k_{i,j}$ = the curie release rate of the k^{th} time step

$C^{k+1}_{i,j}$ = the curie release rate at the $(k+1)^{th}$ time step

p = the slug index, $p = 1, 2, 3, \ldots NP$, and NP is the number of slugs.

In addition, each $(C_p)_{i,j}$ is associated with a discrete spatial coordinate $(Z_p)_{i,j}$. Therefore, at any location, $(Z_p)_{i,j}$, and at any time, t, there is an associated discrete curie content, $(C_p)_{i,j}(t)$.

During a given time step, the velocity of the i^{th} radionuclide in the j^{th} medium of each slug is computed from the characteristics of convective mechanisms

$$\frac{d(Z_p)_{i,j}}{dt} = \frac{V_j}{Rd_{i,j}} \tag{23}$$

where

V_j = water velocity along the j^{th} flow path in the Z direction. The new location of the slug at the $(k + 1)^{th}$ time step is calculated by

$$(Z^{k+1}_p)_{i,j} = (Z^k_p)_{i,j} + \Delta t_k \frac{V_j}{Rd_{i,j}} \tag{24}$$

where

Δt_k = the time increment for the k^{th} time step

$(Z_p^k)_{i,j}$ = the Z location of the slug p at the k^{th} time step

$(Z_p^{k+1})_{i,j}$ = the Z location of the slug p at the $(k + 1)^{th}$ time step.

The slugs in the flow path and the source term at the repository are adjusted for radioactive decay in each time step by solving the Bateman equations. A five-member chain of equations is used in computation of radionuclide quantities as a function of time. For the decay chains with very rapidly decaying nuclides, each of the short-lived radionuclides, i.e., Pu-241, Ra-225, Cm-242, Pb-210, and Np-239, is assumed to remain in secular equilibrium with its immediate precursor. No branching ratios are considered in the decay chains.

The curies released to the accessible environment at Z^a m from the repository, $C^a_{i,j}$, is the sum of slugs transported to the spatial coordinates corresponding to the boundary of the accessible environment, i.e., $(Z_p)_{i,j} \geq Z^a$. Cumulative curies released to the accessable environment for the i^{th} radionuclide along the j^{th} path, $\bar{C}^a_{i,j}$, are the curies in all slugs reaching the boundary integrated from time 0 to t.

$$\bar{C}^a_{i,j}(t) = \sum_{k=1}^{K} \sum_{p=1}^{N_p} (C_p)_{i,j}(t) \qquad \text{(Ci)} \qquad (25)$$

for $(Z_p)_{i,j} \geq Z^a$ where k is the index for time steps, and K is the number of time steps.

Though the capability is not illustrated in the test problems, SPARTAN can compare the performance of a site, i.e., the cumulative curies released to the accessible environment, with the EPA release requirements (EPA, 1984). The measure of performance is simply the "EPA release ratio" (ER),

$$ER = \sum_{i=1}^{N} \frac{\sum_{j=1}^{M} \bar{C}^{a}_{i,j}(t)}{EL_i} \tag{26}$$

where EL_i is the EPA requirement for the i^{th} radionuclide defined in Table 1. Both the "NRC Ratio" and "EPA Release Ratio" are implemented in SPARTAN. However, neither is presented in the sample problems discussed in the following section because the sample problems are intended to assess the accuracy of SPARTAN in terms of analytical solutions. The cumulative curies released, calculated by SPARTAN, are sufficient to provide the necessary comparisons.

3.0 DESCRIPTION OF SAMPLE PROBLEMS

3.1 General Assumptions

This section describes the test problems used for calculation of cumulative releases of radionuclides to the accessible environment under an assumed conceptual repository model and site conditions at Yucca Mountain. The assumptions underlying the models and conditions used for this report are discussed in detail by Sinnock et al. (1984) and are not elaborated in this report. However, it is necessary to itemize the relevant assumptions here to provide a basis for comparing radionuclide releases computed by SPARTAN and those computed by analytical solutions. The relevant assumptions are presented in the following paragraphs.

The stratum assessed for the prospective repository is located in the lower part of the Topopah Spring Member of the Paintbrush Tuff at Yucca Mountain. The total repository area is 6.07×10^6 m^2. The repository will contain 70,000 metric tons of heavy metal (MTHM) in the form of canisters of spent fuel. At the time of emplacement, the spent fuel has been out of reactors for 10 yr, when it is all simultaneously emplaced in the repository. The inventory of waste assumed to be present at the time of emplacement is shown in Table 1. No waste will dissolve or leach from the emplacement location until the spent fuel is 360 yr old (300 yr after closure of the repository). No thermal effects are considered.

All releases of waste from the repository are caused by groundwater that flows through the repository. The amount of water flowing vertically to an area defined by the cross-sectional area of emplacement holes, 2.5% of the flow rate (q_j), will interact with the waste. Two sample problems are presented here to demonstrate the results of the SPARTAN simulations and to compare those results with analytical solutions. Problem 1 uses a flux of 0.5 mm/yr; Problem 2 uses a flux of 5 mm/yr, which represents a situation involving fracture flow (Sinnock et al., 1984). The spent fuel dissolves at a rate that allows the interacting water to become saturated with uranium. The uranium solubility used is 4×10^{-4} kg/m^3. Other radionuclides dissolve congruently with uranium on a mass basis.

The flow path from the repository to the accessible environment is vertically downward through the unsaturated zone to the water table, which is taken to be the accessible environment. A schematic representation of the three pathway types considered is depicted in Figure 1. The first matrix-flow pathway (Path A) transmits all the flux for both problems (0.5 and 5.0 mm/yr) through the portion of the repository underlain by the vitric Calico Hills unit, which comprises 40% of the total repository area. The vitric Calico Hills unit is able to transmit all flux through the pores in the rock matrix. Path A is 250 m long. The second matrix pathway (Path B) transmits all flux for the 0.5-mm/yr case and 1 mm/yr for the 5-mm/yr case through the porous matrix of the Topopah Spring Member and zeolitic Calico Hills unit that underlie 60% of the total repository area. The flow distance along Path B to the water table is 150 m. The third flow pathway (Path C) transmits the 4-mm/yr flux through fractures in the Topopah Spring and zeolitic Calico Hills units for the 5-mm/yr case. The fracture flow pathway is geometrically coincident with Path B.

The values of retardation factors used for individual radionuclides are shown in Table 2. Matrix retardation values are used for flow Paths A and B. For a flux of 4 mm/yr in Problem 2, saturated-fracture-retardation values (Table 2) are used for Path C.

3.2 Problem 1 - Flux of 0.5 mm/yr

The input values of variables needed to calculate a solution to Problem 1 by both SPARTAN and the analytical solution are given in Table 3. Output for this problem consists of the time-dependent cumulative curies for radionuclides that reach the accessible environment (in this case, assumed to be the water table) in 100,000 yr. For the 0.5-mm/yr flux, groundwater travel time from the repository to the water table is 100,000 yr through Path A, 30,000 yr through Path B, and not applicable to Path C because no fracture flow is computed for this flux. Therefore, the only two radionuclides, C-14 and I-129, that reach the water table in the first 100,000 yr travel along Path B and initially arrive 30,000 yr after closure of the repository.

TABLE 2

SORPTION VALUES AND RETARDATION FACTORS

			Rd for Matrix		Rd for Fractures	
Element	Kd (cm^3/g)[a]	Ka ($g/^2cm$)[d]	Zeolitic[e]	Vitric[f]	Unsaturated[g]	Saturated[h]
Am	180	1.8×10^{-4}	3,600	1,800	1.4	1.0
C	0	0	1	1	1.0	1.0
Cm	180	1.8×10^{-4}	3,600	1,800	1.4	1.0
Cs	290	2.9×10^{-4}	5,800	2,900	1.5	1.0
I	0	0	1	1	1.0	1.0
Ni	100[b]	1.0×10^{-4}	2,000	1,000	1.2	1.0
Np	7	7.0×10^{-6}	140	71	1.0	1.0
Pa	64	6.4×10^{-5}	1,300	640	1.1	1.0
Pb	5[b]	5.0×10^{-6}	100	51	1.0	1.0
Pu	64	6.4×10^{-5}	1,300	640	1.1	1.0
Ra	900[c]	9.0×10^{-4}	18,000	9,000	2.8	1.2
Sn	170	1.7×10^{-4}	3,400	1,700	1.3	1.0
Sr	53	5.3×10^{-5}	1,100	530	1.1	1.0
Tc	0.3	3.0×10^{-7}	7	4	1.0	1.0
Th	580[c]	5.8×10^{-4}	12,000	5,800	2.2	1.1
U	1.8	1.8×10^{-6}	37	19	1.0	1.0
Zr	500[b]	5.0×10^{-4}	10,000	5,000	2.0	1.1

a. Unless otherwise indicated, distribution coefficients were inferred from sorption ratios given by Daniels et al. (1982, 1983).
b. Inferred from mid-range retardation factor for tuffs in compilation by Krauskopf, Table 7-1, National Research Council (1983).
c. Barium used as chemical analog for radium (Daniels et al., 1983).
d. Calculated from Kd using surface area given by Daniels et al. (1982).
e. Calculated from Equation 18, using $\gamma = 2$, $n = 0.1$.
f. Calculated from Equation 18, using $\gamma = 2$, $n = 0.2$.
g. Calculated from Equation 20, using $b = 10$ μm.
h. Calculated from Equation 20, using $b = 100$ μm.

TABLE 3

INPUT VALUES OF PARAMETERS FOR PROBLEM 1

Flux through the unsaturated zone	= 0.5 mm/yr
Total repository area	= 6.07×10^6 m^2
Portion of flux interacting with waste	= 2.5%
Solubility of U	= 4×10^{-4} kg/m^3
Waste package lifetime	= 300 yr after closure
Initial inventories	= those specified in Table 1
Retardation factors	= those specified in Table 2

	Path A	Path B	Path C
Distance to water table (m)	250	150	150
Effective porosity	0.2	0.1	0.001
Water velocity (m/yr)	2.5×10^{-3}	5×10^{-3}	0
Flow rate (m^3/yr)	3.04×10^1	4.55×10^1	0
Release rate (1/yr)	1.79×10^{-10}	2.68×10^{-10}	0

3.2.1 SPARTAN Solution

Figure 2 and Table 4 show the cumulative curies released to the water table through Path B. Only two radionuclides, C-14 and I-129, reach the water table through Path B in the first 100,000 yr after repository closure because they are the only nonretarded radionuclides to migrate at the same rate as the flowing water. No other radionuclides reach the water table along Path B within the first 100,000 yr after repository closure.

3.2.2 Analytical Solution

The rate of change of the radionuclide inventory, $m_i(t)$, over time that results from a constant release rate from the repository, $r_i(t)$, and decay constant, λ_i, can be expressed by the following equation:

$$\frac{d}{dt} m_i(t) = -[\lambda_i + r_i(t)]\, m_i(t) \qquad (27)$$

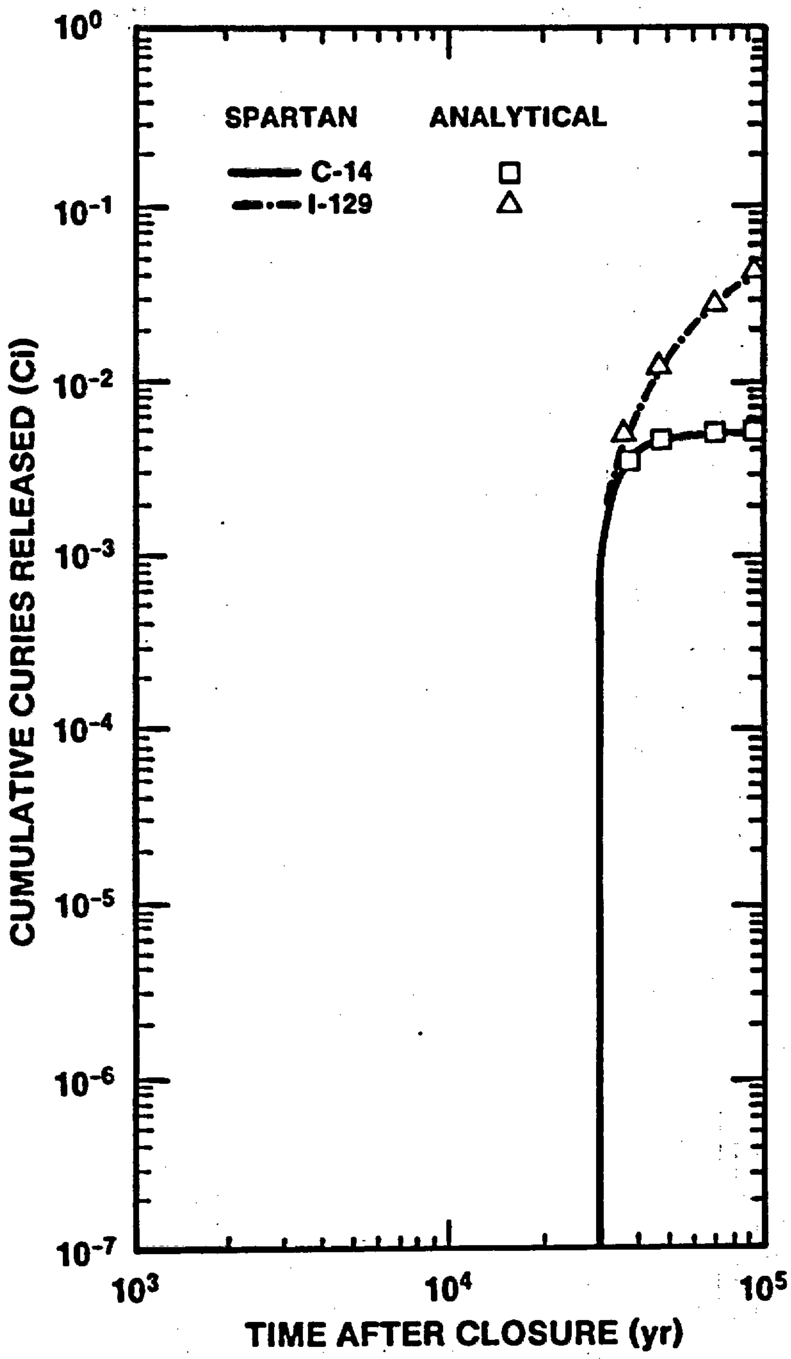


Figure 2. Cumulative Curies of Individual Radionuclides Reaching the Accessible Environment Through Path B in Problem 1.

TABLE 4

CUMULATIVE CURIES RELEASED TO THE ACCESSIBLE ENVIRONMENT THROUGH PATH B FOR PROBLEM 1

Cumulative Curies Released (Ci)	Time After Closure (yr)									
	1×10^4		4×10^4		5×10^4		7×10^4		1×10^5	
	SPARTAN	Analytical	SPARTAN	Analytical	SPARTAN	Analytical	SPARTAN	Analytical	SPARTAN	Analytical
C-14	0	0	3.44×10^{-3}	3.80×10^{-3}	4.47×10^{-3}	5.0×10^{-3}	4.87×10^{-3}	5.46×10^{-3}	4.91×10^{-3}	5.51×10^{-3}
I-129	0	0	6.21×10^{-3}	5.84×10^{-3}	1.24×10^{-2}	1.19×10^{-2}	2.48×10^{-2}	2.40×10^{-2}	4.34×10^{-2}	4.21×10^{-2}

where

$$r_i(t) = R\,U(t - T_f)$$

$U(t - T_f)$ = the unit step function, defined in Equation 7,

T_f = a constant canister lifetime of 300 yr,

R = a constant release rate defined in Equation 13.

For a single-member chain or for the first member in a decay chain, the solution of the equation is

$$m_i(t) = m_i(0)\,e^{-\lambda_i t} \qquad 0 \le t \le T_f$$

and (28)

$$m_i(t) = m_i(0)\,e^{-\lambda_i T_f}\,e^{-(\lambda_i + R)(t - T_f)} \qquad t > T_f \ .$$

The curie release rate for the i^{th} radionuclide through the j^{th} path, $C_{i,j}(t)$, at the repository is

$$C_{i,j}(t) = a_i\,R\,m_i(0)\,e^{-\lambda_i T_f}\,e^{-(\lambda_i + R)(t - T_f)} \qquad t > T_f \ . \tag{29}$$

The curie release rate to the accessible environment, $C_{i,j}(t)$, is the curie release rate at the repository retarded in time by the transport time and reduced by the radioactive decay for a time corresponding to the transport time from the repository to the accessible environment.

$$C^a_{i,j}(t) = U(t - T^r_{i,j})\,C_{i,j}(t - T^r_{i,j})\,e^{-\lambda_i T^r_{i,j}} \tag{30}$$

where

$U(t - T^r_{i,j})$ = the unit step function,

$T^r_{i,j}$ = the transport time of the i^{th} radionuclide to the accessible environment defined in Equation 17.

Integrating $C^a_{i,j,}(t)$ from 0 to t yields the cumulative curies released to the accessible environment by time, t:

$$\overline{C}^a_{i,j}(t) = \frac{a_i R\ m_i(0)}{(\lambda_i + R)} e^{-\lambda_i(T_f + T^r_{i,j})} \left[1 - e^{-(\lambda_i + R)(t - T_f - T^r_{i,j})}\right] \quad . \qquad (31)$$

This analytical solution can be used to calculate the cumulative release of curies to the accessible environment for the single-member chains of C-14 and I-129. The results of the analytical solution of Problem 1 are shown in Table 4.

3.2.3 Comparison of the Results

A comparison of the numerical results from the SPARTAN simulations and from the analytical numerical solutions in Table 4 indicates very close agreement between the numerical and analytical solutions. The results were plotted in Figure 2, but a graphic presentation does not allow much discrimination between two solutions on a reasonable scale. The discrepancies are caused by approximations made in representing the curie releases and by the averaging process of the time-step integration method used to calculate the cumulative curies released. For each k^{th} time step, the curie releases are approximated by an average curie release rate at the k^{th} and $k + 1^{th}$ time step multiplied by the time-step size. The cumulative releases are integrated only approximately by this procedure. The error from these approximations could be reduced by using a time step that is relatively small compared to the half-life of a radionuclide. However, the cost for computing time would increase when computing the 100,000-yr effects using smaller time steps. The results presented in Table 4 are based on a 1,000-yr time step; thus, the discrepancy for C-14, which has a half-life of 5.73×10^3 yr, is greater than that for I-129, which has a half-life of 1.59×10^7 yr.

3.3 Problem 2 - Flux of 5 mm/yr

The input values of parameters for this problem are listed in Table 5. The output for this problem consists of cumulative curies released to the accessible environment versus time for each radionuclide and each path.

TABLE 5

INPUT VALUES OF PARAMETERS FOR PROBLEM 2

Flux through the unsaturated zone	= 5 mm/yr
Total repository area	= 6.07×10^6 m^2
Portion of flux interacting with waste	= 2.5%
Solubility of U	= 4×10^{-4} kg/m^3
Waste package lifetime	= 300 yr after closure
Initial inventories	= those specified in Table 1
Retardation factors	= those specified in Table 2

	Path A	Path B	Path C
Distance to water table (m)	250	150	150
Effective porosity	0.2	0.1	0.001
Water velocity (m/yr)	2.5×10^{-2}	10^{-2}	4.0
Flow rate (m^3/yr)	3.04×10^2	9.1×10^1	3.64×10^2
Release rate (1/yr)	1.8×10^{-9}	5.3×10^{-10}	2.1×10^{-9}

For a flux of 5 mm/yr, water flows through both the fractured pathways and the matrix pathways. The matrix of the vitric unit passes all the flux and all the water that flows through this pathway. Path A begins contributing to releases at the water table about 10,000 yr after closure. Flow through the matrix of the Topopah Spring and zeolitic Calico Hills unit (Path B) is limited to a flux of 1 mm/yr, which is approximately the saturated, hydraulic conductivity of the matrix, and the flow reaches the water table about 30,000 yr after the closure. Portions of flux in excess of 1 mm/yr that flow through the fractures in the Topopah Spring and Calico Hills units (Path C) require only about 37.5 yr to reach the water table. As a result, all the radionuclides from a repository overlying the zeolitic unit begin arriving at the water table shortly after the leaching starts from the waste packages 300 yr after repository closure. Path C is thus the dominant contributor to the total releases.

3.3.1 SPARTAN Solution

Figure 3 shows the cumulative curies released to the accessible environment through Path A. Only three radionuclides, C-14, I-129, and Tc-99, are projected to reach the accessible environment in the first 100,000 yr after repository closure. For Path B, only two nonretarded radionuclides (Figure 4) are projected to reach the accessible environment in the first 100,000 yr after closure. The contributions of individual radionuclides to the cumulative curies released to the accessible environment through fractured pathways are shown in Figure 5.

3.3.2 Analytical Solution

The analytical solution of the one-dimensional transport equation for band release is quite involved [Harada et al. (1980)]. The calculation of analytical solutions for Problem 2 is accomplished by using the UCB NE-10.3 (Kajiwara, 1985) for analytical solution of one-dimensional transport with dispersion for three-member chains. A very small dispersion coefficient of 0.01 m^2/yr was specified in the calculation. The computer code UCB NE-10.3 is the latest version of UCB NE-10 (Pigford, 1980) provided to SNL by T. H. Pigford. The current version inproves some numerical integration techniques of the original UCB NE-10.2 in computing analytical solutions (Kajiwara, 1985). UCB NE-10.3 gives the relative radionuclide concentration and discharge rate as a function of time and path length. The time-dependent release of cumulative curies across the boundary is obtained by integrating the discharge rate in curies. The computer program and input data for Problem 2

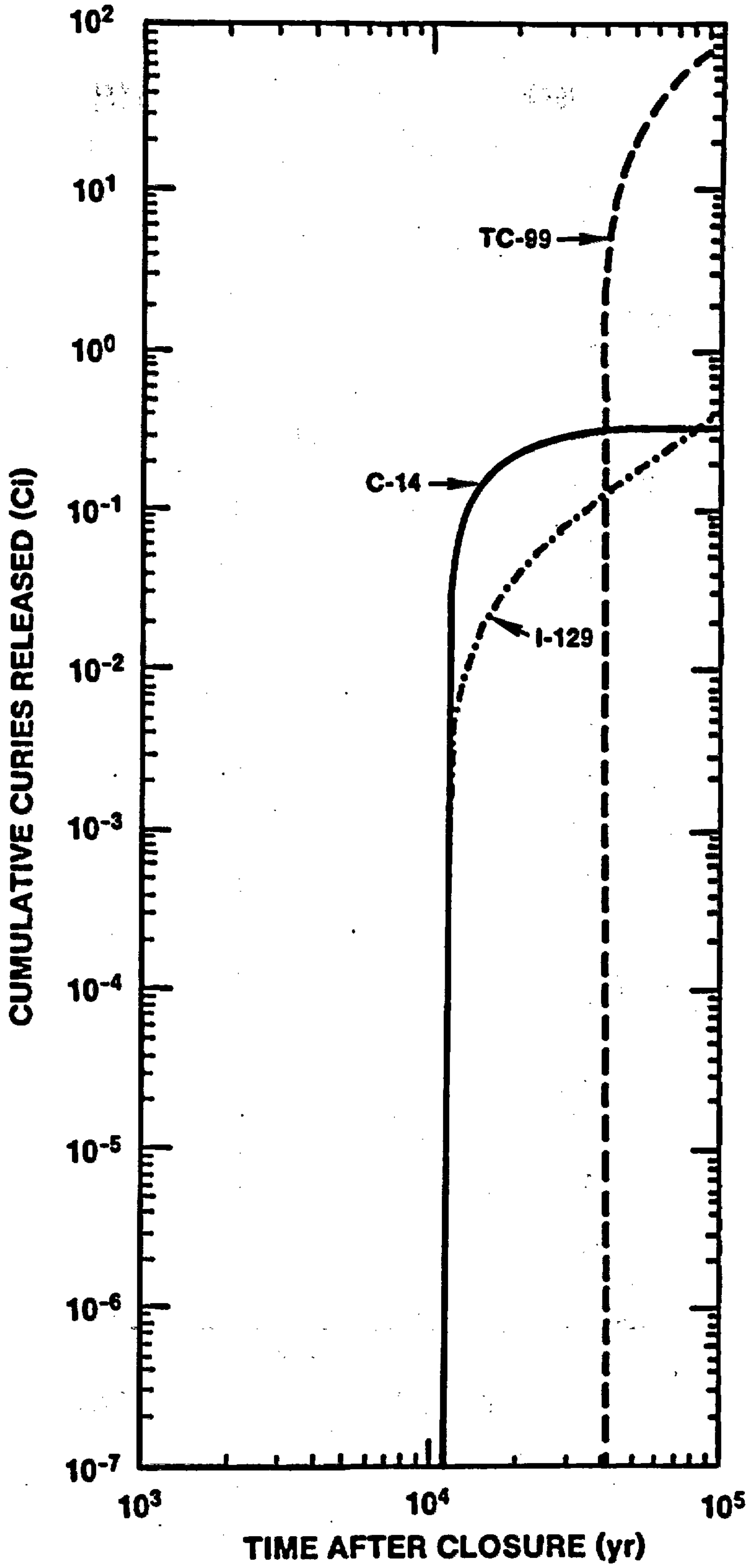


Figure 3. Cumulative Curies of Individual Radionuclides Reaching the Accessible Environment Through Path A in Problem 2

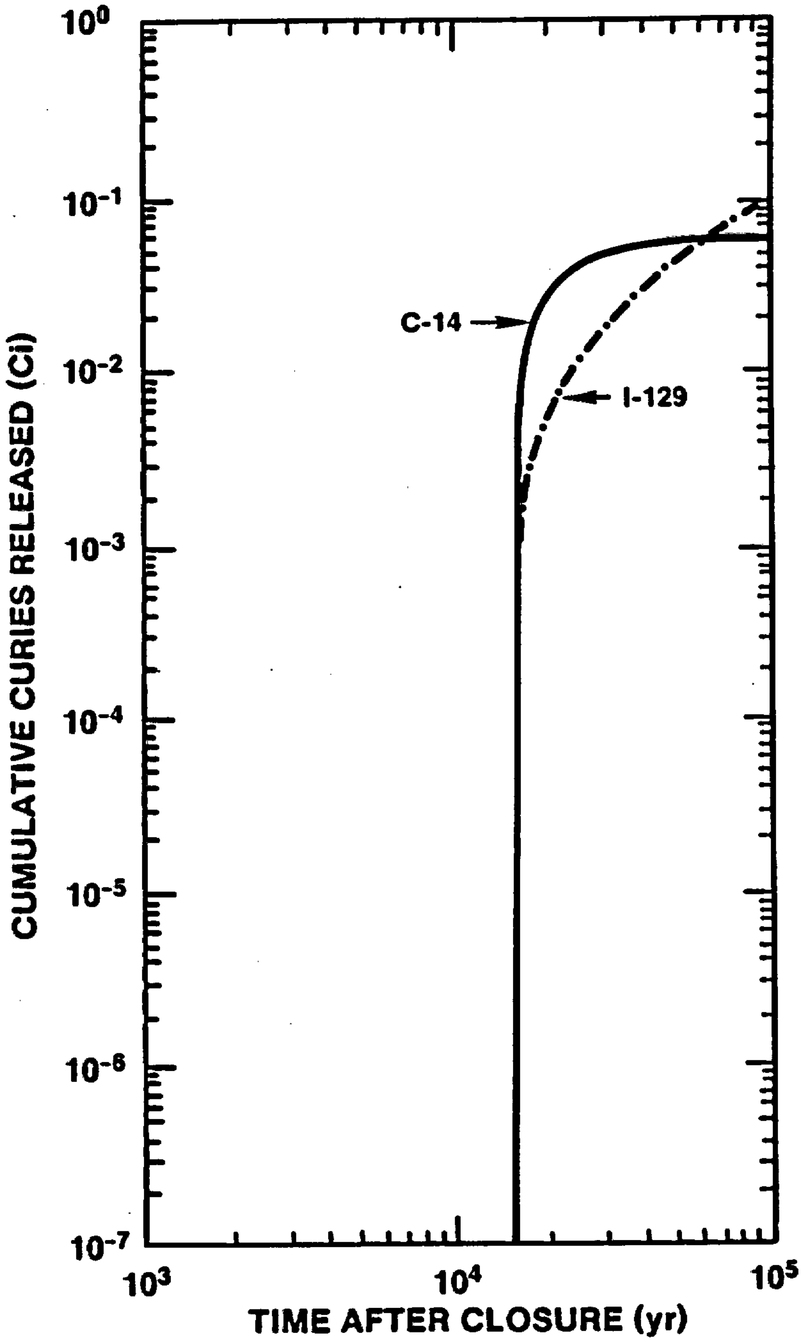


Figure 4. Cumulative Curies of Individual Radionuclides Reaching the Accessible Environment Through Path B in Problem 2

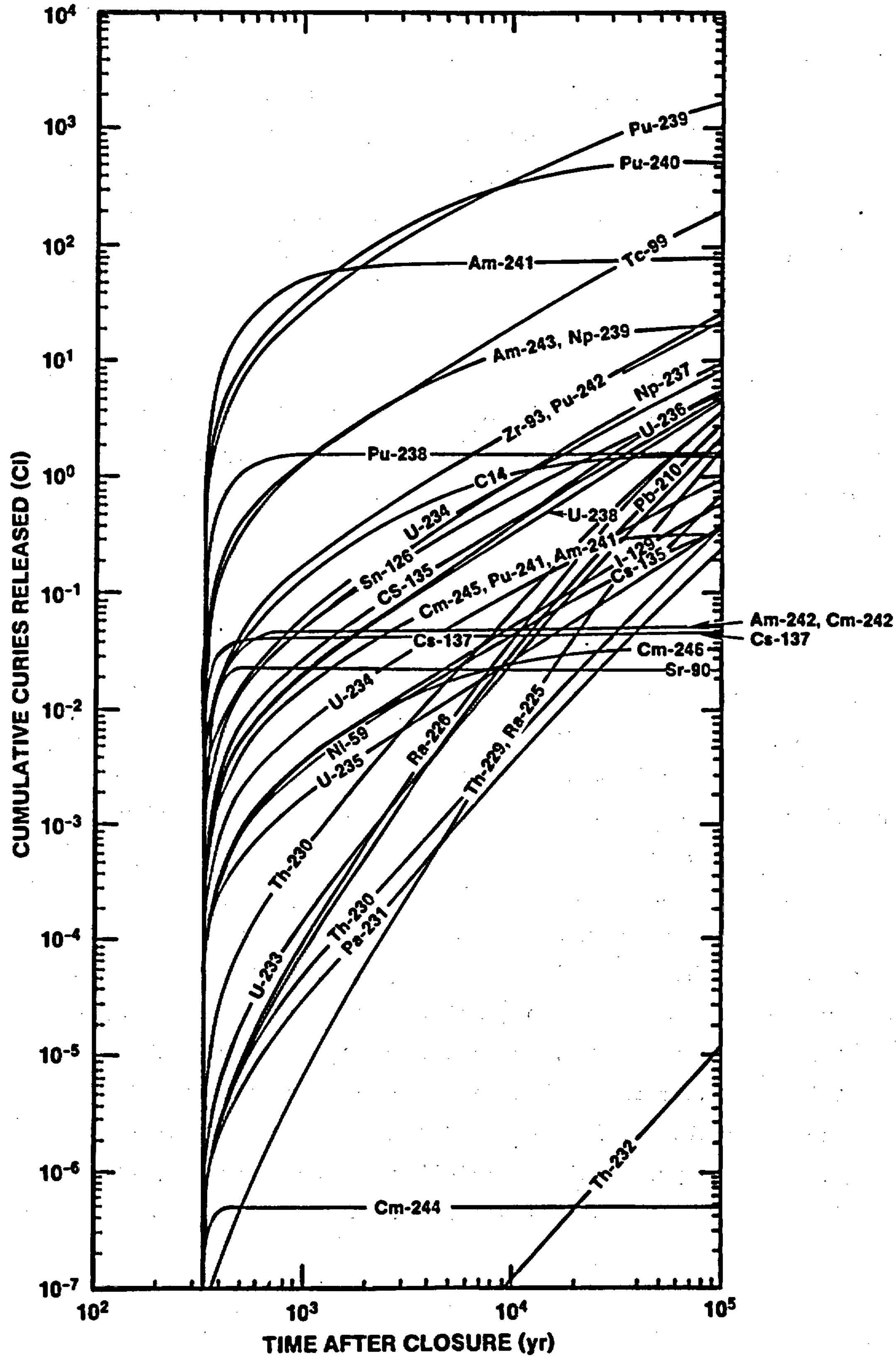


Figure 5. Cumulative Curies of Individual Radionuclides Reaching the Accessible Environment Through Path C in Problem 2

are listed in Appendix B. The computed values for cumulative curies released for individual radionuclides through each path are listed in Tables 6 through 8. Because the UCB NE-10.3 program only computes decay for radionuclide chains up to three members, longer chains are broken down into component three-member chains in calculating the cumulative curies released. Radionuclides assumed to be in secular equilibrium in SPARTAN are not presented in Table 8.

General solutions of the one-dimensional transport equation without dispersion have been shown by Pigford et al. (1980). However, a computer program, UCB NE-25, developed at Lawrence Berkeley Laboratory (LBL) to calculate the analytical solution for dispersionless transport was not available at the time that work was performed.

3.3.3 Comparison of the Results

The results from SPARTAN simulation and from analytical solutions (Tables 6 through 8) agree closely; in all cases, agreement is within 10%, and for long-lived radionuclides agreement is even closer in most cases. A significant finding is that, for radionuclides with relatively short half-lives, the discrepancies are slightly larger, i.e., within 10 to 100%. This greater discrepancy is caused by numerical approximation made in the integration of the curie release rate in SPARTAN. Even with a small value for dispersion, the effects of the dispersion seem to be important for long water flow time and for radionuclides with long half-lives. Although hydrodynamic dispersion is not included in SPARTAN, the execution time of SPARTAN is at least an order of magnitude faster than the calculation time of the analytical solution. Given the computing efficiency of SPARTAN, it may be prudent to enhance this model for use in probabilistic modeling if the a priori probability of scenarios and the statistical distribution of the parameters are available.

TABLE 6

CUMULATIVE CURIES RELEASED TO THE ACCESSIBLE ENVIRONMENT THROUGH PATH A FOR PROBLEM 2

Cumulative Curies Released (Ci)	Time After Closure (yr)							
	10^4		2×10^4		5×10^4		10^5	
	SPARTAN	Analytical*	SPARTAN	Analytical	SPARTAN	Analytical	SPARTAN	Analytical*
C-14	0	1.47×10^{-2}	2.16×10^{-1}	2.17×10^{-1}	3.23×10^{-1}	3.51×10^{-1}	3.26×10^{-1}	3.55×10^{-1}
I-129	0	1.19×10^{-3}	3.73×10^{-2}	3.23×10^{-2}	1.62×10^{-1}	1.56×10^{-1}	3.72×10^{-1}	3.62×10^{-1}
Tc-99	0	0	0	3.79×10^{-35}	1.24×10^{1}	1.42×10^{1}	7.65×10^{1}	7.80×10^{1}

*Calculated by UCB NE-10.3 with dispersion coefficient of 0.01 m^2/yr.

TABLE 7

CUMULATIVE CURIES RELEASED TO THE ACCESSIBLE ENVIRONMENT THROUGH PATH B FOR PROBLEM 2

Cumulative Curies Released (Ci)	Time After Closure (yr)							
	10^4		2×10^4		5×10^4		10^5	
	SPARTAN	Analytical*	SPARTAN	Analytical*	SPARTAN	Analytical*	SPARTAN	Analytical*
C-14	0	1.93×10^{-6}	2.73×10^{-2}	2.22×10^{-2}	5.94×10^{-2}	6.23×10^{-2}	6.03×10^{-2}	6.34×10^{-2}
I-129	0	1.59×10^{-7}	6.22×10^{-3}	6.14×10^{-3}	4.35×10^{-2}	4.31×10^{-2}	1.05×10^{-1}	1.05×10^{-1}

*Calculated by UCB NE-10.3 with dispersion coefficient of 0.01 m^2/yr.

TABLE 8

CUMULATIVE CURIES RELEASED TO THE ACCESSIBLE ENVIRONMENT THROUGH PATH C FOR PROBLEM 2

Cumulative Curies Released (Ci)	Time After Closure (yr) 10^3 SPARTAN	10^3 Analytical*	5×10^3 SPARTAN	5×10^3 Analytical*	10^4 SPARTAN	10^4 Analytical*	10^5 SPARTAN	10^5 Analytical*
C-14	1.82×10^{-1}	1.79×10^{-1}	7.28×10^{1}	7.45×10^{-1}	1.14×1^{-0}	1.16×10^{0}	1.31×10^{0}	1.71×10^{0}
Tc-99	1.85×10^{0}	1.85×10^{0}	9.36×10^{0}	9.56×10^{0}	1.88×10^{1}	1.91×10^{1}	1.62×10^{2}	1.66×10^{2}
I-129	4.78×10^{-3}	4.70×10^{-3}	2.44×10^{-2}	2.45×10^{-2}	4.93×10^{-2}	4.92×10^{-2}	4.91×10^{-1}	4.93×10^{-1}
Ni-59	4.29×10^{-3}	4.24×10^{-3}	2.15×10^{-2}	2.17×10^{-2}	4.25×10^{-2}	4.27×10^{-2}	2.93×10^{-1}	2.99×10^{-1}
Cs-135	3.89×10^{-2}	3.84×10^{-2}	1.99×10^{-1}	2.00×10^{-1}	4.01×10^{-1}	4.02×10^{-1}	3.97×10^{0}	4.00×10^{0}
Sn-126	6.86×10^{-2}	6.77×10^{-2}	3.45×10^{-1}	3.48×10^{-1}	6.85×10^{-1}	6.88×10^{-1}	5.07×10^{0}	5.16×10^{0}
Zr-93	2.43×10^{-1}	2.42×10^{-1}	1.25×10^{0}	1.26×10^{0}	2.53×10^{0}	2.53×10^{0}	2.44×10^{1}	2.46×10^{1}
Sr-90	2.31×10^{-2}	1.83×10^{-2}	2.31×10^{-2}	1.83×10^{-2}	2.31×10^{-3}	1.83×10^{-2}	2.31×10^{-2}	1.83×10^{-2}
Cs-137	4.74×10^{-2}	3.81×10^{-2}	4.75×10^{-2}	3.81×10^{-2}	4.75×10^{-2}	3.81×10^{-2}	4.75×10^{-3}	3.81×10^{-2}
Cm-244	5.01×10^{-7}	2.77×10^{-7}	5.01×10^{-7}	2.77×10^{-7}	5.01×10^{-7}	2.77×10^{-7}	5.01×10^{-7}	2.77×10^{-7}
Pu-240	5.95×10^{1}	5.86×10^{1}	2.45×10^{2}	2.50×10^{2}	3.94×10^{2}	4.00×10^{2}	5.04×10^{2}	6.35×10^{2}
U-236	3.34×10^{-2}	3.27×10^{-2}	1.86×10^{-1}	1.85×10^{-1}	4.05×10^{-1}	4.01×10^{-1}	5.01×10^{0}	4.95×10^{0}
Th-232	1.46×10^{-9}	1.40×10^{-9}	2.69×10^{-8}	2.53×10^{-8}	1.06×10^{-7}	1.01×10^{-7}	1.26×10^{-5}	1.20×10^{-5}
Cm-245	2.43×10^{-2}	2.40×10^{-2}	1.07×10^{-1}	1.08×10^{-1}	1.82×10^{-1}	1.84×10^{-1}	3.05×10^{-1}	3.59×10^{-1}
Am-241	6.65×10^{1}	6.58×10^{1}	6.93×10^{1}	9.01×10^{1}	6.95×10^{1}	9.02×10^{1}	6.95×10^{1}	9.02×10^{1}
Np-237	8.05×10^{-2}	7.45×10^{-2}	4.70×10^{-1}	4.36×10^{-1}	9.63×10^{-1}	8.92×10^{-1}	9.65×10^{0}	9.00×10^{0}
U-233	2.66×10^{-4}	2.45×10^{-4}	5.62×10^{-4}	4.98×10^{-3}	2.17×10^{-2}	1.95×10^{-2}	1.89×10^{0}	1.69×10^{0}
Th-229	1.13×10^{-5}	7.65×10^{-6}	4.60×10^{-5}	4.31×10^{-4}	5.69×10^{-3}	2.76×10^{-3}	1.58×10^{0}	7.09×10^{-1}
Cm-246	4.53×10^{-3}	4.46×10^{-3}	1.80×10^{-2}	1.84×10^{-2}	2.78×10^{-2}	2.83×10^{-2}	3.11×10^{-2}	4.11×10^{-2}
Pu-242	2.30×10^{-1}	2.28×10^{-1}	1.17×10^{0}	1.18×10^{0}	2.36×10^{0}	2.36×10^{0}	2.17×10^{1}	2.19×10^{1}
U-238	4.62×10^{-2}	4.56×10^{-2}	2.36×10^{-1}	2.37×10^{-1}	4.77×10^{-1}	4.77×10^{-1}	4.76×10^{0}	4.79×10^{0}
Am-242	5.25×10^{-2}	5.22×10^{-2}	5.25×10^{-2}	5.38×10^{-2}	5.25×10^{-2}	5.38×10^{-2}	5.25×10^{-2}	5.38×10^{-2}
Pu-238	1.59×10^{0}	1.41×10^{0}	1.58×10^{0}	1.42×10^{0}	1.59×10^{0}	1.42×10^{0}	1.59×10^{0}	1.42×10^{0}
U-234	1.13×10^{-1}	1.01×10^{-1}	5.77×10^{-1}	5.26×10^{-1}	1.15×10^{0}	1.05×10^{0}	1.02×10^{1}	9.33×10^{0}
Th-230	1.07×10^{-3}	9.56×10^{-4}	1.98×10^{-2}	1.72×10^{-2}	7.27×10^{-2}	6.46×10^{-2}	5.18×10^{0}	4.61×10^{0}
Ra-226	1.88×10^{-4}	7.26×10^{-5}	9.62×10^{-3}	3.26×10^{-3}	4.87×10^{-2}	1.66×10^{-2}	5.07×10^{0}	1.79×10^{0}
Am-243	1.87×10^{0}	1.85×10^{0}	8.00×10^{0}	8.16×10^{0}	1.33×10^{1}	1.35×10^{1}	1.97×10^{1}	2.39×10^{1}
Pu-239	4.08×10^{1}	4.03×10^{1}	1.97×10^{2}	1.99×10^{2}	3.72×10^{2}	3.75×10^{2}	1.37×10^{3}	1.45×10^{3}
U-235	2.35×10^{-3}	2.31×10^{-3}	1.24×10^{-2}	1.25×10^{-2}	2.60×10^{-2}	2.59×10^{-2}	3.43×10^{-1}	3.41×10^{-1}
Pa-231	4.48×10^{-5}	6.99×10^{-4}	7.66×10^{-4}	4.42×10^{-3}	2.81×10^{-3}	9.75×10^{-3}	2.01×10^{-1}	2.25×10^{-1}

*Calculated by UCB NE-10.3 with dispersion coefficient of 0.01 m^2/yr.

4.0 CONCLUSIONS

A computer model that provides a simple performance assessment of radionuclide transport (SPARTAN) has been developed to simulate the postclosure performance of the Yucca Mountain repository site. The computer model presented in the report is a useful tool for the systems studies required for the NNWSI environmental assessment document (DOE, 1984). The test problems presented in this report show good agreement between the SPARTAN simulations and the analytical solutions. Thus, for a simple systems performance assessment, SPARTAN can be used with a high degree of confidence for the types of problems addressed in this report. The computation time required by SPARTAN is low enough that its enhancement for probabilistic assessments of repository performance may be warranted.

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APPENDIX A

COMPUTER SOURCE LISTINGS OF SPARTAN

This section contains a detailed computer listing for SPARTAN. The data were built into the program as data statements. SPARTAN is written in FORTRAN and is compiled and executed in a CRAY computer.

```
 PROGRAM COMPARE
 DIMENSION RTCUR(3,100,5,14),RTCURS(3,100,2,4),RATIO(5,14),
*DEF(100),SRC(100),DISCI(100),FRM(100),TFAC(100),YR(100)
 DIMENSION REC(10),TT(3,10),VS(3,10),FL(3,10,3)
*,DR(3,10,3),TL(3,10,3),FR(3,10,3)
*,TTC(10),TTB(10),RECM(10),TTM(10)
 DIMENSION AL(5,14),NEC(14),CONI(5,14),CONN(5,14),HLS(2,4),
*ALS(2,4),SPA(5,14),AM(5,14),RNA(2,4),RCH(5,14),CONIS(2,4),
*HL(5,14),CUM(5,14),AMS(2,4),RCI(5,14),RCIS(2,4)
 DIMENSION ALP(2,4),CURS(2,4),CUMS(2,4),PAR(2,4),NECS(4),
*CUR(5,14),SPAS(2,4),PAC(2,4)
 DIMENSION RL(5,14),RLS(2,4),CIR(5,14),CIRS(2,4)
 DIMENSION CITOT(4,10,100),AERAT(4,10,100),AETOT(4,10,100)
 DIMENSION CIRAT(4,10,100),AECID(4,10,100),
*RC(100,5,14)
 DIMENSION DIS(3,100,5,14),AGIN(100,5,14),RDF(3,5,14),
*RDFS(3,2,4),AGINS(100,2,4),RCS(100,2,4),
*SUR(4,100,5,14),SURS(4,100,2,4),SUC(4,100,5,14),SUCS(4,100,2,4)
 DIMENSION TM21(14),TM31(14),TM41(14),TM51(14),TM32(14),TM42(14),
*TM52(14),TM53(14),TM54(14),TM43(14),CONIW(5,14),CONNW(5,14),
*DCON(5,14)
 DIMENSION EP(3),FRA(3),FRF(3),DI(3),FLUX(3,10),NP(10)
 DATA(EP(I),I=1,3)/0.2,0.1,0.001/
 DATA(FRF(I),I=1,3)/0.4,0.6,0.6/
 DATA(FRA(I),I=1,3)/0.25,0.025,0.0025/
 DATA(DI(I),I=1,3)/250.,150.,150./
 DATA(RCH(1,I),I=1,3)/"C-14","TC-99","I-129"/
 DATA(RCH(I,4),I=1,4)/"CM-244","PU-240","U-236","TH-232"/
 DATA(RCH(I,5),I=1,5)/"CM-245","AM-241","NP-237",
*"U-233","TH-229"/
 DATA(RCH(I,14),I=1,5)/"CM-246","PU-242",
*"U-238","TH-230*","RA-226*"/
 DATA(RCH(I,6),I=1,5)/"AM-242","PU-238","U-234",
*"TH-230","RA-226"/
 DATA(RCH(I,7),I=1,4)/"AM-243","PU-239","U-235","PA-231"/
 DATA(RCH(1,I),I=8,13)/"NI-59","CS-135","SN-126","ZR-93",
*"SR-90","CS-137"/
 DATA(AM(1,I),I=1,3)/14.,99.,129./
 DATA(AM(I,4),I=1,4)/244.,240.,236.,232./
 DATA(AM(I,5),I=1,5)/245.,  241.,237.,233.,229./
 DATA(AM(I,14),I=1,5)/246.,242.,238.,  230.,226.  /
 DATA(AM(I,6),I=1,5)/242.,  238.,234.,230.,226.  /
 DATA(AM(I,7),I=1,4)/243.,239.,235.,231./
 DATA(AM(1,I),I=8,13)/59.,135.,126.,93.,90.,137./
 DATA(HL(1,J),J=1,3)/5.73E3,2.15E5,1.59E7/
 DATA(HL(I,4),I=1,4)/17.6,6.58E3,2.39E7,1.4E10/
 DATA(HL(I,5),I=1,5)/9.3E3,  458.,2.14E6,1.62E5,7.34E3/
 DATA(HL(I,14),I=1,5)/5.5E3,3.79E5,4.51E9,  8.4E4,1.6E3  /
 DATA(HL(I,6),I=1,5)/152.  ,86.,2.47E5,8.4E4,1.6E3  /
 DATA(HL(I,7),I=1,4)/7.95E3,  2.44E4,7.1E8,3.25E4/
 DATA(HL(1,I),I=8,13)/8.E4,3.E6,1.E5,9.5E5,29.,30./
 DATA(NEC(I),I=1,14)/1,1,1,4,5,5,4,1,1,1,1,1,1,5/
 DATA(RNA(I,1),I=1,2)/"PU-241","RA-225"/
 DATA(RNA(I,2),I=1,2)/"CM-242","PB-210"/
 DATA(RNA(I,4),I=1,2)/"U-234*","PB-210*"/
 DATA RNA(1,3)/"NP-239"/
 DATA(ALS(I,1),I=1,2)/5.25E-2,17.11/
 DATA(ALS(I,2),I=1,2)/1.54,3.11E-2/
 DATA(ALS(I,4),I=1,2)/2.8E-4,3.11E-2/
 DATA ALS(1,3)/108.28/
 DATA(NECS(I),I=1,4)/2,2,1,2/
 DATA(SPAS(I,1),I=1,2)/1.12E2,3.92E4/
 DATA(SPAS(I,2),I=1,2)/3.32E3,7.63E1/
 DATA(SPAS(I,4),I=1,2)/6.18E-3,7.63E1/
 DATA SPAS(1,3)/2.33E5/
 DATA(RL(1,I),I=1,3)/7000.,7.0E5,7.0E4/
 DATA(RL(J,4),J=1,4)/7000.,7000.,7000.,7000./
 DATA(RL(J,5),J=1,5)/7000.,7000.,7000.,7000.,7000./
 DATA(RL(J,6),J=1,5)/7000.,7000.,7000.,7000.,7000./
 DATA(RL(J,14),J=1,5)/7000.,7000.,7000.,7000.,7000./
 DATA(RL(J,7),J=1,4)/7000.,7000.,7000.,7000./
 DATA(RL(1,I),I=8,13)/7.E4,7.E4,7.E4,7.E4,7.E4,7.E4/
 DATA(RLS(I,1),I=1,2)/7.E4,7.E4/
 DATA(RLS(I,2),I=1,2)/7000.,7.E4/
 DATA(RLS(I,4),I=1,2)/7000.,7.E4/
 DATA RLS(1,3)/7.E4/
 DATA(RDF(1,1,I),I=1,3)/1.,4.,1./
 DATA(RDF(1,I,4),I=1,4)/1800.,640.,19.,5800./
 DATA(RDF(1,I,5),I=1,5)/1800.,1800.,71.,19.,5800./
 DATA(RDF(1,I,14),I=1,5)/1800.,640.,19.,5800.,9000./
 DATA(RDF(1,I,6),I=1,5)/1800.,640.,19.,5800.,9000./
 DATA(RDF(1,I,7),I=1,4)/1800.,640.,19.,640./
 DATA(RDF(1,1,I),I=8,13)/1000.,2900.,1700.,5000.,530.,2900./
 DATA(RDFS(1,I,1),I=1,2)/640.,9000./
 DATA(RDFS(1,I,2),I=1,2)/1800.,51./
 DATA(RDFS(1,I,4),I=1,2)/19.,51./
 DATA RDFS(1,1,3)/71./
 DATA(RDF(2,1,I),I=1,3)/1.,7.,1./
 DATA(RDF(2,I,4),I=1,4)/3600.,1300.,37.,12000./
 DATA(RDF(2,I,5),I=1,5)/3600.,3600.,140.,37.,12000./
 DATA(RDF(2,I,14),I=1,5)/3600.,1300.,37.,12000.,18000./
 DATA(RDF(2,I,6),I=1,5)/3600.,1300.,37.,12000.,18000./
 DATA(RDF(2,I,7),I=1,4)/3600.,1300.,37.,1300./
 DATA(RDF(2,1,I),I=8,13)/2000.,5800.,3400.,10000.,1100.,5800./
 DATA(RDFS(2,I,1),I=1,2)/1300.,18000./
 DATA(RDFS(2,I,2),I=1,2)/3600.,100./
 DATA(RDFS(2,I,4),I=1,2)/37.,100./
 DATA RDFS(2,1,3)/140./
 DATA(RDF(3,1,I),I=1,3)/1.,1.,1./
 DATA(RDF(3,I,4),I=1,4)/1.,1.,1.,1.1/
 DATA(RDF(3,I,5),I=1,5)/1.,1.,1.0,1.0,1.1/
 DATA(RDF(3,I,14),I=1,5)/1.,1.,1.0,1.1,1.2/
 DATA(RDF(3,I,6),I=1,5)/1.0,1.0,1.0,1.1,1.2/
 DATA(RDF(3,I,7),I=1,4)/1.,1.,1.0,1./
 DATA(RDF(3,1,I),I=8,13)/1.,1.,1.,1.1,1.,1./
 DATA(RDFS(3,I,1),I=1,2)/1.,1.2/
 DATA(RDFS(3,I,2),I=1,2)/1.,1./
 DATA(RDFS(3,I,4),I=1,2)/1.0,1.0/
 DATA RDFS(3,1,3)/1.0/
 DATA(TFAC(I),I=1,100)/100*1000./
CCC     DOE-28-10
 DATA(CONI(1,I),I=1,3)/2.2E4,5.35E7,1.33E7/
 DATA(CONI(I,4),I=1,4)/7.57E5,1.39E8,2.43E8,70./
 DATA(CONI(I,5),I=1,5)/8.03E4,3.46E7,3.08E7,2.8E2,9.2E-3/
 DATA(CONI(I,14),I=1,5)/9.28E3,2.87E7,6.73E10,1.E-8,1.E-8/
 DATA(CONI(I,6),I=1,5)/7.2E4,8.0E+6,8.38E5,1.48E1,5.24E-4/
 DATA(CONI(I,7),I=1,4)/5.30E6,3.31E8,5.23E8,8.23/
 DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,2.65E7,
*6.03E7/
 DATA(CONIS(I,1),I=1,2)/4.3E7,1.45E-7/
 DATA(CONIS(I,2),I=1,2)/1.79E2,6.42E-5/
 DATA(CONIS(I,4),I=1,2)/1.E-8,1.E-8/
 DATA CONIS(1,3)/4.21/
CCC      DOE-28-1000
C        DATA(CONI(1,I),I=1,3)/1.89E4,5.35E7,1.33E7/CONI
C        DATA(CONI(I,4),I=1,4)/1.E-99,1.27E8,2.65E8,7.E3/
C        DATA(CONI(I,5),I=1,4)/7.58E4,9.43E7,2.22E4,3.94E-1/
C        DATA(CONI(I,6),I=1,3)/7.95E3,2.87E7,6.73E10/
C        DATA(CONI(I,14),I=1,4)/9.06E6,2.16E4,70.85,0.92/
C        DATA(CONI(I,7),I=1,4)/4.9E6,3.20E8,5.56E8,5.43E2/
C        DATA(CONI(1,I),I=8,13)/2.77E4,2.14E7,1.18E6,2.95E7,6.64E-4,
C       *6.7E-3/
C        DATA(CONIS(I,1),I=1,3)/1.06E2,1.79E7,1.89E-3/
```

```
C       DATA(CONIS(I,2),I=1,3)/7.92E2,1.96,4.4E3/
C       DATA CONIS(1,3)/3.91/
      NCHNS =14
      NNECS=4
      IPRINT=1
      IRATE=0
      ITOTAL=0
      NL=3
C      IV=3
C      IV=1
      IV=2
      C1=1.13E13
      C2=3.1558E7
      C3=.693147
      C5=1.
      SL=4.E-4
      UI=6.7967E7
      AR=6.07E6
      DO 2 I=1,NCHNS
      N=NEC(I)
      DO 2 J=1,N
      AL(J,I)=C3/HL(J,I)
      C4=HL(J,I)*C2
      SPA(J,I)=C1/(C4*AM(J,I))
      CONI(J,I)=CONI(J,I)*C5*.001
    2 CONTINUE
C      NF=10
      NF=2
      NT=100
      TOT=0.
      DO 18 I=1,NT
      TOT=TOT+TFAC(I)
   18 YR(I)=TOT
      DO 22 I=1,NF
C      REC(I)=I*0.0005
      IF(I.EQ.1)REC(I)=0.0005
      IF(I.EQ.2)REC(I)=0.005
      FLUX(1,I)=REC(I)
      IF(REC(I).LE.1.E-3)GO TO 20
      FLUX(2,I)=0.001
      GO TO 21
   20 FLUX(2,I)=REC(I)
      NP(I)=2
   21 FLUX(3,I)=REC(I)-FLUX(2,I)
      IF (FLUX(3,I).GT.0.) NP(I)=3
   19 NL=NP(I)
      DO 22 L=1,NL
      VS(L,I)=FLUX(L,I)/EP(L)
C      TT(L,I)=DI(L)/VS(L,I)+2000.
      TT(L,I)=DI(L)/VS(L,I)
      DO 22 IC=1,3
      FL(L,I,IC)=AR*FLUX(L,I)*FRA(IC)*FRF(L)
      DR(L,I,IC)=FL(L,I,IC)*SL
      FR(L,I,IC)=DR(L,I,IC)/UI
      TL(L,I,IC)=UI/DR(L,I,IC)
   22 CONTINUE
      DO 24 L=1,3
      PRINT 100
      DO 24 I=1,NF
      PRINT 101,REC(I),FLUX(L,I),VS(L,I),TT(L,I),FL(L,I,1)
     *,FL(L,I,2),FL(L,I,3)
   24 FLUX(L,I)=1000.*FLUX(L,I)
      DO 4 I=1,NCHNS
      N = NEC(I)
      IF(N.EQ.1)GO TO 3
      TM21(I)=1./(AL(2,I)-AL(1,I))
      IF(N.EQ.2)GO TO 3
      TM31(I)=1./(AL(3,I)-AL(1,I))
      TM32(I)=1./(AL(3,I)-AL(2,I))
      IF(N.EQ.3)GO TO 3
      TM41(I)=1./(AL(4,I)-AL(1,I))
      TM42(I)=1./(AL(4,I)-AL(2,I))
      TM43(I)=1./(AL(4,I)-AL(3,I))
      IF(N.EQ.4)GO TO 3
      TM51(I)=1./(AL(5,I)-AL(1,I))
      TM52(I)=1./(AL(5,I)-AL(2,I))
      TM53(I)=1./(AL(5,I)-AL(3,I))
      TM54(I)=1./(AL(5,I)-AL(4,I))
    3 CONTINUE
    4 CONTINUE
      ALP(1,1)=AL(1,5)/ALS(1,1)
      ALP(2,1)=AL(5,5)/ALS(2,1)
      ALP(1,2)=AL(1,6)/ALS(1,2)
      ALP(2,2)=AL(5,6)/ALS(2,2)
      ALP(1,3)=AL(1,7)/ALS(1,3)
      ALP(1,4)=AL(3,14)/ALS(1,4)
      ALP(2,4)=AL(5,14)/ALS(2,4)
      IF (IV.EQ.1) DTT=50.
      IF (IV.EQ.2) DTT=350.
      IF (IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      TOTCI=0.
      DO 167 I=1,NCHNS
      N=NEC(I)
      DO 167 J=1,N
      RCI(J,I)=DCON(J,I)*SPA(J,I)*1000.*1.E-5
C      PRINT 104,I,J,RCI(J,I)
C 104 FORMAT (1X,2I10,1PE10.2)
  167 TOTCI=TOTCI+RCI(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(5,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      PAR(1,4)=DCON(3,14)
      PAR(2,4)=DCON(5,14)
      DO 168 MI=1,NNECS
      MN=NECS(MI)
      DO 168 MJ=1,MN
      RCIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)*1000.*1.E-5
C      PRINT 104,MJ,MI,RCIS(MJ,MI)
  168 TOTCI=TOTCI+RCIS(MJ,MI)
      TOTCI=TOTCI/1000.
C      PRINT 105,TOTCI
C 105 FORMAT (1X,3(1PE10.2,1X))
      IF (IV.EQ.1) DTT=50.
      IF (IV.EQ.2) DTT=350.
      IF (IV.EQ.3) DTT=1050.
      CALL BAT(NCHNS,AL,DTT,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,DCON)
      DO 198 I=1,NCHNS
      N=NEC(I)
      DO 198 J=1,N
      IF (RCI(J,I).LT.TOTCI) RCI(J,I)=TOTCI
C      RDF(3,J,I)=100.
      CONIW(J,I)=DCON(J,I)
  198 CONI(J,I)=DCON(J,I)
      PAR(1,1)=DCON(1,5)
      PAR(2,1)=DCON(5,5)
      PAR(1,2)=DCON(1,6)
      PAR(2,2)=DCON(5,6)
      PAR(1,3)=DCON(1,7)
      PAR(1,4)=DCON(3,14)
      PAR(2,4)=DCON(5,14)
      DO 196 MI=1,NNECS
      MN=NECS(MI)
      DO 196 MJ=1,MN
      IF (RCIS(MJ,MI).LT.TOTCI) RCIS(MJ,MI)=TOTCI
C      RDFS(3,MJ,MI)=100.
  196 CONIS(MJ,MI)=PAR(MJ,MI)*ALP(MJ,MI)
C      DO 5000 IC=1,3
      IC=2
      T=0.
      DO 203 K=1,NT
      DISCI(K)=0.
  203 SRC(K)=0.
      DO 202 K=1,NT
      T=T+TFAC(K)
      CALL BAT(NCHNS,AL,T,NEC,CONI,TM21,TM31,TM41,TM32,TM42,TM43,
     *TM51,TM52,TM53,TM54,CONN)
C      DEF(K)=1.-EXP(-T/10000.)
      DEF(K)=1.
      FRM(K)=SL*AR*0.0005*0.025*DEF(K)/UI
      DO 200 I=1,NCHNS
      N=NEC(I)
      DO 200 J=1,N
      AGIN(K,J,I)=(CONN(J,I)+CONIW(J,I))/2.
      RC(K,J,I)=AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)/RCI(J,I)
      DISCI(K)=DISCI(K)+AGIN(K,J,I)*SPA(J,I)*1000.*FRM(K)
      SRC(K)=SRC(K)+RC(K,J,I)
      CONIW(J,I)=CONN(J,I)
  200 CONTINUE
      PAC(1,1)=AGIN(K,1,5)
      PAC(2,1)=AGIN(K,5,5)
      PAC(1,2)=AGIN(K,1,6)
      PAC(2,2)=AGIN(K,5,6)
      PAC(1,3)=AGIN(K,1,7)
      PAC(1,4)=AGIN(K,3,14)
      PAC(2,4)=AGIN(K,5,14)
      DO 201 MI=1,NNECS
      MN=NECS(MI)
      DO 201 MJ=1,MN
      AGINS(K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)
      RCS(K,MJ,MI)=AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)/RCIS(MJ,MI)
      DISCI(K)=DISCI(K)+AGINS(K,MJ,MI)*SPAS(MJ,MI)*1000.*FRM(K)
  201 SRC(K)=SRC(K)+RCS(K,MJ,MI)
  202 CONTINUE
      DO 500 M=1,NF
      PRINT 308,REC(M)
      NL=NP(M)
      DO 211 L=1,NL
      T=0.
      DO 211 KA=1,NT
      CIRAT(L,M,KA)=0.
      CITOT(L,M,KA)=0.
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      AETOT(L,M,KA)=O.
      T=T+TFAC(KA)
      DO 212 IB=1,3
      NA=NECS(IB)
      DO 212 JB=1,NA
      SUCS(L,KA,JB,IB)=O.
  212 SURS(L,KA,JB,IB)=O.
      DO 211 IA=1,NCHNS
      NA=NEC(IA)
      DO 211 JA=1,NA
      DIS(L,KA,JA,IA)=DR(L,M,IC)*AGIN(KA,JA,IA)*DEF(KA)*1000./UI
      RTCUR(L,KA,JA,IA)=O.
      SUC(L,KA,JA,IA)=O.
  211 SUR(L,KA,JA,IA)=O.
      DO 250 L=1,NL
      T=O.
      DO 250 K=1,NT
      T=T+TFAC(K)
      DO 210 IB =1,NCHNS
      NB=NEC(IB)
      DO 210 JB=1,NB
      CONIW(JB,IB)=DIS(L,K,JB,IB)
      IF(K.EQ.1)CONNW(JB,IB)=O.
  210 CONTINUE
      DT=TFAC(K)
      CALL BAT(NCHNS,AL,DT,NEC,CONIW,TM21,TM31,TM41,TM32,TM42,TM43
     *TM51,TM52,TM53,TM54,DCON)
      DO 216 IB =1,NCHNS
      NB=NEC(IB)
      DO 216 JB=1,NB
      IF  (CONIW(JB,IB).LT.1.E-999)GO TO 216
      RATIO(JB,IB)=DCON(JB,IB)/CONIW(JB,IB)
  216 CONTINUE
      IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 218
      GO TO 219
  218 PRINT 302,T
      PRINT 320
      PRINT 309
 219  CONTINUE
      SCIRAT=O.
      DO 220 IB =1,NCHNS
      NB=NEC(IB)
      DO 220 JB=1,NB
      CONNW(JB,IB)=CONNW(JB,IB)*RATIO(JB,IB)+DCON(JB,IB)*DT
      CUR(JB,IB)=SPA(JB,IB)*CONNW(JB,IB)
      RTCUR(L,K,JB,IB)=DCON(JB,IB)*SPA(JB,IB)
      SCITOT=SCITOT+CUR(JB,IB)
      CIR(JB,IB)=CUR(JB,IB)/RL(JB,IB)
      SCIRAT=SCIRAT+CIR(JB,IB)
      CUM(JB,IB)=CONNW(JB,IB)
  220 CONTINUE
      PAR(1,1)=CONNW(1,5)
      PAR(2,1)=CONNW(5,5)
      PAR(1,2)=CONNW(1,6)
      PAR(2,2)=CONNW(5,6)
      PAR(1,3)=CONNW(1,7)
      PAR(1,4)=CONNW(3,14)
      PAR(2,4)=CONNW(5,14)
      PAC(1,1)=DCON(1,5)
      PAC(2,1)=DCON(5,5)
      PAC(1,2)=DCON(1,6)
      PAC(2,2)=DCON(5,6)
      PAC(1,3)=DCON(1,7)
      PAC(1,4)=DCON(3,14)
      PAC(2,4)=DCON(5,14)
      DO 260 MI=1,NNECS
      MN=NECS(MI)
      DO 260 MJ=1,MN
      CUMS(MJ,MI)=PAR(MJ,MI)*ALP(MJ.
      CURS(MJ,MI)=CUMS(MJ,MI)*SPAS(M.,MI)
      CIRS(MJ,MI)=CURS(MJ,MI)/RLS(MJ,MI)
  266 RTCURS(L,K,MJ,MI)=PAC(MJ,MI)*ALP(MJ,MI)*SPAS(MJ,MI)
      SCIRAT=SCIRAT+CIRS(MJ,MI)
      SCITOT=SCITOT+CURS(MJ,MI)
  260 CONTINUE
      CIRAT(L,M,K)=SCIRAT
      CITOT(L,M,K)=SCITOT
      IF(M.EQ.1.AND.IC.EQ.2.AND.L.EQ.1)GO TO 223
      GO TO 250
  223 CONTINUE
      NCHNS7=NCHNS-7
      DO 240 IB =1,NCHNS7
      NB=NEC(IB)
      DO 240 JB=1,NB
      IF(IB.EQ.2.OR.IB.EQ.3)GO TO 221
      IF(JB.NE.1)GO TO 221
      IF(IB.EQ.1)GO TO 340
      IF(IB.EQ.4)GO TO 341
      IF(IB.EQ.5)GO TO 342
      IF(IB.EQ.6)GO TO 343
      IF(IB.EQ.7)GO TO 344
 340  PRINT 321
      PRINT 315
      GO TO 221
 341  PRINT 321
      PRINT 311
      GO TO 221
 342  PRINT 321
      PRINT 312
      GO TO 221
 343  PRINT 321
      PRINT 313
      GO TO 221
 344  PRINT 321
      PRINT 314
  221 CONTINUE
      PRINT 310,RCH(JB,IB),DIS(L,K,JB,IB),CUR(JB,IB),CUM(JB,IB),
     *AGIN(K,JB,IB),CIR(JB,IB),RC(K,JB,IB),RTCUR(L,K,JB,IB)
      IF(IB.NE.3)GO TO 230
      DO 231 I7=8,13
  231 PRINT 310,RCH(JB,I7),DIS(L,K,JB,I7),CUR(JB,I7),CUM(JB,I7),
     *AGIN(K,JB,I7),CIR(JB,I7),RC(K,JB,I7),RTCUR(L,K,JB,I7)
  230 CONTINUE
      IF(IB.EQ.5) GO TO 5
      IF(IB.EQ.6)GO TO 6
      IF(IB.EQ.7) GO TO 7
      GO TO 224
    5 GO TO (8,224,224,224,9)JB
    8 PRINT 317,RNA(1,1),CURS(1,1),CUMS(1,1),AGINS(K,1,1),CIRS(1,1),
     *RCS(K,1,1),RTCURS(L,K,1,1)
      GO TO 224
    9 PRINT 317,RNA(2,1),CURS(2,1),CUMS(2,1),AGINS(K,2,1),CIRS(2,1),
     *RCS(K,2,1),RTCURS(L,K,2,1)
      GO TO 224
    6 GO TO (11,224,224,224,12)JB
   11 PRINT 317,RNA(1,2),CURS(1,2),CUMS(1,2),AGINS(K,1,2),CIRS(1,2),
     *RCS(K,1,2),RTCURS(L,K,1,2)
      GO TO 224
   12 PRINT 317,RNA(2,2),CURS(2,2),CUMS(2,2),AGINS(K,2,2),CIRS(2,2),
     *RCS(K,2,2),RTCURS(L,K,2,2)
      DO 15 I4=1,3
   15 PRINT 310,RCH(I4,14),DIS(L,K,I4,14),CUR(I4,14),CUM(I4,14),
     *AGIN(K,I4,14),CIR(I4,14),RC(K,I4,14),RTCUR(L,K,I4,14)
      PRINT 317,RNA(1,4),CURS(1,4),CUMS(1,4),AGINS(K,1,4),CIRS(1,4),
     *RCS(K,1,4),RTCURS(L,K,1,4)
      DO 16 I4=4,5
   16 PRINT 310,RCH(I4,14),DIS(L,K,I4,14),CUR(I4,14),CUM(I4,14),
     *AGIN(K,I4,14),CIR(I4,14),RC(K,I4,14),RTCUR(L,K,I4,14)
      PRINT 317,RNA(2,4),CURS(2,4),CUMS(2,4),AGINS(K,2,4),CIRS(2,4),
     *RCS(K,2,4),RTCURS(L,K,2,4)
      GO TO 224
    7 GO TO (13,224,224,224)JB
   13 PRINT 317,RNA(1,4),CURS(1,4),CUMS(1,4),AGINS(K,1,4),CIRS(1,4),
     *RCS(K,1,4),RTCURS(L,K,1,4)
  224 CONTINUE
  240 CONTINUE
  250 CONTINUE
      DO 290 L=1,NL
      T=O.
      DO 280 K=1,NT
      T=T+TFAC(K)
      DO 270 IB =1,NCHNS
      NB=NEC(IB)
      DO 270 JB=1,NB
      RT=TT(L,M)*RDF(L,JB,IB)
      RTT=TOT-RT
      IF  (RTT.LT.O..OR.T.GT.RTT)GO TO 270
      KRT=O
      TRT=T+RT
      IF  (TRT.LT.O.)GO TO 279
      TRT=TRT-TFAC(KT)
  278 KRT=KRT+1
  279 CONTINUE
      SUR(L,KRT,JB,IB)=SUR(L,KRT,JB,IB)
     *+RTCUR(L,KRT,JB,IB)*DEF(K)/DEF(KRT)*TFAC(K)
  270 CONTINUE
      DO 280 MI=1,NNECS
      MN=NECS(MI)
      DO 280 MJ=1,MN
      RTS=TT(L,M)*RDFS(L,MJ,MI)
      RTTS=TOT-RTS
      IF(RTTS.LT.O..OR.T.GT.RTTS)GO TO 280
      KRTS=O
      TRTS=T+RTS
      DO 288 KT=1,NT
      IF  (TRTS.LT.O.) GO TO 289
      TRTS=TRTS-TFAC(KT)
  288 KRTS=KRTS+1
  289 CONTINUE
      SURS(L,KRTS,MJ,MI)=SURS(L,KRTS,MJ,MI)
     *+RTCURS(L,KRTS,MJ,MI)*DEF(K)/DEF(KRTS)*TFAC(K)
  280 CONTINUE
  290 CONTINUE
      DO 460 K=1,NT
      DO 493 IA=1,NCHNS
      NA=NEC(IA)
      DO 493 JA=1,NA
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  493 SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
      DO 494 IB=1,NNECS
      NB=NECS(IB)
      DO 494 JB=1,NB
  494 SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
  460 CONTINUE
      DO 296 L=1,NL
      DO 291 IA=1,NCHNS
      NA=NEC(IA)
      DO 291 JA=1,NA
      STOT=0.
      STOTC=0.
      DO 291 K=1,NT
      STOT=STOT+SUR(L,K,JA,IA)
C       STOT=STOT+SUR(L,K,JA,IA)/RL(JA,IA)
      IF (K.EQ.1.OR.STOT.EQ.O.)GO TO 297
      STOTC=STOTC*RTCUR(L,K,JA,IA)/RTCUR(L,K-1,JA,IA)
     **DEF(K-1)/DEF(K)+SUR(L,K,JA,IA)
C     */RL(JA,IA)
  297 CONTINUE
      SUR(L,K,JA,IA)=STOT
      SUC(L,K,JA,IA)=STOTC
  291 CONTINUE
      DO 292 IB=1,NNECS
      NB=NECS(IB)
      DO 292 JB=1,NB
      STOTS=0.
      STOTCS=0.
      DO 292 K=1,NT
      STOTS=STOTS+SURS(L,K,JB,IB)
C       STOTS=STOTS+SURS(L,K,JB,IB)/RLS(JB,IB)
      IF (K.EQ.1.OR.STOTS.EQ.O.) GO TO 298
      STOTCS=STOTCS*RTCURS(L,K,JB,IB)/RTCURS(L,K-1,JB,IB)
     **DEF(K-1)/DEF(K)+SURS(L,K,JB,IB)
C     */RLS(JB,IB)
  298 CONTINUE
      SURS(L,K,JB,IB)=STOTS
      SUCS(L,K,JB,IB)=STOTCS
  292 CONTINUE
      DO 295 K=1,NT
      SAECID=0.
      SAETOT=0.
      SAERAT=0.
      DO 293 IA=1,NCHNS
      NA=NEC(IA)
      DO 293 JA=1,NA
      SAECID=SAECID+SUC(L,K,JA,IA)
      SAETOT=SAETOT+SUR(L,K,JA,IA)
  293 SAERAT=SAERAT+SUR(L,K,JA,IA)/RL(JA,IA)
C       SAECID=SAECID+SUC(L,K,JA,IA)
C       SAETOT=SAETOT+SUR(L,K,JA,IA)*RL(JA,IA)
C  293 SAERAT=SAERAT+SUR(L,K,JA,IA)
      DO 294 IB=1,NNECS
      NB=NECS(IB)
      DO 294 JB=1,NB
      SAECID=SAECID+SUCS(L,K,JB,IB)
      SAETOT=SAETOT+SURS(L,K,JB,IB)
  294 SAERAT=SAERAT+SURS(L,K,JB,IB)/RLS(JB,IB)
C       SAECID=SAECID+SUCS(L,K,JB,IB)
C       SAETOT=SAETOT+SURS(L,K,JB,IB)*RLS(JB,IB)
C  294 SAERAT=SAERAT+SURS(L,K,JB,IB)
      AECID(L,M,K)=SAECID
      AETOT(L,M,K)=SAETOT
      AERAT(L,M,K)=SAERAT
  295 CONTINUE
  296 CONTINUE
      DO 360 K=1,NT
      DO 393 IA=1,NCHNS
      NA=NEC(IA)
      DO 393 JA=1,NA
      SUR(4,K,JA,IA)=SUR(1,K,JA,IA)+SUR(2,K,JA,IA)+SUR(3,K,JA,IA)
  393 SUC(4,K,JA,IA)=SUC(1,K,JA,IA)+SUC(2,K,JA,IA)+SUC(3,K,JA,IA)
      DO 394 IB=1,NNECS
      NB=NECS(IB)
      DO 394 JB=1,NB
      SURS(4,K,JB,IB)=SURS(1,K,JB,IB)+SURS(2,K,JB,IB)+SURS(3,K,JB,IB)
  394 SUCS(4,K,JB,IB)=SUCS(1,K,JB,IB)+SUCS(2,K,JB,IB)+SUCS(3,K,JB,IB)
      CIRAT(4,M,K)=CIRAT(1,M,K)+CIRAT(2,M,K)+CIRAT(3,M,K)
      CITOT(4,M,K)=CITOT(1,M,K)+CITOT(2,M,K)+CITOT(3,M,K)
      AETOT(4,M,K)=AETOT(1,M,K)+AETOT(2,M,K)+AETOT(3,M,K)
      AERAT(4,M,K)=AERAT(1,M,K)+AERAT(2,M,K)+AERAT(3,M,K)
      AECID(4,M,K)=AECID(1,M,K)+AECID(2,M,K)+AECID(3,M,K)
  360 CONTINUE
      DO 366 L=1,NL
      IF (IC.NE.2) GO TO 351
      IF (IPRINT.EQ.1.OR.IPRINT.EQ.3) GO TO 339
      GO TO 350
  339 PRINT 103,L
      PRINT 322
      DO 330 K=1,NT
      PRINT 323,YR(K),CITOT(L,M,K),CIRAT(L,M,K),AETOT(L,M,K),
     *AERAT(L,M,K),SUR(L,K,1,1),SUR(L,K,1,2),
     *SUR(L,K,1,3),SUR(L,K,1,8),SUR(L,K,1,9),SUR(L,K,1,10)
  330 CONTINUE
      PRINT 326
      DO 331 K=1,NT
      PRINT 323,YR(K),SUR(L,K,1,11),SUR(L,K,1,12),SUR(L,K,1,13),
     *SUR(L,K,1,4),SUR(L,K,2,4),SUR(L,K,3,4),SUR(L,K,4,4),
     *SUR(L,K,1,5),SURS(L,K,1,1),SUR(L,K,2,5)
  331 CONTINUE
      PRINT 327
      DO 332 K=1,NT
      PRINT 323,YR(K),SUR(L,K,3,5),SUR(L,K,4,5),SUR(L,K,5,5),
     *SURS(L,K,2,1),SUR(L,K,1,14),SUR(L,K,1,6),SURS(L,K,1,2),
     *SUR(L,K,2,14),SUR(L,K,2,6),SUR(L,K,3,14)
  332 CONTINUE
      PRINT 328
      DO 333 K=1,NT
      PRINT 323,YR(K),SUR(L,K,3,6),SUR(L,K,4,6),SUR(L,K,5,6),
     *SURS(L,K,2,4),SUR(L,K,1,7),SURS(L,K,1,3),SUR(L,K,2,7),
     *SUR(L,K,3,7),SUR(L,K,4,7),AECID(L,M,K)
  333 CONTINUE
      PRINT 329
      DO 334 K=1,NT
      PRINT 323,YR(K),SURS(L,K,1,4),SUR(L,K,4,14),SUR(L,K,5,14),
     *SURS(L,K,2,4)
  334 CONTINUE
  350 CONTINUE
      IF (IPRINT.EQ.2.OR.IPRINT.EQ.3) GO TO 439
      GO TO 351
  439 PRINT 322
      DO 430 K=1,NT
      PRINT 323,YR(K),CITOT(L,M,K),CIRAT(L,M,K),AETOT(L,M,K),
     *AERAT(L,M,K),SUC(L,K,1,1),SUC(L,K,1,2),
     *SUC(L,K,1,3),SUC(L,K,1,8),SUC(L,K,1,9),SUC(L,K,1,10)
  430 CONTINUE
      PRINT 326
      DO 431 K=1,NT
      PRINT 323,YR(K),SUC(L,K,1,11),SUC(L,K,1,12),SUC(L,K,1,13),
     *SUC(L,K,1,4),SUC(L,K,2,4),SUC(L,K,3,4),SUC(L,K,4,4),
     *SUC(L,K,1,5),SUCS(L,K,1,1),SUC(L,K,2,5)
  431 CONTINUE
      PRINT 327
      DO 432 K=1,NT
      PRINT 323,YR(K),SUC(L,K,3,5),SUC(L,K,4,5),SUC(L,K,5,5),
     *SUCS(L,K,2,1),SUC(L,K,1,14),SUC(L,K,1,6),SUCS(L,K,1,2),
     *SUC(L,K,2,14),SUC(L,K,2,6),SUC(L,K,3,14)
  432 CONTINUE
      PRINT 328
      DO 433 K=1,NT
      PRINT 323,YR(K),SUC(L,K,3,6),SUC(L,K,4,6),SUC(L,K,5,6),
     *SUCS(L,K,2,4),SUC(L,K,1,7),SUCS(L,K,1,3),SUC(L,K,2,7),
     *SUC(L,K,3,7),SUC(L,K,4,7),AECID(L,M,K)
  433 CONTINUE
      PRINT 329
      DO 434 K=1,NT
      PRINT 323,YR(K),SUCS(L,K,1,4),SUC(L,K,4,14),SUC(L,K,5,14),
     *SUCS(L,K,2,4)
  434 CONTINUE
  351 CONTINUE
  366 CONTINUE
      IF (ITOTAL.NE.1) GO TO 500
      PRINT 102
      DO 361 K=1,NT
      PRINT 101,YR(K),CIRAT(4,M,K),CITOT(4,M,K),AETOT(4,M,K),
     *AERAT(4,M,K),AECID(4,M,K)
  361 CONTINUE
  500 CONTINUE
  100 FORMAT(1H1,3X,"RECHARGE M/YR",3X," FLUX M/YR   ",
     *3X,"VELOCITY M/YR",2X,
     *"TRAVEL TIME YR",2X,"25% FLUX CUM/YR",2X,"2.5% FLUX",5X,
     *".25% FLUX")
  101 FORMAT(5X,7(1PE10.2,5X))
  102 FORMAT(//8X,"TIME",10X,"CIRAT",10X,"CITOT",10X,"AETOT",
     *10X,"AERAT",10X,"AECID")
  103 FORMAT(//,"******",I2,"TH PATH ******")
  300 FORMAT(10X,"UNDECAYED")
  301 FORMAT(5X,A8,"GM=",1PE10.2,10X,"CI=",1PE10.2)
  302 FORMAT(80X,"TIME =",1PE10.2)
  307 FORMAT(15X,A8)
  308 FORMAT(/49X,"RECHARGE RATE =",1PE10.2,"(MM/YR)")
  309 FORMAT(26X,"DISS RATE GM/YR",4X,"CUM CI",9X,"CUM GMS",9X,
     *"KGMS LEFT",6X,"CUM CI/RL",4X,"NRC-RATIO",4X,"RTCUR")
  310 FORMAT(17X,A8,5(1PE10.2,6X),1PE10.2,4X,1PE10.2)
  311 FORMAT(3X,"CHAIN 1 - THORIUM SERIES")
  312 FORMAT(3X,"CHAIN 2 - NEPTUNIUM SERIES")
  313 FORMAT(3X,"CHAIN 3 - URANIUM SERIES")
  314 FORMAT(3X,"CHAIN 4 - ACTINIUM SERIES")
  315 FORMAT(3X,"ACTIVATION PRODUCTS")
  316 FORMAT(3X,I3,3X,I3,3X,5(1PE10.2,5X),10X,"TIME =",1PE10.2)
  317 FORMAT(17X,A8,16X,4(1PE10.2,6X),1PE10.2,4X,1PE10.2)
  318 FORMAT(10X,3(1PE10.2,10X))
  319 FORMAT(1H1,7X,"TIME",10X,"RECHARGE",10X,"TOTAL CURIES")
  320 FORMAT(/1X,"============================================================"/)
  321 FORMAT(1X,"***********")
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 322 FORMAT(//2X,"TIME",2X,"TOTAL CURIES",2X,"DIS EPA RATIO",
     *2X," AE-TOTAL ",2X,"AE-EPA RATIO",2X," C-14 AE ",2X,
     *" TC-99 AE ",2X," I-129 AE ",2X," NI-59 AE ",2X,
     *" CS-135 AE ",2X," SN-126 AE"/)
 323 FORMAT(11(1PE10.2,2X))
 325 FORMAT(99X,"RECHARGE RATE =",1PE10.2)
 326 FORMAT(/,5X,"TIME",4X,
     *" ZR-93 AE ",2X," SR-90 AE ",2X," CS-137 AE",
     *2X," CM-244 AE",2X," PU-240 AE",2X," U-236 AE ",2X,
     *" TH-232 AE",2X," CM-245 AE",2X," PU-241 AE",2X,
     *" AM-241 AE"/)
 327 FORMAT(/,5X,"TIME",4X," NP-237 AE",2X,
     *" U-233 AE ",2X," TH-229 AE",2X," RA-225 AE",
     *2X," CM-246 AE",2X," AM-242 AE",2X," CM-242 AE",2X,
     *" PU-242 AE",2X," PU-238 AE",2X," U-238 AE "/)
 328 FORMAT(/,5X,"TIME",4X," U-234 AE",2X," TH-230 AE",2X,
     *" RA-226 AE",2X," PB-210 AE",2X," AM-243 AE",
     *2X," NP-239 AE",2X," PU-239 AE",2X," U-235 AE ",2X
     *"PA-231 AE",2X,"AECID"/)
 329 FORMAT(/,5X,"TIME",4X,"U-234* AE",2X,"TH-230* AE",2X,
     *"RA-226* AE",2X,"PB-210* AE"/)
9999 STOP
     END
     SUBROUTINE BAT(NCHNS,AL,T,NEC,CONI,TM21,TM31,TM41,TM32,TM42,
     *TM43,TM51,TM52,TM53,TM54,CONN)
     DIMENSION AL(5,14),TM21(14),TM31(14),TM41(14),TM32(14),
     *TM43(14),TM42(14),EXT(5,14),NEC(14),CONI(5,14),CONN(5,14),
     *TM51(14),TM52(14),TM53(14),TM54(14)
     DO 2 I=1,NCHNS
     N=NEC(I)
     DO 2 J=1,N
     CONN(J,I)=0.
     Z=-AL(J,I)*T
     IF(Z.GT.-1.E1000)GO TO 5
     EXT(J,I)=0.
     GO TO 6
5    EXT(J,I)=EXP(Z)
6    CONTINUE
2    CONTINUE
     DO 3 I=1,NCHNS
     C1=CONI(1,I)
     C2=CONI(2,I)
     C3=CONI(3,I)
     C4=CONI(4,I)
     C5=CONI(5,I)
     N=NEC(I)
     CONN(1,I)=C1*EXT(1,I)
      IF(N.EQ.1)GO TO 4
     X=AL(1,I)*TM21(I)*C1
     Y=-X+C2
     CONN(2,I)=X*EXT(1,I)+Y*EXT(2,I)
     IF(N.EQ.2)GO TO 4
     X=AL(1,I)*AL(2,I)*C1
     X1=X*TM21(I)*TM31(I)*EXT(1,I)
     Y=-X*TM21(I)*TM32(I)+AL(2,I)*C2*TM32(I)
     Y1=Y*EXT(2,I)
     Z=X*TM31(I)*TM32(I)-AL(2,I)*C2*TM32(I)+C3
     Z1=Z*EXT(3,I)
     CONN(3,I)=X1+Y1+Z1
     IF(N.EQ.3)GO TO 4
     X=AL(1,I)*AL(2,I)*AL(3,I)*C1
      Y=AL(2,I)*AL(3,I)*C2
     X1=X*TM21(I)*TM31(I)*TM41(I)*EXT(1,I)
     Y1=-X*TM21(I)*TM32(I)*TM42(I)
     Y1=Y1+Y*TM32(I)*TM42(I)
     Y1=Y1*EXT(2,I)
     Z1=X*TM31(I)*TM32(I)*TM43(I)
     Z1=Z1-Y*TM32(I)*TM43(I)
     Z1=Z1+C3*AL(3,I)*TM43(I)
     Z1=Z1*EXT(3,I)
     W1=-X*TM41(I)*TM42(I)*TM43(I)
     W1=W1+Y*TM42(I)*TM43(I)
     W1=W1-AL(3,I)*C3*TM43(I)+C4
     W1=W1*EXT(4,I)
     CONN(4,I)=X1+Y1+Z1+W1
     IF(N.EQ.4)GO TO 4
     A1=AL(1,I)*AL(2,I)*AL(3,I)*AL(4,I)*C1
     A2=AL(2,I)*AL(3,I)*AL(4,I)*C2
     A3=AL(3,I)*AL(4,I)*C3
      U=A1*TM21(I)*TM31(I)*TM41(I)*TM51(I)
     U=U*EXT(1,I)
     V=-A1*TM21(I)*TM32(I)*TM42(I)*TM52(I)
     V=V+A2*TM32(I)*TM42(I)*TM52(I)
     V=V*EXT(2,I)
     W=A1*TM31(I)*TM32(I)*TM43(I)*TM53(I)
     W=W-A2*TM32(I)*TM43(I)*TM53(I)
     W=W+A3*TM43(I)*TM53(I)
     W=W*EXT(3,I)
     X=-A1*TM41(I)*TM42(I)*TM43(I)*TM54(I)
     X=X+A2*TM42(I)*TM43(I)*TM54(I)
     X=X-A3*TM43(I)*TM54(I)
     X=X+AL(4,I)*C4*TM54(I)
     X=X*EXT(4,I)
     Y=A1*TM51(I)*TM52(I)*TM53(I)*TM54(I)
     Y=Y-A2*TM52(I)*TM53(I)*TM54(I)
     Y=Y+A3*TM53(I)*TM54(I)
     Y=Y-TM54(I)*AL(4,I)*C4
      Y=(Y+C5)*EXT(5,I)
     CONN(5,I)=U+V+W+X+Y
4    CONTINUE
3    CONTINUE
      RETURN
      END
```

APPENDIX B

COMPUTER SOURCE LISTINGS OF UCB-NE-10.3

This section contains a detailed computer program and the input data used to calculate the analytical solutions.

```
      PROGRAM NE103(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON/CAL1/BC(3,3),GC(3,3),RC(3,3),C(12),FN(3),RX(3),TN(3)
      COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
      COMMON/CAL3/ ANAME(3),AT(3),COEFK(3),CURIN(3),HLIFE(3),PR(3)
     +            ,RCGW(3),DIF,VEL,FLW,TS,T1,Z1,IT,IZ
      COMMON/CAL4/ CNA(3),CNB(3),CNC(3)
      DIMENSION RR(3),CN(3),CX(3)
      DIMENSION CND(3),CNE(3),PT(225,5,3),YR(225),
     *PT1(225),PT2(225),PT3(225),PT4(225),PT5(225)
      DIMENSION IPAK(70)
      DATA QNA/7H       /
      CALL VSTART(.75,0)
      CALL PAGE(8.5,11.)
      DO 1 I=1,3
      DO 1 J=1,3
      BC(I,J)= 0.
      BT(I,J)= 0.
      GC(I,J)= 0.
      RC(I,J)= 0.
      DO 1 K=1,3
      GS(I,J,K)= 0.
    1 CONTINUE
    5 CONTINUE
      READ(5,501) ICRL,IA,IB,IC,ID,IE,IF,NIDIF
      IF(ICRL.EQ.99) GO TO 480
      IF(NIDIF.EQ.0)NIDIF=1
      IF(IA.EQ.0) GO TO 10
      INUC= IA
      READ(5,502)  (ANAME(I),HLIFE(I),CURIN(I),COEFK(I),RCGW(I),PR(I),
     +             I=1,IA)
   10 IF(IB.EQ.0)  GO TO 20
      READ(5,501)  IDIN,IDOUT,ICAL,IDIV,IBC
   20 IF(IC.EQ.0)  GO TO 30
      READ(5,503)  DIF,VEL,FLW
   30 IF(ID.EQ.0)  GO TO 40
      READ(5,504)  IREL,TS,TL
   40 IF(IE.EQ.0)  GO TO 50
      READ(5,505)  IT,IDT,T1
   50 IF(IF.EQ.0)  GO TO 60
      READ(5,505)  IZ,IDZ,Z1
   60 CONTINUE
      DO 999 IDIF=1,NIDIF
      IF (IDIF.GT.1)DIF=DIF/10.
      IF(IREL.EQ.3) GO TO 80
      DO 70 I=1,INUC
   70 PR(I)= TL
   80 CONTINUE
      DO 90 I=1,3
      CND(I)=0.
      CNE(I)=0.
   90 CONTINUE
      KT=0
C     ATOMIC CONSTANTS
      AK= 1.16683E18
      FK= DIF/VEL
      VMIN= 1.E100
      VMAX= 0.
      DO 100 K=1,INUC
      A= ALOG(2.)/HLIFE(K)
      B= PR(K)
      R(K)= A
      RX(K)=A
      TN(K)= B
      V(K)=  VEL/COEFK(K)
      AT(K)= CURIN(K)
      IF(IDIN.EQ.1) AT(K)= AT(K)*AK/A
      IF(VMIN.GT.V(K)) VMIN= V(K)
      IF(VMAX.LT.V(K)) VMAX= V(K)
      RR(K)= A
      IF(IREL.NE.1) RR(K)= A+1./B
  100 CONTINUE
      BC(1,1)= AT(1)
      E1= EXP(-R(1)*TS)
      WA= BC(1,1)*E1
      CN(1)= WA
      IF(IDIN.EQ.1) CN(1)= CN(1)*R(1)/AK
      IF(INUC.NE.1) GO TO 102
      ANAME(2)= QNA
      ANAME(3)= QNA
      GO TO 110
  102 CONTINUE
      R12= R(1)-R(2)
      XA= -R(1)/R12
      BC(2,1)=-AT(1)*R(1)/R12
      BC(2,1)=-AT(1)*R(1)/R12*PR(1)/PR(2)
      BC(2,2)= AT(2)-BC(2,1)
      RC(1,2)= R(1)/V(1)-R(2)/V(2)
      GC(1,2)= 1.0/V(1)-1.0/V(2)
      BT(1,2)= RC(1,2)/GC(1,2)
      BT(2,2)= RR(2)
      GS(1,2,1)= GMF(1,2,1)
      GS(1,1,2)= GMF(1,1,2)
      GS(2,2,2)= GMF(2,2,2)
      GS(1,2,2)= GMF(1,2,2)
      RV1= R(1)/V(1)
      C(1)= RV1/(RC(1,2)-RR(1)*GC(1,2))
      IF(INUC.EQ.2) GO TO 120
      R23= RR(2)-RR(3)
      R31= RR(3)-RR(1)
      RRR= AT(1)*R(1)*R(2)*PR(1)/PR(3)
      BC(3,1)= -RRR/(R12*R31)
      BC(3,2)= -RRR/(R12*R23)-AT(2)*R(2)/R23*PR(2)/PR(3)
      BC(3,3)= -RRR/(R23*R31)+AT(2)*R(2)/R23*PR(2)/PR(3)+AT(
      RC(2,1)= -RC(1,2)
      RC(3,1)= R(3)/V(3)-R(1)/V(1)
      RC(1,3)= -RC(3,1)
      RC(3,2)= R(3)/V(3)-R(2)/V(2)
      RC(2,3)= -RC(3,2)
      GC(2,1)= -GC(1,2)
      GC(3,1)= 1.0/V(3)-1.0/V(1)
      GC(1,3)= -GC(3,1)
      GC(3,2)= 1.0/V(3)-1.0/V(2)
      GC(2,3)= -GC(3,2)
      BT(1,3)= RC(1,3)/GC(1,3)
      BT(2,3)= RC(2,3)/GC(2,3)
      BT(3,3)= RR(3)
      GS(1,3,1)= GMF(1,3,1)
      GS(2,3,2)= GMF(2,3,2)
      GS(1,1,3)= GMF(1,1,3)
      GS(1,3,3)= GMF(1,3,3)
      GS(2,2,3)= GMF(2,2,3)
      GS(2,3,3)= GMF(2,3,3)
      GS(3,3,3)= GMF(3,3,3)
      RV2= R(2)/V(2)
      RV3= RV1*RV2
      C(2)= RV2/(RC(2,3)-RR(2)*GC(2,3))
      C(3)= RV2/(RC(2,3)-RR(1)*GC(2,3))
      C(4)= RV1/(RC(1,3)-RR(1)*GC(1,3))*C(3)
      CA= RV3/(GC(1,3)*RC(2,3)-GC(2,3)*RC(1,3))
      CB= RV3/(GC(3,2)*RC(1,2)-GC(1,2)*RC(3,2))
      CC= RV3/(GC(3,1)*RC(2,1)-GC(2,1)*RC(3,1))
      C(5)= GC(1,3)*CA/(RC(1,3)-RR(1)*GC(1,3))
      C(6)= GC(2,3)*CA/(RC(2,3)-RR(1)*GC(2,3))
      C(7)= RV2/(RC(3,2)-RR(1)*GC(3,2))*C(1)
      C(8)= GC(3,2)*CB/(RC(3,2)-RR(1)*GC(3,2))
      C(9)= GC(1,2)*CB/(RC(1,2)-RR(1)*GC(1,2))
      C(10)= RV3/(RC(3,1)-RR(1)*GC(3,1))/(RC(2,1)-RR(1)*GC(2,
      C(11)= GC(3,1)*CC/(RC(3,1)-RR(1)*GC(3,1))
      C(12)= GC(2,1)*CC/(RC(2,1)-RR(1)*GC(2,1))
  120 CONTINUE
      IF(ICAL.EQ.1) GO TO 440
C     FOR FIXED TIME
      FD= 9./FLOAT(IDZ)
      DO 420 M=1,IT
```

```
      BC(2,2)= AT(2)-BC(2,1)
      E2= EXP(-R(2)*TS)
      WA= BC(2,1)*E1+BC(2,2)*E2
      CN(2)= WA
      IF(IDIN.EQ.1) CN(2)= CN(2)*R(2)/AK
      IF(INUC.NE.2) GO TO 104
      ANAME(3)= QNA
      GO TO 110
  104 CONTINUE
      R23= R(2)-R(3)
      R31= R(3)-R(1)
      RRR= AT(1)*R(1)*R(2)
      XB= -R(2)/R23
      XC= -R(1)*R(2)/(R12*R31)
      XD= -R(1)*R(2)/(R12*R23)
      XE= -R(1)*R(2)/(R31*R23)
      E3= EXP(-TS*R(3))
      BC(3,1)= -RRR/(R12*R31)
      BC(3,2)= -RRR/(R12*R23)-AT(2)*R(2)/R23
      BC(3,3)= -RRR/(R23*R31)+AT(2)*R(2)/R23+AT(3)
      WA=BC(3,1)*E1+BC(3,2)*E2+BC(3,3)*E3
      CN(3)=WA
      IF(IDIN.EQ.1) CN(3)= CN(3)*R(3)/AK
  110 CONTINUE
      DO 112 K=1,INUC
      AT(K)= CN(K)/(PR(K)*FLW)
  112 IF(IDIN.EQ.1) AT(K)= AT(K)*AK/R(K)
C     PRINT OUT OF INITIAL CONDITIONS
      IF (IDIF.GT.1) GO TO 113
      CALL TITLE1(INUC,IREL,ICAL,IDIN,CN)
  113 PRINT 506,DIF
      BC(1,1)= AT(1)
      BT(1,1)= RR(1)
      GS(1,1,1)= GMF(1,1,1)
      IF(INUC.EQ.1) GO TO 120
      R12= RR(1)-RR(2)
      T2= T1*10.**(M-1)
      KM= 1
      GO TO 402
  401 CONTINUE
      T2= T2*5.0
      KM= 0
  402 CONTINUE
      CALL TITLE2(ICAL,IDOUT,T2)
      DO 416 N=1,IZ
      DO 416 L=1,IDZ
      FL= L
      Z2= Z1*10.**(N-1)*(1.+FD*(FL-1.))
      IER= 0
      CALL CALC(INUC,0,T2,Z2)
      IF(IER.EQ.1) GO TO 417
      DO 403 LL=1,INUC
  403 CN(LL)= FN(LL)
      IF(IREL.NE.1) GO TO 407
      IF(T2.LE.TL) GO TO 407
      BAND RELEASE
      IER= 0
      CALL CALC(INUC,1,T2,Z2)
      IF(IER.EQ.1) GO TO 417
      DO 405 LL=1,INUC
  405 CN(LL)= CN(LL)-FN(LL)
  407 CONTINUE
      CMAX= O.
      DO 409 LL=1,INUC
      WA= CN(LL)/AT(1)
      IF(CMAX.LT.WA) CMAX= WA
      CNA(LL)= WA
  409 CNB(LL)= WA*R(LL)/R(1)
      IF(IDOUT.NE.1) GO TO 413
      DO 411 LL=1,INUC
      CNA(LL)= R(LL)*CN(LL)*FLW/AK
  411 CNB(LL)= CNA(LL)/RCGW(LL)
  413 CONTINUE
      ZMAX= VMIN*T2
      IF(ZMAX.GT.Z2) GO TO 415
      IF(CMAX.LT.1.E-15) GO TO 417
  415 CONTINUE
      CALL PRINTR(INUC,IDOUT,ICAL,Z2,CND)
  416 CONTINUE
  417 CONTINUE
      IF(IDIV.EQ.1) GO TO 420
      IF(KM.EQ.1) GO TO 401
  420 CONTINUE
      GO TO 5

      FOR FIXED LOCATION

  440 CONTINUE
      FD= 9./FLOAT(IDT)
      DO 460 M=1,IZ
      Z2= Z1*10.**(M-1)
      KM= 1
      GO TO 442
  441 CONTINUE
      Z2= Z2*5.0
      KM= 0
  442 CONTINUE
      CALL TITLE2(ICAL,IDOUT,Z2)
      TX= O.
      QA= O.
      QB1= O.
      QB2= O.
      QC1= O.
      QC2= O.
      QC3= O.
      DO 454 N=1,IT
      DO 454 L=1,IDT
      FL= L
      T2= T1*10.**(N-1)*(1.+FD*(FL-1.))
C
      IER= O
      CALL CALC(INUC,O,T2,Z2)
      IF(IER.EQ.1) GO TO 456
      DO 443 LL=1,INUC
  443 CN(LL)= FN(LL)
      IF(IREL.NE.1) GO TO 446
      IF(T2.LE.TL) GO TO 446
C
C     BAND RELEASE
C
      IER= O
      CALL CALC(INUC,1,T2,Z2)
      IF(IER.EQ.1) GO TO 456
      DO 444 LL=1,INUC
  444 CN(LL)= CN(LL)-FN(LL)
  446 CONTINUE
      DET= T2-TX
      IF(IDOUT.EQ.0) GO TO 1000
      E1= EXP(-R(1)*DET)
      QA= QA*E1+(1.0-E1)*CN(1)/R(1)
      CX(1)= QA
      IF(INUC.EQ.1) GO TO 1000
      E2= EXP(-R(2)*DET)
      QB1= QB1*E1+(1.0-E1)*CN(1)*XA/R(1)
      QB2= QB2*E2+(1.0-E2)*(CN(2)-CN(1)*XA)/R(2)
      CX(2)= QB1+QB2
      IF(INUC.EQ.2) GO TO 1000
      E3= EXP(-R(3)*DET)
      QC1= QC1*E1+(1.0-E1)*CN(1)*XC/R(1)
      QC2= QC2*E2+(1.0-E2)*(XB*CN(2)+XD*CN(1))/R(2)
      QC3= QC3*E3+(1.0-E3)*(CN(3)-XB*CN(2)+XE*CN(1))/R(3)
      CX(3)= QC1+QC2+QC3
 1000 CONTINUE
      CMAX= 0.0
      DO 447 LL=1,INUC
      WA= CN(LL)/AT(1)
      IF(CMAX.LT.WA) CMAX= WA
      CNA(LL)= WA
  447 CNB(LL)= WA*R(LL)/R(1)
      IF(IDOUT.NE.1) GO TO 450
      DO 448 LL=1,INUC
      CNA(LL)= R(LL)*CN(LL)*FLW/AK
      CND(LL)=CND(LL)+DET*(CNE(LL)+CNA(LL))/2.
      WA= R(LL)*CX(LL)*FLW/AK
      CNC(LL)= WA/RCGW(LL)
  448 CNB(LL)= CNA(LL)/RCGW(LL)
      DO 449 LL=1,INUC
  449 CNE(LL)=CNA(LL)
  450 CONTINUE
      TX= T2
      TMAX= Z2/VMIN+TL
      IF(TMAX.GT.T2) GO TO 452
      IF(CMAX.LT.1.E-15) GO TO 456
  452 CONTINUE
      TS2= T2+TS
      CALL PRINTR(INUC,IDOUT,ICAL,TS2,CND)
      KT=KT+1
      YR(KT)=TS2
      DO 600 JJ=1,INUC
  600 PT(KT,IDIF,JJ)=CND(JJ)
  454 CONTINUE
  456 CONTINUE
      IF(IDIV.EQ.1) GO TO 460
      IF(KM.EQ.1) GO TO 441
  460 CONTINUE
  999 CONTINUE
      IV=2
      IC=2
      NT=KT
      TST=10.
      PTMIN=1.E-7
      DO 910 L=1,INUC
      CALL RESET("ALL")
      CALL AREA2D(7.5,10.)
      CALL HEADIN("CUMMULATIVE CURIES RELEASED FOR           $"
     *,100,1.5,3)
      CALL HEADIN("300 YEARS OLD INVENTORIES$",100,1.,3)
      CALL HEADIN("(FLUX THROUGH 2.5% OF MINED AREA)$",100,.75,3)
      CALL XNAME("TIME AFTER CLOSURE (YR)$",100)
      CALL YNAME("CUMMULATIVE CURIES RRELEASE (CI)$",100)
      DO 809 K=1,NT
      PT1(K)=PT(K,1,L)
```

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      PT2(K)=PT(K,2,L)
      PT3(K)=PT(K,3,L)
      PT4(K)=PT(K,4,L)
      PT5(K)=PT(K,5,L)
  809 CONTINUE
      DO 810 K=1,NT
      IF  (PT1(K).LT.PTMIN)  PT1(K)=PTMIN
      IF  (PT2(K).LT.PTMIN)  PT2(K)=PTMIN
      IF  (PT3(K).LT.PTMIN)  PT3(K)=PTMIN
      IF  (PT4(K).LT.PTMIN)  PT4(K)=PTMIN
      IF  (PT5(K).LT.PTMIN)  PT5(K)=PTMIN
  810 CONTINUE
      CALL NOCHEK
      CALL GRACE(0.0)
      CALL LOGLOG(TST,1.8,PTMIN,1.)
      IDUM=LINEST(IPAK,70,10)
      CALL LEGLIN
      CALL CURVE(YR,PT1,NT,0)
      IF  (NIDIF.EQ.1) GO TO 900
      CALL DASH
      CALL CURVE(YR,PT2,NT,0)
      CALL RESET("DASH")
      IF  (NIDIF.EQ.2) GO TO 900
      CALL DOT
      CALL CURVE(YR,PT3,NT,0)
      CALL RESET("DOT")
      IF  (NIDIF.EQ.3) GO TO 900
      CALL CHNDOT
      CALL CURVE(YR,PT4,NT,0)
      CALL RESET("CHNDOT")
      IF  (NIDIF.EQ.4) GO TO 900
      CALL CHNDSH
      CALL CURVE(YR,PT5,NT,0)
      CALL RESET("CHNDSH")
  900 CONTINUE
      CALL LINESP(2.)
      CALL LINES("D=100.$",IPAK,1)
      CALL LINES("D=10.$",IPAK,2)
      CALL LINES("D=1.$",IPAK,3)
      CALL LINES("D=0.1$",IPAK,4)
      CALL LINES("D=0.01$",IPAK,5)
      CALL LEGEND(IPAK,5,0.5,5.2)
      CALL FRAME
      CALL ENDPL(1)
  910 CONTINUE
      GO TO 5
      CALL DONEPL
  480 STOP
  501 FORMAT(8I2)
  502 FORMAT(A7,5F8.0)
  503 FORMAT(3F8.0)
  504 FORMAT(I1,2F8.0)
  505 FORMAT(I1,I3,2F8.0)
  506 FORMAT(/"******",F10.4,"******"/)
      END
      SUBROUTINE CALC(INUC,IK,T,Z)
      COMMON/CAL1/BC(3,3),GC(3,3),RC(3,3),C(12),FN(3),R(3),TL(3)
      DIMENSION TM(3),B(3,3)
      DO 10 I=1,INUC
   10 TM(I)= 1.0
      IF(IK.EQ.0) GO TO 30
      DO 20 I=1,INUC
   20 TM(I)= EXP(-R(I)*TL(I))
   30 CONTINUE
      DO 40 I=1,INUC
      DO 40 J=1,INUC
   40 B(I,J)= BC(I,J)*TM(J)
      DO 50 I=1,INUC
   50 TM(I)= T
      IF(IK.EQ.0) GO TO 70
      DO 60 I=1,INUC
   60 TM(I)= T-TL(I)
   70 CONTINUE
      TA= TM(1)
      XA= EFN(1,1,1,TA,Z)
      FN(1)= B(1,1)*XA
      IF(INUC.EQ.1) GO TO 100
      TB= TM(2)
      XB= EFN(2,2,2,TB,Z)
      XC= EFN(1,1,2,TB,Z)
      YA= RC(1,2)/GC(1,2)
      IF(YA.LT.0.) GO TO 200
      XD= EFN(1,2,2,TB,Z)
      XE= EFN(1,2,1,TB,Z)
      XM= XE-XD
      GO TO 210
  200 CONTINUE
      XM= EFG(1,2,2,TB,Z)
  210 CONTINUE
      FN(2)= B(2,2)*XB+B(2,1)*XC+B(1,1)*C(1)*(XC-XA+XM)
      IF(INUC.EQ.2) GO TO 100
      TC= TM(3)
      XF= EFN(3,3,3,TC,Z)
      XG= EFN(2,2,3,TC,Z)
      XH= EFN(1,1,3,TC,Z)
      YB= RC(2,3)/GC(2,3)
      IF(YB.LT.0.) GO TO 220
      XI= EFN(2,3,3,TC,Z)
      XJ= EFN(2,3,2,TC,Z)
      XN= XJ-XI
      GO TO 230
  220 CONTINUE
      XN= EFG(2,3,3,TC,Z)
  230 CONTINUE
      YC= RC(1,3)/GC(1,3)
      IF(YC.LT.0.) GO TO 240
      XK= EFN(1,3,3,TC,Z)
      XL= EFN(1,3,1,TC,Z)
      XO= XL-XK
      GO TO 250
  240 CONTINUE
      XO= EFG(1,3,3,TC,Z)
  250 CONTINUE
      XS= -C(9)*XM
      XT= -C(8)*XN
      XU= C(5)*XO
      FN(3)= B(3,3)*XF+B(3,2)*XG+B(3,1)*XH
     +        + B(2,2)*C(2)*(XG-XB+XN)+B(2,1)*C(3)*(XH-XC+XN)
     +        + B(1,1)*(XH*C(4)+XC*C(7)+XA*C(10)
     +        + XS+XT+XU)
      CONTINUE
  100 RETURN
      END
      FUNCTION EFN(I,J,K,T,Z)
      COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
      EXTERNAL FNM
      EXTERNAL FUNF,FUNG,FUNU,FUNV,FUNR
      EXTERNAL ERFL,ERFS
      TT= T
      ZZ= Z
      XT= V(K)*TT
      XL= GS(I,J,K)
      XG=XL
      BB= BT(I,J)
      IF(XL.LE.0.0) GO TO 100
      IF(FK.LT.1.0) GO TO 200
      IF(Z.LT.XT) GO TO 200
      GO TO 200
  100 CONTINUE

      INFINITE SERIES APPROX. COMPLEX ERF

      AXL=ABS(XL)
      W=0.5*Z/FK-BB*TT


      S=0.5*ABS(Z)*SQRT(AXL)/FK
      X=0.5*ABS(Z)/SQRT(FK*XT)
      Y=0.5*XT*SQRT(AXL/(FK*XT))
      CALL ESYM(W,S,X,Y,ANS)
      EFN=0.5*ANS/SQRT(AXL)
      IF(IBC.EQ.1) EFN=0.5*ANS
      RETURN
  200 CONTINUE

      RATIONAL APPROXIMATION

      AZ= ABS(Z)
      XG=SQRT(XL)
      XB= SQRT(4.*FK*XT)
      XC= BT(I,J)
      FK2= 2.*FK
      YM= (AZ-XT*XG)/XB
      AYM= ABS(YM)
      IF(AYM.LT.0.5) GO TO 201
      GO TO 202
  201 CONTINUE
      X= AZ/FK2*(1.-XG)-XC*T
      X= EXP(X)
      Y= 1.0-ERFS(YM)
      X= X*Y
      GO TO 203
  202 CONTINUE
      XS= AZ/FK2*(1.-XG)-XC*T
      Y= ERFL(YM)
      IF(YM.LT.0.) GO TO 204
      X= XS-YM*YM
      X= EXP(X)*Y
      GO TO 203
  204 CONTINUE
      X= XS-YM*YM
      Y= EXP(-YM*YM)*Y
      X= EXP(XS)*(2.0+Y)
  203 CONTINUE
      YP= (AZ+XT*XG)/XB
      AYP= ABS(YP)
      IF(AYP.LT.0.5) GO TO 205
      GO TO 206
```

```
  205 CONTINUE
      W= AZ/FK2*(1.+XG)-XC*T
      W= EXP(W)
      Y= 1.0-ERFS(YP)
      W= W*Y
      GO TO 207
  206 CONTINUE
      W= AZ/FK2*(1.+XG)-XC*T-YP*YP
      W= EXP(W)*ERFL(YP)
  207 CONTINUE
      EFN= (X-W)/XG/2.0
      IF(IBC.EQ.1) EFN= (X+W)/2.0
      RETURN
      END
      FUNCTION EFG(I,J,K,T,Z)
      COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
      EXTERNAL FNM
      ZZ= Z
      TT= T
      BB= BT(I,J)
      XL= GS(I,J,K)
      XT1= V(K)*TT
      XT2= V(I)*TT
      XB1= SQRT(4.*FK*XT1)
      XB2= SQRT(4.*FK*XT2)
      IF(XL.LT.0.) GO TO 100
      XG= SQRT(XL)
      YM1= (Z-XT1*XG)/XB1
      YM2= (Z-XT2*XG)/XB2
      EPS= YM1*YM2
      IF(EPS.LT.0.) GO TO 100
      IF(ABS(YM1).LT.0.5) GO TO 100
      IF(ABS(YM2).LT.0.5) GO TO 100
      GO TO 200
  100 CONTINUE
C
C        NUMERICAL INTEGRATION
C
      AL1= SQRT(XT1/FK/4.)
      IF(IBC.EQ.1) AL1=ZZ/SQRT(XT1*4.*FK)
      AL2= SQRT(XT2/FK/4.)
      IF(IBC.EQ.1) AL2=ZZ/SQRT(XT2*4.*FK)
      AL=AMIN1(AL1,AL2)
      AH=AMAX1(AL1,AL2)
      XG= XL
      N= 20
      AS= AH-AL
      IF(AS.GT.1.) N= 100
      RES= 0.0
      AD= AS/FLOAT(N)
      DO 110 LL=1,N
      ALL= AL+AD*FLOAT(LL-1)
      AHH= AL+AD*FLOAT(LL)
      CALL GAUSS(FNM,ALL,AHH,RESULT)
  110 RES= RES+RESULT
      EFP= 2./1.7724538*RES
      AP= AL2-AL1
      IF (IBC.EQ.1) AP=AL1-AL2
      EFG= SIGN(EFP,AP)
      RETURN
  200 CONTINUE
C
C          RATIONAL APPROXIMATION
C
      AZ= ABS(Z)
      XG= BT(I,J)
      FK2= 2.*FK
      XS= AZ/FK2*(1.0-XG)-XC*T
      X1= XS-YM1*YM1
      X2= XS-YM2*YM2
      X1= EXP(X1)*ERFL(YM1)
      X2= EXP(X2)*ERFL(YM2)
      X= X2-X1
      YP1= (Z+XT1*XG)/XB1
      YP2= (Z+XT2*XG)/XB2
      WS= AZ/FK2*(1.0+XG)-XC*T
      W1= WS-YP1*YP1
      W2= WS-YP2*YP2
      W1= EXP(W1)*ERFL(YP1)
      W2= EXP(W2)*ERFL(YP2)
      W= W2-W1
      EFG= (X-W)/XG/2.
      IF(IBC.EQ.1) EFG= (X+W)/2.
      RETURN
      END
      FUNCTION ERFL(X)
      DIMENSION P(6),Q(6),R(4),S(4)
      DATA (P(I),I= 1,6)/22.898992851659,26.094746956075,14.571898596926
     +,4.2677201070898,.56437160686381,-6.0858151959688E-06/,
     +(Q(I),I=1,6)/22.898985749891,51.933570687552,50.273202863803,26.28
     +8795758761,7.5688482293618,1.0/,
     +(R(I),I=1,4)/-1.21308276389978E-02,-.119903955268146 ,-.2439110294
     +88626,-3.24319519277746E-02/,
     +(S(I),I=1,4)/4.30026643452770E-02,.489552441961437,1.4377122793711
     +8,1.0/
      DATA SQPI/.564189583547756/
      AX= ABS(X)
      IF(AX.GT.4.0) GO TO 200
      A= P(1)+AX*(P(2)+AX*(P(3)+AX*(P(4)+AX*(P(5)+AX*P(6)))))
      A= A/(Q(1)+AX*(Q(2)+AX*(Q(3)+AX*(Q(4)+AX*(Q(5)+AX*Q(6))))))
      ERFL= SIGN(A,X)
      RETURN
  200 CONTINUE
      X2= 1./AX/AX
      B= X2*(R(1)+X2*(R(2)+X2*(R(3)+X2*R(4))))/(S(1)+X2*(S(2)+X2*(S(3)+
     +   X2*S(4))))
      A= (SQPI+B)/AX
      ERFL= SIGN(A,X)
      RETURN
      END
      FUNCTION ERFS(X)
      AX= ABS(X)
      ER= 0.0
      ES= 1.0
      PAI= SQRT(3.14159265358979)
      DO 10 I= 1,15
      XI= FLOAT(I)
      ES= -ES*AX**2/XI*(2.*XI-1.)/(2.*XI+1.)
      ER= ER+ES
   10 CONTINUE
      ERF= 2.0/PAI*(ER+1.0)*AX
      ERFS= SIGN(ERF,X)
      RETURN
      END
      FUNCTION FNM(X)
      COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
      IF(IBC.EQ.1) GO TO 10
      XA= ZZ/(4.0*FK*X)
      XB= XG*X*X+XA*XA
      XB= ZZ/FK/2.0-XB-BB*TT
      IF(XB.GT.650.) GO TO 20
      FNM= EXP(XB)
      RETURN
   10 XA= ZZ/(4.*FK*X)
      XB= X*X+XA*XA*XG
      XB= ZZ/FK/2.0-XB-BB*TT
      IF(XB.GT.650.) GO TO 20
      FNM=EXP(XB)
      RETURN
C     ERROR
   20 FNM= 0.
      IER= 1
      RETURN
      END
      FUNCTION GMF(I,J,K)
      COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
      GMF= 1.0+4.0*FK*(R(K)-BT(I,J))/V(K)
      RETURN
      END
      SUBROUTINE PRINTR(INUC,IDOUT,ICAL,TZ,CND)
      COMMON/CAL4/ CNA(3),CNB(3),CNC(3)
      DIMENSION LISA1(5),LISA2(5),LISA3(5),LYAN1(5),LYAN2(5),LYAN3(5)
      DIMENSION CND(3)
      DATA LISA1/29H(15X,1PE10.3,2(4X,E10.3,20X))/
     +     ,LISA2/30H(15X,1PE10.3,2(4X,2E10.3,10X))/
     +     ,LISA3/26H(15X,1PE10.3,2(4X,3E10.3))/
     +     ,LYAN1/29H(15X,1PE10.3,3(4X,E10.3,20X))/
     +     ,LYAN2/30H(15X,1PE10.3,3(4X,2E10.3,10X))/
     +     ,LYAN3/26H(15X,1PE10.3,3(4X,3E10.3))/
      IF(ICAL.NE.1) GO TO 10
      IF(IDOUT.EQ.1) GO TO 100
   10 CONTINUE
      IF(INUC.EQ.2) GO TO 20
      IF(INUC.EQ.3) GO TO 30
      WRITE(6,LISA1) TZ,CNA(1),CNB(1)
      RETURN
   20 WRITE(6,LISA2) TZ,(CNA(I),I=1,2),(CNB(I),I=1,2)
      RETURN
   30 WRITE(6,LISA3) TZ,(CNA(I),I=1,3),(CNB(I),I=1,3)
      RETURN
  100 CONTINUE
      IF(INUC.EQ.2) GO TO 120
      IF(INUC.EQ.3) GO TO 130
C      WRITE(6,LYAN1) TZ,CNA(1),CNB(1),CNC(1)
      WRITE(6,LYAN1) TZ,CNA(1),CNB(1),CND(1)
      RETURN
C 120 WRITE(6,LYAN2) TZ,(CNA(I),I=1,2),(CNB(I),I=1,2),(CNC(I),I=1,2)
  120 WRITE(6,LYAN2) TZ,(CNA(I),I=1,2),(CNB(I),I=1,2),(CND(I),I=1,2)
      RETURN
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C  130 WRITE(6,LYAN3) TZ,(CNA(I),I=1,3),(CNB(I),I=1,3),(CNC(I),I=1,3)
   130 WRITE(6,LYAN3) TZ,(CNA(I),I=1,3),(CNB(I),I=1,3),(CND(I),I=1,3)
       RETURN
       END
       SUBROUTINE TITLE1(INUC,IREL,ICAL,IDIN,CNX)
       COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
       COMMON/CAL3/ ANAME(3),AT(3),COEFK(3),CURIN(3),HLIFE(3),PR(3)
      +            ,RCGW(3),DIF,VEL,FLW, TS,T1,Z1,IT,IZ
       DIMENSION A(3),B(2),D(2),CNX(3),F(2)
       DATA A(1),A(2),A(3),B(1),B(2),D(1),D(2)/7HBAND RL,7HEXP  RL,7HPREF
      + RL,7HFIXED Z,7HFIXED T,7H(CI/M3),7H (N/M3)/
       DATA F(1),F(2)/7HSOURCE ,7HCONC. B/
       WRITE(6,600) INUC
   600 FORMAT(1H1,//////40X,*--- MIGRATION OF *,I1,*-MEMBER CHAIN THRU A
      +SORBING MEDIUM ---*,///55X,*--- INPUT DATA ---*)
       WRITE(6,601) VEL,DIF,FLW
   601 FORMAT(//40X,*1. HYDRO DATA*,//55X,*VELOCITY DISPERSN  FLOWRATE*,/
      +57X,*(M/Y)      (M2/Y)       (M3/Y)*,//55X,1PE8.2,2(2X,E8.2))
       WRITE(6,602) A(IREL),TS
   602 FORMAT(//40X,*2. RELEASE DATA*,//55X,*RELEASE MODE  *,A7,/55X,*LEA
      +D TIME  *,1PE8.2,*  (Y)*)
       C= B(1)
       IF(ICAL.NE.1) C= B(2)
       G= F(1)
       IF(IBC.EQ.1) G= F(2)
       WRITE(6,603) C,G,T1,IT,Z1,IZ
   603 FORMAT(//40X,*3. CALCULATION DATA*,//55X,A7,8X,A7,*CONDITION*,
      +//55X,*T FROM *,1PE8.2,* (Y)    TO X10--*,I1,/55X,*Z FROM *,
      +E8.2,*  (M)    TO X10--*,I1)
       WRITE(6,604) (ANAME(I),HLIFE(I),R(I),COEFK(I),V(I),I=1,INUC)
   604 FORMAT(//40X,*4. NUCLIDES DATA*,//20X,*NUCLIDE*,6X,*HALF LIFE*,6X,
      +*DECAY CST*,6X,*KI VALUE*,7X,*VELOCITY*,/22X,*(-)*,11X,*(Y) *,10X,
      +*(1/Y)*,10X,*(-)*,12X,*(M/Y)*,/3(20X,A7,1P4E15.3,/))
       E= D(1)
       IF(IDIN.NE.1) E= D(2)
       WRITE(6,605) E,E,(ANAME(I),CURIN(I),CNX(I),PR(I),RCGW(I),I=1,INUC)
   605 FORMAT(//20X,*NUCLIDE*,6X,*CONC.  IN*,6X,*CONC.  ST*,6X,*LEACHTIME
      +*,6X,*RCG WATER*,/22X,*(-)*,11X,A7,8X,A7,8X,*(Y)*,11X,*(CI/M3)*,/3
      +(20X,A7,1P4E15.3,/))
       WRITE(6,606)
   606 FORMAT(1H1)
       RETURN
       END
       SUBROUTINE TITLE2(ICAL,IDOUT,TZ)
       COMMON/CAL3/ ANAME(3),AT(3),COEFK(3),CURIN(3),HLIFE(3),PR(3)
      +            ,RCGW(3),DIF,VEL,FLW,TS,T1,Z1,IT,IZ
       DATA A,B/5H   T=,5H   Z=/
       C= A
       IF(ICAL.EQ.1) C= B
       IF(IDOUT.EQ.1) GO TO 10
       WRITE(6,650) C,TZ,(ANAME(I),I=1,3),(ANAME(I),I=1,3)
       RETURN
    10 WRITE(6,650) C,TZ,(ANAME(I),I=1,3),(ANAME(I),I=1,3)
      +,(ANAME(I),I=1,3)
       RETURN
   650 FORMAT(///A5,1PE10.3,14X,3(2X,A7,1X),4X,3(2X,A7,1X)
      +,4X,3(2X,A7,1X))
       END
       SUBROUTINE GAUSS(FNM,A,B,Q)
       Q= 0.
       AB= (A+B)/2.
       BA=  B-A
C
C      10 POINT GAUSSIAN-LEGENDRE QUADRATURE FORMULA
C
       C= .4869533*BA
       Q= .03333567*(FNM(AB+C)+FNM(AB-C))
       C= .4325317*BA
       Q= Q+.07472567*(FNM(AB+C)+FNM(AB-C))
       C= .3397048*BA
       Q= Q+.1095432*(FNM(AB+C)+FNM(AB-C))
       C= .2166977*BA
       Q= Q+.1346334*(FNM(AB+C)+FNM(AB-C))
       C= .07443717*BA
       Q= Q+.1477621*(FNM(AB+C)+FNM(AB-C))
       Q= Q*BA
       RETURN
       END
       SUBROUTINE ESYM(W,S,X,Y,ANS)
       COMMON/CAL2/GS(3,3,3),BT(3,3),R(3),V(3),FK,XG,ZZ,IBC,IER,BB,TT,XT
       PHI=ACOS(-1.)
       SUM1=0.
       SUM2=0.
       N=1
       IF(IBC.EQ.0)THEN
       COE1=-SIN(S)
       COE2=COS(S)
       ELSE
       COE1=COS(S)
       COE2=SIN(S)
       END IF
       ANSS=0.
    70 SUM1=SUM1+FUNR(N,X)*FUNF(N,X,Y,W)
       SUM2=SUM2+FUNR(N,X)*FUNG(N,X,Y,W)
       IF(ABS(X).LT.1.E-30) THEN
       ANS=2.*EXP(W)*(COE1+COE2*Y/PHI)-2.*SUM1*FUNV(X)*COE1+
      *2.*SUM2*FUNV(X)*COE2
       ELSE
       IF(ABS(X).LT.0.5) THEN
       XXX=1.-ERFS(X)
       ELSE
       XXX=ERFL(X)*EXP(-X**2)
       END IF
       ANS=2.*EXP(W)*COE1*(XXX-FUNU(X)*(1.-COS(2.*X*Y)))-
      *2.*COE1*FUNV(X)*SUM1+2.*EXP(W)*COE2*FUNU(X)*SIN(2.*X*Y)
      *2.*COE2*FUNV(X)*SUM2
       END IF
       IF (ABS(ANS).LT.1.E-100) GO TO 80
       AAA=(ANS-ANSS)/ANS
       IF (ABS(AAA).LT.1.E-16) GO TO 60
       ANSS=ANS
       N=N+1
       GO TO 70
    80 ANS=0.
    60 RETURN
       END
       FUNCTION FUNF(N,X,Y,W)
       FLN=FLOAT (N)
       PP=EXP(W+FLN*Y-FLN**2/4.)
       QQ=EXP(W-FLN*Y-FLN**2/4.)
       FUNF=2.*X*EXP(W-FLN**2/4.)-X*COS(2.*X*Y)*(PP+QQ)
      *+FLN*SIN(2.*X*Y)*(PP-QQ)
       RETURN
       END
       FUNCTION FUNG(N,X,Y,W)
       FLN=FLOAT(N)
       PP=EXP(W+FLN*Y-FLN**2/4.)
       QQ=EXP(W-FLN*Y-FLN**2/4.)
       FUNG=X*SIN(2.*X*Y)*(PP+QQ)+FLN*COS(2.*X*Y)*(PP-QQ)
       RETURN
       END
       FUNCTION FUNR(N,X)
       FLN=FLOAT(N)
       FUNR=1./(FLN**2+4.*X**2)
       RETURN
       END
       FUNCTION FUNU(X)
       PHI=ACOS(-1.)
       IF(X.EQ.0.)GO TO 5
       FUNU=EXP(-X**2)/(2.*PHI*X)
       RETURN
     5 FUNU=1.E99
       RETURN
       END
       FUNCTION FUNV(X)
       PHI=ACOS(-1.)
       FUNV=2.*EXP(-X**2)/PHI
       RETURN
       END
[EOR]
 1 1 1 1 1 1 1 5
   C-14 5.73E039.79E+04      1.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1     350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
  TC-99 2.15E059.10E+05      4.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1     350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
  I-129 1.59E072.31E+03      1.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1     350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
  NI-59 8.00E042.10E+03   1000.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1     350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
 CS-135 3.00E061.89E+04   2900.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 9.10E01
1     350. 1.87E09
5  9     100.
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```
1 10     250.
 1 1 1 1 1 1 1 5
 SN-126 1.00E053.35E+04  1700.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
  ZR-93 9.50E051.19E+05  5000.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
1 1 1 1 1 1 1 5
 SR-90 2.90E013.63E+09   530.0 3.0E-05 5.60E08
1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 1 1 1 1 1 1 5
 CS-137 3.00E015.25E+09  2900.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 CM-244 1.76E016.30E+07  1800.0 3.0E-05 5.60E08
 PU-240 6.58E033.14E+07   640.0 3.0E-05 5.60E08
  U-236 2.39E071.53E+04    19.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 PU-240 6.58E033.14E+07   640.0 3.0E-05 5.60E08
  U-236 2.39E071.53E+04    19.0 3.0E-05 5.60E08
 TH-232 1.40E107.70E-06  5300.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 CM-245 9.30E031.26E+04  1800.0 3.0E-05 5.60E08
 NP-237 2.44E062.17E+04    71.0 3.0E-05 5.60E08
  U-233 1.62E052.65E+00    19.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 NP-237 2.44E062.17E+04    71.0 3.0E-05 5.60E08
  U-233 1.60E052.65E+00    19.0 3.0E-05 5.60E08
 TH-229 7.34E031.96E-03  5300.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
  U-234 2.47E055.18E+03    19.0 3.0E-05 5.60E08
 TH-230 8.40E042.87E-01  5300.0 3.0E-05 5.60E08
 RA-226 1.60E035.18E-04  9000.0 3.0E-05 5.60E08
 1 1 1 1 1
   100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
  CM-246 5.50E032.45E+03  1800.0 3.0E-05 5.60E08
  PU-242 3.79E051.12E+05   640.0 3.0E-05 5.60E08
   U-238 4.51E092.24E+04    19.0 3.0E-05 5.60E08
  1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
   U-238 4.51E092.24E+04    19.0 3.0E-05 5.60E08
  TH-230 8.40E042.87E-01  5300.0 3.0E-05 5.60E08
  RA-226 1.60E035.18E-04  9000.0 3.0E-05 5.60E08
  1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 AM-243 7.95E039.81E+05  1800.0 3.0E-05 5.60E08
 PU-239 2.44E042.03E+07   640.0 3.0E-05 5.60E08
  U-235 7.10E081.12E+03    19.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
 1 3 1 1 1 1 1 5
 PU-239 2.44E042.03E+07   640.0 3.0E-05 5.60E08
  U-235 7.10E081.12E+03    19.0 3.0E-05 5.60E08
 PA-231 3.25E043.71E+02   641.0 3.0E-05 5.60E08
 1 1 1 1 1
    100. 2.5E-02 3.04E02
1    350. 5.60E08
5  9     100.
1 10     250.
99
5 MM/YR PATH 1
 1 1 1 1 1 1 1 5
   C-14 5.73E039.79E+04     1.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  TC-99 2.15E059.10E+05     7.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  I-129 1.59E072.31E+03     1.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  NI-59 8.00E042.10E+03  2000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 CS-135 3.00E061.89E+04  5800.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 SN-126 1.00E053.35E+04  3400.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  ZR-93 9.50E051.19E+05 10000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  SR-90 2.90E013.63E+09  1100.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 CS-137 3.00E015.25E+09  5800.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 CM-244 1.76E016.30E+07  3600.0 3.0E-05 1.87E09
 PU-240 6.58E033.14E+07  1300.0 3.0E-05 1.87E09
  U-236 2.39E071.53E+04    37.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1    350. 1.87E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
```

```
PU-240 6.58E033.14E+07  1300.0 3.0E-05 1.87E09
 U-236 2.39E071.53E+04    37.0 3.0E-05 1.87E09
TH-232 1.40E107.70E-06 12000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
CM-245 9.30E031.26E+04  3600.0 3.0E-05 1.87E09
NP-237 2.44E062.17E+04   140.0 3.0E-05 1.87E09
 U-233 1.62E052.65E+00    37.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
NP-237 2.44E062.17E+04   140.0 3.0E-05 1.87E09
 U-233 1.62E052.65E+00    37.0 3.0E-05 1.87E09
TH-229 7.34E031.96E-03 12000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
 U-234 2.47E055.18E+03    37.0 3.0E-05 1.87E09
TH-230 8.40E042.87E-01 12000.0 3.0E-05 1.87E09
RA-226 1.60E035.18E-04 18000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
CM-246 5.50E032.45E+03  3600.0 3.0E-05 1.87E09
PU-242 3.79E051.12E+05  1300.0 3.0E-05 1.87E09
 U-238 4.51E092.24E+04    37.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
 U-238 4.51E092.24E+04    37.0 3.0E-05 1.87E09
TH-230 8.40E042.87E-01 12000.0 3.0E-05 1.87E09
RA-226 1.60E035.18E-04 18000.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
AM-243 7.95E039.81E+05  3600.0 3.0E-05 1.87E09
PU-239 2.44E042.03E+07  1300.0 3.0E-05 1.87E09
 U-235 7.10E081.12E+03    37.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
PU-239 2.44E042.03E+07  1300.0 3.0E-05 1.87E09
 U-235 7.10E081.12E+03    37.0 3.0E-05 1.87E09
PA-231 3.25E043.17E+02  1301.0 3.0E-05 1.87E09
 1 1 1 1 1
    100. 1.0E-02 9.10E01
1   350. 1.87E09
5 9    100.
1 10   150.
99
5 MM/YR PATH2
 1 1 1 1 1 1 1 5
  C-14 5.73E039.79E+04      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
 TC-99 2.15E059.10E+05      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
 I-129 1.59E072.31E+03      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
 NI-59 8.00E042.10E+03      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
CS-135 3.00E061.89E+04      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
SN-126 1.00E053.35E+04      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
 ZR-93 9.50E051.19E+05      1.1 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
 SR-90 2.90E013.63E+09      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 1 1 1 1 1 1 5
CS-137 3.00E015.25E+09      1.0 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
CM-244 1.76E016.30E+07    1.001 3.0E-05 4.68E08
PU-240 6.58E033.14E+07    1.002 3.0E-05 4.67E08
 U-236 2.39E071.53E+04    1.003 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
PU-240 6.58E033.14E+07    1.002 3.0E-05 4.67E08
 U-236 2.39E071.53E+04    1.003 3.0E-05 4.67E08
TH-232 1.40E107.70E-06    1.100 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
CM-245 9.30E031.26E+04    1.001 3.0E-05 4.67E08
AM-241 4.58E021.12E+08    1.003 3.0E-05 4.67E08
NP-237 2.44E062.17E+04    1.002 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
AM-241 4.58E021.12E+08    1.003 3.0E-05 4.67E08
NP-237 2.44E062.17E+04    1.002 3.0E-05 4.67E08
 U-233 1.62E052.65E+00    1.001 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
NP-237 2.44E062.17E+04    1.002 3.0E-05 4.67E08
 U-233 1.62E052.65E+00    1.003 3.0E-05 4.67E08
TH-229 7.34E031.96E-03    1.100 3.0E-05 4.67E08
 1 1 1 1 1
    100. 4.0E+00 3.64E02
1   350. 4.67E08
5 9    100.
1 10   150.
 1 3 1 1 1 1 1 5
AM-242 1.52E027.04E+05    1.001 3.0E-05 4.67E08
PU-238 8.60E011.27E+08    1.002 3.0E-05 4.67E08
 U-234 2.47E055.18E+03      1.0 3.0E-05 4.67E08
 1 1 1 1 1
```

```
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 PU-238 8.60E011.27E+08    1.002 3.0E-05 4.67E08
  U-234 2.47E055.18E+03      1.0 3.0E-05 4.67E08
 TH-230 8.40E042.87E-01      1.1 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
  U-234 2.47E055.18E+03      1.0 3.0E-05 4.67E08
 TH-230 8.40E042.87E-01      1.1 3.0E-05 4.67E08
 RA-226 1.60E035.18E-04      1.2 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 CM-246 5.50E032.45E+03    1.000 3.0E-05 4.67E08
 PU-242 3.79E051.12E+05    1.001 3.0E-05 4.67E08
  U-238 4.51E092.24E+04    1.002 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 PU-242 3.79E051.12E+05    1.001 3.0E-05 4.67E08
  U-238 4.51E092.24E+04      1.0 3.0E-05 4.67E08
 TH-230 8.40E041.94E-10      1.1 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
  U-238 4.51E092.24E+04      1.0 3.0E-05 4.67E08
 TH-230 8.40E041.94E-10      1.1 3.0E-05 4.67E08
 RA-226 1.60E039.88E-09      1.2 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 AM-243 7.95E039.81E+05    1.001 3.0E-05 4.67E08
 PU-239 2.44E042.03E+07    1.002 3.0E-05 4.67E08
  U-235 7.10E081.12E+03    1.003 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 PU-239 2.44E042.03E+07    1.002 3.0E-05 4.67E08
  U-235 7.10E081.12E+03    1.003 3.0E-05 4.67E08
 PA-231 3.25E043.71E-01    1.001 3.0E-05 4.67E08
 1 1 1 1 1
     100. 4.0E+00 3.64E02
1     350. 4.67E08
5  9     100.
1 10     150.
99
4 MM/YR PATH 3
 1 1 1 1 1 1 1 5
   C-14 5.73E039.79E+04      1.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  TC-99 2.15E059.10E+05      7.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  I-129 1.59E072.31E+03      1.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  NI-59 8.00E042.10E+03   2000.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 CS-135 3.00E061.89E+04   5800.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 SN-126 1.00E053.35E+04   3400.0 3.0E-05 3.73E09
 1 1 1 1 1
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1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  ZR-93 9.50E051.19E+05  10000.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
  SR-90 2.90E013.63E+09   1100.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 1 1 1 1 1 1 5
 CS-137 3.00E015.25E+09   5800.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 CM-244 1.76E016.30E+07   3600.0 3.0E-05 3.73E09
 PU-240 6.58E033.14E+07   1300.0 3.0E-05 3.73E09
  U-236 2.39E071.54E+04     37.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 PU-240 6.58E033.14E+07   1300.0 3.0E-05 3.73E09
  U-236 2.39E071.54E+04     37.0 3.0E-05 3.73E09
 TH-232 1.40E107.70E-06  12000.0 3.0E-05 3.73E09
 1 1 1 1 1
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1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 CM-245 9.30E031.26E+04   3600.0 3.0E-05 3.73E09
 NP-237 2.44E062.17E+04    140.0 3.0E-05 3.73E09
  U-233 1.62E052.65E+00     37.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 NP-237 2.44E062.17E+04    140.0 3.0E-05 3.73E09
  U-233 1.62E052.65E+00     37.0 3.0E-05 3.73E09
 TH-229 7.34E031.96E-03  12000.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 CM-246 5.50E032.45E+03   3600.0 3.0E-05 3.73E09
 PU-242 3.79E051.12E+05   1300.0 3.0E-05 3.73E09
  U-238 4.51E092.24E+04     37.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
  U-234 2.47E055.18E+03     37.0 3.0E-05 3.73E09
 TH-230 8.40E042.87E-01  12000.0 3.0E-05 3.73E09
 RA-226 1.60E035.18E-04  18000.0 3.0E-05 3.73E09
 1 1 1 1 1
     100. 0.5E-02 4.55E01
1     350. 3.73E09
5  9     100.
1 10     150.
```

```
 1 3 1 1 1 1 1 5
  U-238 4.51E092.24E+04     37.0 3.0E-05 3.73E09
 TH-230 8.40E042.87E-01 12000.0 3.0E-05 3.73E09
 RA-226 1.60E035.18E-04 18000.0 3.0E-05 3.73E09
 1 1 1 1 1
    100. 0.5E-02 4.55E01
1    350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 AM-243 7.95E039.81E+05  3600.0 3.0E-05 3.73E09
 PU-239 2.44E042.03E+07  1300.0 3.0E-05 3.73E09
  U-235 7.10E081.12E+03    37.0 3.0E-05 3.73E09
 1 1 1 1 1
    100. 0.5E-02 4.55E01
```

```
1    350. 3.73E09
5  9     100.
1 10     150.
 1 3 1 1 1 1 1 5
 PU-239 2.44E042.03E+07  1300.0 3.0E-05 3.73E09
  U-235 7.10E081.12E+03    37.0 3.0E-05 3.73E09
 PA-231 3.25E043.71E+02  1301.0 3.0E-05 3.73E09
 1 1 1 1 1
    100. 0.5E-02 4.55E01
1    350. 3.73E09
5  9     100.
1 10     150.
99
0.5 MM/YR PATH2
```

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