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MATHEMATICAL ASPECTS OF THE YEAR 2000 RADIOLOGICAL STUDY

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The Year 2000 Radiological Study, a series of regional evaluations of radiological dose from nuclear facility operation, is based on a series of complex, interlinked computer codes designated as the HERMES model. These codes are used to model the release, environmental transport, biological uptake, and resulting radiological dose to regional populations which result from operation of large numbers of nuclear facilities within a region. Characteristics of these computer codes, and their application to specific regional studies, are described.

INTRODUCTION

The Year 2000 Radiological Study, performed for the U. S. Atomic Energy Commission by the Hanford Engineering Development Laboratory, comprises a series of regional evaluations of potential radiological dose in the year 2000 resulting from utilization of nuclear facilities for power generation. The first regional study, completed in 1972, considered the region including the Upper Mississippi and Lower Missouri river basins (1). A second study, now underway, considers the Tennessee and Cumberland river valleys. This Tennessee Valley Region Study is being performed in cooperation with Oak Ridge National Laboratory, the Tennessee Valley Authority, and the National Oceanic and Atmospheric Administration.

DESCRIPTION OF COMPUTER MODEL

The Year 2000 Radiological Study utilizes a set of computer codes, called HERMES (1). These codes are designed to assess the radiological impact on a regional population from normal operation of the projected nuclear industry in the year 2000. There are four separate code elements in HERMES that together comprise the simulators for the generation, transport and impact of a radionuclide emission inventory within a study region.

SOURCE MAP

The first code element of this group assembles and correlates information, from hand prepared data banks, to produce a monthly mean nuclide inventory emitted to the atmosphere and regional waterways. These data consider plant type, age,operating factor and scheduled maintenance down time. The output data banks also include information for use in the other codes such as; nuclide symbols, half life, plant location, startup time, stack height, etc.

AIR TRANSPORT

The second code element, the air transport simulator, calculates the regional air concentrations, monthly surface deposition and long term surface buildup from the postulated atmospheric radionuclide emission inventory. These calculations are made for unique points within the region that are taken to represent the center of population density for a subelement of the region, denoted hereinafter as a "centroid". The centroidal areas are, in general, the counties in the region. The calculated data for the centroid are then assumed to be constant over the entire area designated by this point.

The air transport simulator is based upon the Gaussian plume model first suggested by Chamberlain and enhanced by Pasquill. The particular form of equation chosen for this study is that given in Meteorology and Atomic Energy (2) for long-term average concentrations from a single continuous point.

$$\bar{\chi}_{\text{long term average/sector}} = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{0.01\, f\, \dot{Q}}{\sigma_z\, \bar{u}\, (2\pi x/n)} \left(\frac{Q_x}{Q_o}\right)_d \exp\left(-\lambda_r \frac{x}{\bar{u}}\right) \exp\left(\frac{-(h+\Delta h)^2}{2\sigma_z^2}\right) \qquad (1)$$

where

$\bar{\chi}$ = average air concentration
f = percent frequency with which wind blows from a given sector
$2\pi x/n$ = sector width for each of n sectors at distance x.
$\dot{Q}$ = long term average emission rate
σ_n = long term average standard deviation of vertical distribution of pollutant
$\bar{u}$ = long term average wind speed
$(Q_x/Q_o)_d$ = suspension ratio for particulate plume elements
λ_r = disintegration constant for nuclide being considered
$x/\bar{u}$ = travel time
h = emission elevation
Δh = thermally induced plume rise

The factor f is evaluated for six thermal stability categories and six wind speed groupings for each of 16 sectors for use in the code. These data are derived from analysis of weather records of the National Oceanic and Atmospheric Administration (NOAA) stations in and around the region. The technique for analysis was presented by Turner (3) in 1964. This analysis scheme considers the solar altitude, cloud cover and wind speed to categorize the data by Pasquill (4) stability classes. The σ_z factor is evaluated, as a function of downwind distance and stability class by

- graphical means (0 to 2.5 Km)
- $\sigma_z = 1000\ ax^b$ (2.5 to 70 Km)
- σ_z = mixing layer depth (> 70 Km).

The factor h is defined for each plant type in the data from the first code elements of HERMES. The Δh factor (thermally induced plume rise) is determined as a function of stability and wind speed by methods suggested by Briggs (5). The code contains provisions for modifying the $2\pi x/n$ factor to permit an accounting for air flow within the confines of a valley.

The plume losses due to dry deposition to the underlying surface are accounted for, as a function of thermal stability, wind speed, and distance, by depleting the source term (for particulate matter) by the suspension ratio

$$\left(\frac{Q_x}{Q_o}\right)_d = \exp\left[\int_0^x \frac{dx}{\sigma_z \exp(h^2/2\sigma_z{}^2}\right]^{-\left(\frac{2}{\pi}\right)^{\frac{1}{2}} Vd/\bar{u}} . \qquad (2)$$

This equation is presolved for an initial set of conditions for Vd (the deposition velocity) and $\bar{u}$, different suspension ratios may then be easily found by

$$\left(\frac{Q_x}{Q_o}\right)_a^{(Vd/\bar{u})_b} = \left(\frac{Q_x}{Q_o}\right)_b^{(Vd/\bar{u})_a} . \qquad (3)$$

Horst (6) has shown that an alternative "surface depletion" method of calculating the plume depletion via dry deposition may more nearly represent the actual physical conditions. There is, however, some significant computational time involved when a great many calculations are being made. It is not evident that the slight increase in computational accuracy that would be achieved is worth the added cost when all of the other assumptions associated with a regional study are considered.

Plume depletion processes attributable to monthly precipitation event statistics are calculated. The mechanism employed to simulate this phenomenon is an adaptation of the material given in Meteorology and Atomic Energy, (2) under the authorship of Engelmann, pages 208-220. An expression, given in Equation (4), was derived to fit the mid-point values of the rainfall/washout coefficient curves given in Figures 5.10 of the cited reference.

$$\Lambda = \exp^{(ln\ R*C1\ +\ C2)} \qquad (4)$$

where

Λ = below cloud washout coefficient
R = precipitation rate
C1 = 0.60206
C2 = 7.6009

This equation is evaluated for the appropriate monthly mean precipitation rates, as a function of sector, stability and wind speed. This coefficient is added to another constant 3×10^{-5} which provides an approximation of the plume depletion coefficient for in-cloud scavenging. These depletion factors are applied to the plume by the expression

$$WD = \exp^{-(\lambda_w + \lambda_c)t_p} . \quad (5)$$

where

WD = wet plume depletion
λ_w = below-cloud coefficient
λ_c = in-cloud coefficient
t_p = time of precipitation events

The plume losses due to radioactive decay during transit from source to receptor are given by the exponential $\exp^{-\lambda_r t}$. There is a potential that, during this time period, the radioactive decay processes that occur may produce daughter products (within the radionuclide inventory being considered). This factor is considered in the code, where appropriate, by

$$N_2 = N_1{}^o \frac{\lambda_{r1}}{\lambda_{r2} - \lambda_{r1}} \left[\exp^{-\lambda_{r2}t} - \exp^{\lambda_{r2}t}\right] . \quad (6)$$

where

N = number of atoms and the subscripts 1 and 2 refer to parent and daughter nucleus.

Every source point has a potential for contributing to the average air concentration at every centroid and each of these cases must be considered. However, it is also intuitively obvious that the available travel time $\bar{u}/x$ may be greater than the time available from a consideration of the percent of time the wind is blowing from the proper sector, f, (which is a function of stability and wind speed categorization). A check in the code is made for this factor and a jump to the next calculational case is made if the test is negative. Each case where all conditions are satisfied for calculation of air concentration from a source point at a centroid will have an effective time of residence (dwell time) at that centroid, i.e., Dwell time = Time available - Travel time. The calculated instantaneous air concentrations for each centroid are weighted by the "dwell time" to give a time weighted monthly mean as a function of source contribution.

The wet and dry plume depletion processes referenced above are assumed to be active through the entire travel path of the pollutant plume. At each centroid a calculation is made to estimate the mean monthly surface deposition for that location. This calculation employs adaptations of the techniques referenced above. The time parameter used in this case is the "dwell time" previously defined. The calculated values, for a centroid point (m^2), are assumed to be representative of the surface deposition over the entire subregion represented by that point. There is a potential for some error in this calculational scheme. However, it is believed that any gains in accuracy provided by a scheme such as using many more calculational points and then taking some sort of mean would not materially change the results.

The mean monthly nuclide surface depositions must, over a period of years, result in a buildup in concentration as a function of radionuclide half life and solubility ratio. The code calculates an estimate of this long-term factor by considering that each month's deposits represent an approximation of the monthly deposition for any prior year. These monthly mean values are then iteratively considered to be deposited then decayed and subjected to a wash-away fractionation for all prior years of operation of a plant complex.

WATER TRANSPORT

The third code subelement of the HERMES group is the water transport module. This code uses the data output from the two predecessor HERMES subelements to simulate the regional transport of radionuclide effluent injected into the waterways. The calculational routines in the water transport code are designed to utilize these data, and information categorizing the regional river characteristics, to provide concentrations of dissolved radionuclides and radionuclides adsorbed on sediments. In addition, concentrations of dissolved radionuclides are calculated for lakes fed by local runoff, shallow ground water recharged locally, and artesian ground water recharged from distant sources.

The water transport code calculational procedures first consider the regional rivers, then the ground water. Categorization of the river networks by segments (reaches) of discrete characteristics permits an orderly consideration of the entire system. Calculations are made for each reach to estimate the sediment load from

$$S = a\,Q^{b} . \qquad (7)$$

where

S = sediment load
Q = stream flow
a,b = empirically derived curve fitting parameters

Equation (8) may then be evaluated.

$$C_jS_jQ_j \simeq \left[C_oS_oQ_o \; e^{-\lambda_r t} + \sum_{1}^{n} C_iS_iQ_i + \frac{C_o \; e^{-\lambda_r t} + C_j^k}{2}\left(S_jQ_j - S_oQ_o - \sum_{1}^{n} S_iQ_i\right)\right] \qquad (8)$$

where

C = sediment adsorbed concentration of radionuclide
i = input
j = new value
k = an iterative value
n = number of input values
o = old value

Initial evaluation of Equation (8) is made by setting $C_j^{k=1}$, in the right hand member of Equation (8) to

$$C_j^{k=1} = \frac{1}{S_jQ_j}\left[C_oS_oQ_o \; e^{-\lambda_r t} + \sum_{1}^{n} C_iS_iQ_i\right]. \qquad (9)$$

If Equation (8) is satisfied to within 99 percent, the calculational procedures continue to the next reach. However, if a 99 percent agreement is not initially achieved, the code proceeds to obtain convergence to the desired result by iteratively obtaining a new value of C_j^k from the current value of the product $C_jS_jQ_j$ and substituting this in the right hand member of Equation (8). The net result of this is the derivation of a value for either scour or deposition of adsorbed radionuclide concentrations as given by

$$\Lambda = \frac{C_o + C_j^k}{2} \left[S_j Q_j - \left(\sum_1^n S_i Q_i + S_o Q_o \right) \right] . \quad (10)$$

where

Λ = scour or deposition of sediment (a negative value indicates deposition).

The dissolved radionuclide burden for the river is obtained by use of a "distribution coefficient" (K_d) that represents the adsorbed to solute ratio characteristic of the particular reach and radionuclide being considered. Values for K_d are obtained by analysis of bed sediment response to introduction of selected radionuclides and assuming that the same characteristics would apply to other chemically similar materials. If $K_d \neq 0$, the value for the radionuclide solute concentration is obtained from

$$C_w = \frac{C_j}{K_d} . \quad (11)$$

where

C_w = water concentration of nuclide.

For the radionuclide tritium, where both C_j and K_d are zero, this entire procedure is invalid and bypassed since this substance exists in the system as tritiated water, and the concentrations are calculated from

$$C_{w_j} = \frac{1}{Q_j} \left[C_{w_o} Q_o e^{-\lambda_r t} + \sum_1^n C_{w_i} Q_i \right] . \quad (12)$$

The data files that prescribe the radionuclide concentrations to the river ways in association with overland runoff are obtained by solution of

$$C_w = \frac{\sum_1^a F_M A}{Q(K_d S+1)} . \quad (13)$$

where

F = surface deposition of radionuclides from the atmosphere per unit area
P = precipitation rate
A = centroidal area
R = annual runoff
M = monthly average
Y = annual average
a = summation over all pertinent centroidal areas

These data are injected into the rivers at the physical locations where the natural drainage outfall occurs.

The composite of the above calculations are then correlated with descriptive data for the river drinking water source and recreation points to provide output files of dissolved and suspended radionuclide concentrations and river bed radionuclide concentrations.

The groundwater radionuclide concentrations are defined for each centroid, where the drinking water source is not the river system, by

$$C_W = \frac{F_M}{P_M \frac{R}{P_Y} (K_d + 1)} \quad . \qquad (14)$$

DOSE

Radiological dose evaluations are calculated using the radionuclide concentration output files from the Air Transport and Water Transport codes and a data file giving a demographic description of the study region. The code evaluates the various pathways that can lead to population dose, and calculates the radiation dose and dose commitment to eight population groups. In addition, the integrated population dose (man-rems/year) and 50 year dose commitment for the study region are calculated. The dose rate used is defined as:

- The summation of 12 monthly exposure values. The external exposure is a monthly calculation and the internal exposure includes contributions from each month's internal disposition for the study year.

The dose commitment is defined as:

- The long term contribution due to uptake during the study year (usually 2000). This value, termed the 50 year dose commitment was the dose an individual would be committed to during the following 50 years due to the body burden from radioactive material ingested during the study year.

The dose calculations do consider the accumulation over the previous years of long-lived radionuclides in the environs. Potential doses are calculated for internal and external whole body exposure and to six selected organs (skin, lungs, GI tract, bone, thyroid, and liver).

The regional population is divided into the following categories for this study:

- Infant (ages < 1)
- Child (age 1 to 11)
- Teenager (age 12 to 19)
- Adult (ages > 19) .

Integrated dose (man-rem) is the sum over all population segments considered of the products of the dose received by a person of that segment and the number of people in the segment.

Table 1 gives the several pathways for which dose calculations are made. Air and water concentrations in the environs are used directly to calculate dose to the various body organs from air inhalation, air submersion, water ingestion and water immersion. River sediment concentrations are used to calculate expected external exposure from fishing, hunting, picnicking, etc., along the river shoreline. Deposition from airborne plumes on farm lands and from irrigation practices are used to estimate external exposure received during hunting or farming. This deposition is also considered as a dose source term for animal food crops, animal products and other foods directly consumed by the population of the region.

External exposure dose factors (DF) are derived on the assumption that the contaminated environs have a sufficient volume that the dimensions thereof may be considered infinite with respect to the relative range of the radiation emissions. This assumption permits the development of an equivalence between the energy emitted per cc of media and the energy absorbed per cc of the media. Then a conversion of MeV per disintegration to rem with corrective factors for energy absorption between air or water and tissue plus the appropriate geometry.

The dose from air submersion is calculated from a consideration of 2π geometry. This choice of geometry is obvious for

TABLE I

Exposure Pathways and Foods

AIR SUBMERSION
TRITIUM TRANSPIRATION
AIR INHALATION
DRINKING WATER
SWIMMING
BOATING
EXPOSURE TO SOIL
EXPOSURE TO SHORELINE SILT
AQUATIC FOODS

- Sports Fish
- Waterfowl
- Fresh Ocean Fish
- Processed Ocean Fish
- Shell Fish
- Secondary Water

TERRESTRIAL FOODS

- Fresh Berries
- Processed Berries
- Fresh Tree Fruit
- Processed Tree Fruit
- Fresh Melons
- Fresh Potatoes
- Fresh Root Vegetables
- Processed Root Vegetables
- Fresh Green Leafy Vegetables
- Processed Green Leafy Vegetables
- Fresh Other Vegetables
- Grain and Grain Products
- Rice and Rice Products
- Wheat and Wheat Products
- Fresh Milk
- Milk Products
- Butter
- Beef and Lamb
- Fresh Pork
- Processed Pork
- Fresh Whole Eggs
- Poultry
- Upland Game Birds
- Fresh Citrus Fruit
- Processed Citrus Fruit
- Fresh Tropical Fruit
- Processed Tropical Fruit

gamma radiation. For beta, with the shorter ranges in air, the physical arrangement approaches a 4π geometry. However, since the beta radiation is of limited penetrating power, it will irradiate the skin from only one side, as opposed to the two sides of the much greater penetration power of gamma radiation. The DF for air submersion is calculated from

$$DF_{sub} = 8.87 \times 10^{-7} (\overline{E}_{\rho} + \overline{E}_{\gamma}) \ . \qquad (15)$$

where

E = effective energy per disintegration (MeV) at the appropriate tissue depth
β = beta radiation
λ = gamma radiation

The constant takes into account the density of air and MeV to rem conversion.

The dose from contaminated ground is attributed to a large nearly uniform thin sheet of deposited radionuclides from the air and/or irrigation practices. A standard height of one meter was selected as the appropriate point for calculation of dose factors. At this height only gamma radiation is considered important. A factor of 0.5 is included to estimate the effect of ground roughness and any small loss in heavy clothing. Similar considerations apply for river bank activities. The dose factor is calculated from

$$DF_{gnd} = (0.15)\ (0.869) \sum_{i=1}^{n} (A_i)(R_i)(P_i)\ . \tag{16}$$

where

A = fractional abundance of photons in the nuclide
R = exposure rate
P = fraction of surface dose which penetrates to a skin depth of 7×10^{-3} cm or total body depth of 5 cm.

Water immersion is considered to be a 4π problem for gamma radiation and a 2π problem for beta radiation following the general concepts stated for air submersion.

The dose factor is calculated from

$$DF_{wi} - 2.13 \times 10^{-6}\ (\bar{E}_{\gamma} + 1/2\ \bar{E}_{\beta}). \tag{17}$$

Inhalation dose is calculated by consideration of the air concentration, the breathing rate and an occupancy factor. The occupancy factor was derived by assuming that each person spends the large majority of his time in the centroid of residence.

The dose factor varies as a function of radionuclide, person type and organ. A separate factor is required for annual dose and dose commitment. For inhalation of soluble radionuclides, these dose factors are obtained by Equation (18).

$$DF_{\text{internal organ}} = \frac{0.074\ \varepsilon}{m}\ \tau_E^0\ f_a \left(1.\ -\ \exp\left(\frac{-0.693t}{\tau_E^0}\right)\right) \tag{18}$$

For inhalation of insoluble radionuclides and all internal organs except the longs, these dose factors are obtained by Equation (19).

$$DF_{\text{internal organ}} = \frac{0.0064\, f_2' \,\varepsilon\, \tau_E^o \,\tau_E^L}{\tau_B^L \, 0.4805\, m}\left[0.693t_1 - \tau_E^L - \tau_E^o + \left(\frac{(\tau_E^L)^2\, e^{\left(\frac{-0.693t_1}{\tau_E^L}\right)} \quad (\tau_E^o)^2\, e^{\left(\frac{-0.693t_1}{\tau_E^o}\right)}}{\tau_E^L - \tau_E^o}\right)\right] \tag{19}$$

Inhalation dose factors for GI tract-LLI are obtained by Equation (20).

$$DF_{\text{GI tract - LLI}} = \frac{0.0256\, \tau' \,\varepsilon\, f^*}{m} f_a \exp\left(\frac{-0.693\, t'}{T_R}\right) \tag{20}$$

where

ε = effective energy of a specific nuclide in a specific organ
f^* = fraction of nuclide escaping absorption in GI tract ahead of the long lower intestine (LLI)
f_2' = fraction of nuclide from blood reaching specific organ
f_a = fraction of nuclide reaching specific organ
τ_B^L = biological half-life of nuclide in lung
τ_E^o = effective half-life of nuclide in organ
τ_E^L = effective half-life of nuclide in lung
t = time of dose calculation
t_1 = time inhalation stops
T_R = radioactive half-life
t' = travel time from mouth to LLI
τ' = travel time through GI-LLI
m = mass of organ

Equations for ingestion dose factor are very similar to those for inhalation, i.e.

$$DF_{\text{internal organ}} = \frac{0.074\ \epsilon \tau_E^o\ f_w}{m} \left(1. - \exp\left(\frac{-0.693\ t}{\tau_E^o}\right)\right) \tag{21}$$

and

$$DF_{\text{GI-LLI}} = \frac{0.0256\ \epsilon\tau'}{m}\ f^* \left(\exp\left(\frac{-0.693\ t'}{T_R}\right)\right). \tag{22}$$

where

f_w = fraction of ingested nuclide reaching the organ

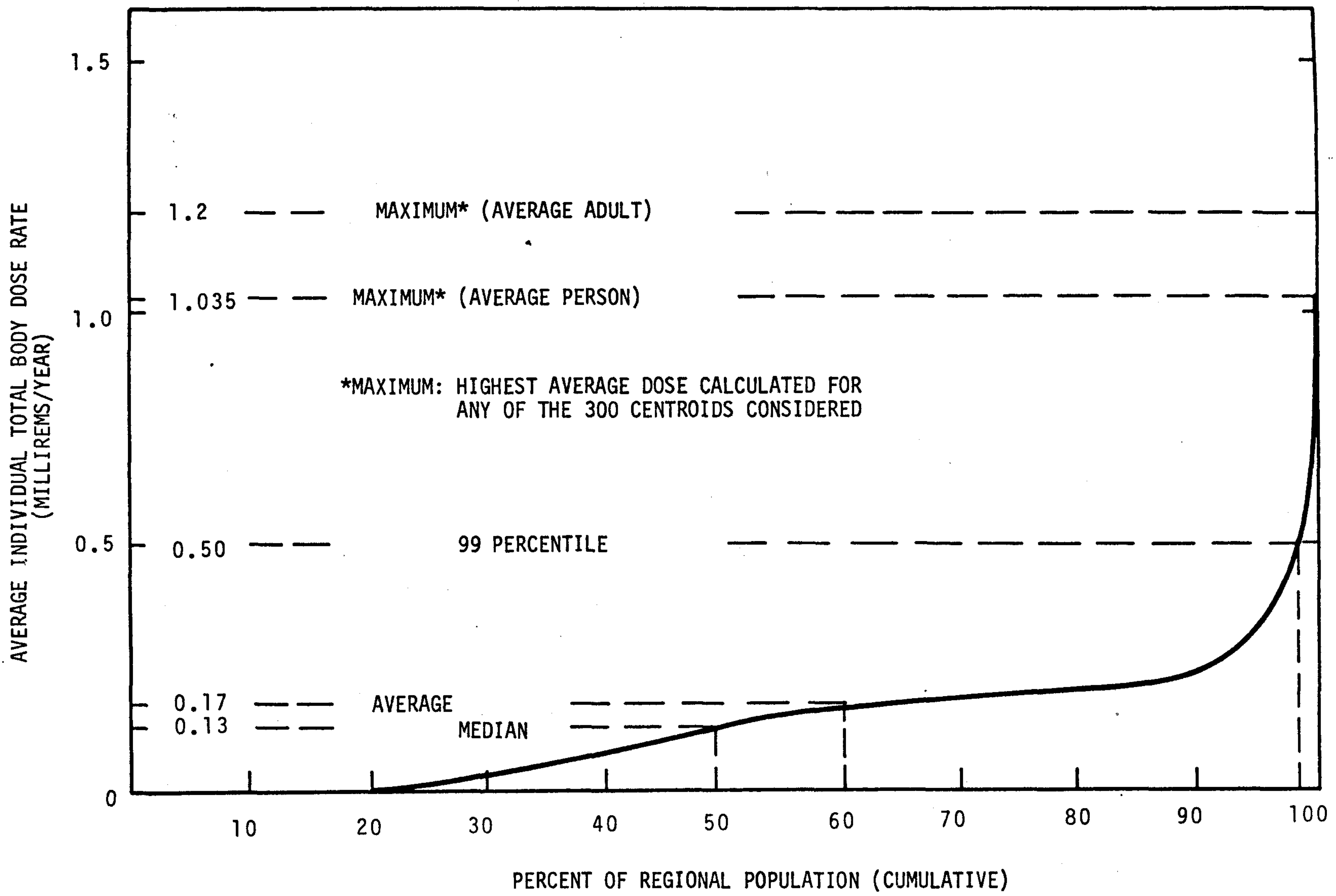
The linked codes in the HERMES computer model produce, as an end product, the estimated radiological dose to a regional population group as a result of the operation of nuclear facilities within the region and its immediate contiguous environs. The data files required for this evaluation are voluminous. It is then necessary to very carefully prescribe the data interfaces between the code elements. It is also necessary to be very careful in the ordering of the computational sequence in order that maximum utilization of the particular computer resources may be obtained to effect minimum processing time. The codes, as they are now structured,have versions that may be run on a UNIVAC 1108, CDC CYBER 74 and a CDC 7600. All of these codes differ slightly in the utilization factor but produce identical results.

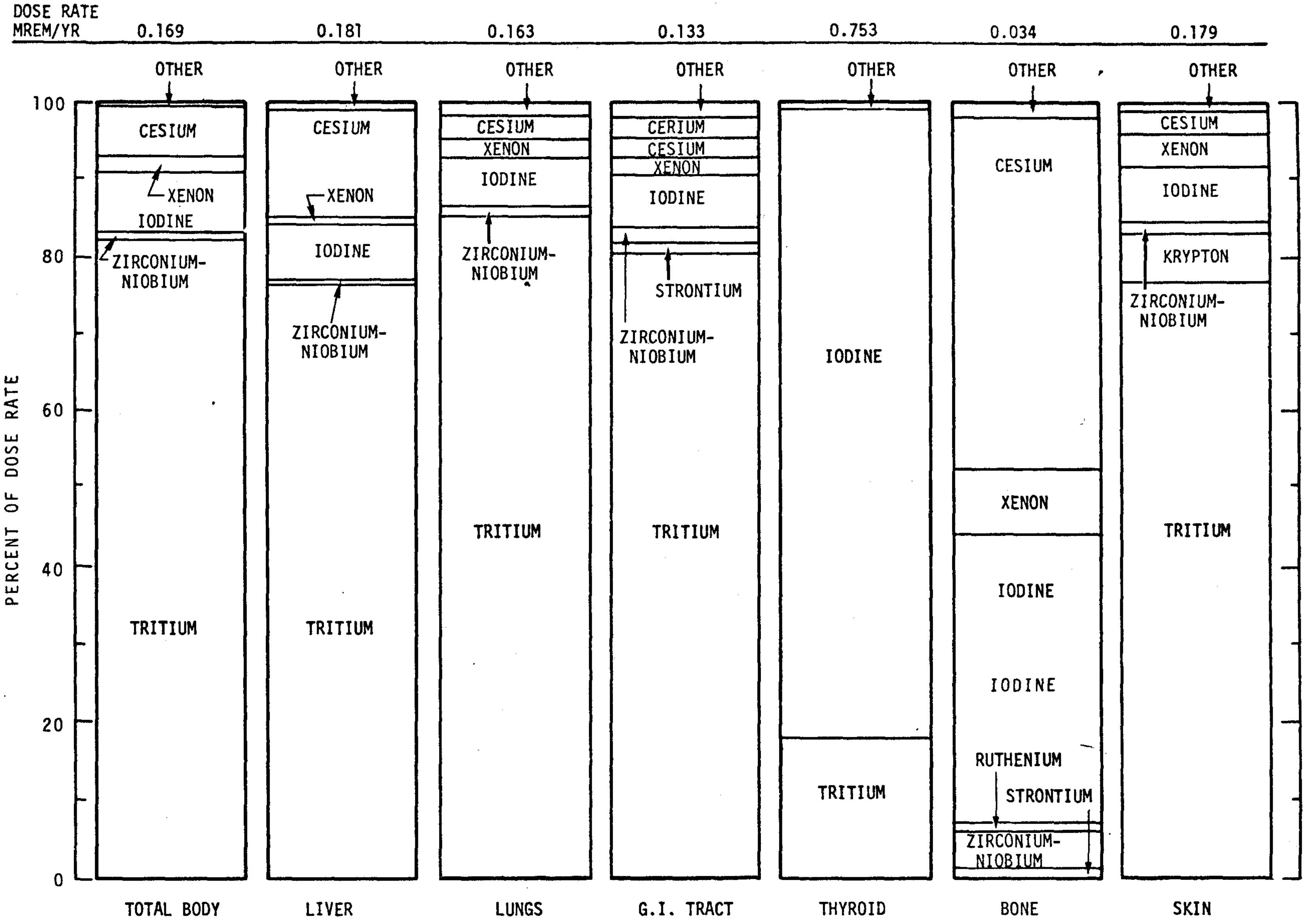
In common with most computer code study efforts, HERMES has undergone several changes since its inception. The current version is now being used to study the Tennessee Valley Region. However, the study of the Upper Mississippi River basin, performed using an earlier version of HERMES, indicated a distribution of dose rate resulting from operation of nuclear facilities as shown in Figure 1. The average dose indicated for the region was 0.17 millirems per year, and the highest average adult dose calculated for any of the 300 centroids included in the study was about 1.2 millirems per year. By comparison, the average dose rate from naturally occurring radioactivity in the region is about 150 millirems per year.

Of the approximately 50 radionuclides considered in the

Figure 1 - Distribution of Total-Body Radiation Received by the Population

Figure 2 - Contributions by Radionuclides (Average Individual)


AVERAGE INDIVIDUAL TOTAL BODY DOSE RATE (MILLIREMS/YEAR)
1.5
1.2
MAXIMUM* (AVERAGE ADULT)
1.035
1.0
MAXIMUM* (AVERAGE PERSON)
*MAXIMUM: HIGHEST AVERAGE DOSE CALCULATED FOR ANY OF THE 300 CENTROIDS CONSIDERED
0.5
0.50
99 PERCENTILE
0.17
AVERAGE
0.13
MEDIAN
0
10
20
30
40
50
60
70
80
90
100
PERCENT OF REGIONAL POPULATION (CUMULATIVE)


DOSE RATE
MREM/YR
0.169
0.181
0.163
0.133
0.753
0.034
0.179
PERCENT OF DOSE RATE
100
80
60
40
20
0
OTHER
CESIUM
XENON
IODINE
ZIRCONIUM-NIOBIUM
TRITIUM
OTHER
CESIUM
XENON
IODINE
ZIRCONIUM-NIOBIUM
TRITIUM
OTHER
CESIUM
XENON
IODINE
ZIRCONIUM-NIOBIUM
TRITIUM
OTHER
CERIUM
CESIUM
XENON
IODINE
STRONTIUM
ZIRCONIUM-NIOBIUM
TRITIUM
OTHER
IODINE
TRITIUM
OTHER
CESIUM
XENON
IODINE
IODINE
RUTHENIUM
STRONTIUM
ZIRCONIUM-NIOBIUM
OTHER
CESIUM
XENON
IODINE
KRYPTON
ZIRCONIUM-NIOBIUM
TRITIUM
TOTAL BODY
LIVER
LUNGS
G.I. TRACT
THYROID
BONE
SKIN

study, only a few calculated to contribute significantly to population dose. As is shown in Figure 2, tritium, iodine, and cesium were indicated as the major contributors to total body dose and to the various organ doses considered. The major pathways indicated to contribute to dose were air inhalation, transpiration of tritium and exposure to soil containing deposited radionuclides. The ingestion of foods and drinking water contributed significantly only to dose to thyroid and bone.

The calculated dose rates in all centroids were very small; dose patterns in the region, however, were strongly influenced by the location of fuel reprocessing plants, which were indicated as the major sources of tritium.

The general patterns of radiation dose incidence calculated in the Upper Mississippi River Basin are expected to be observed in the Tennessee Valley Region Study, although some difference will result both from differences in the physical characteristics of the two regions and from improvements in the HERMES model. Preliminary results from the Tennessee Valley Region calculations, however, strongly reinforce the conclusion of the Upper Mississippi regional study, that radiological dose from nuclear facility operation is negligible.

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