The Mesorad Dose Assessment Model

Vol. 1: Technical Basis

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FOREWORD

This report is the culmination of an extensive effort involving the NRC staff who may be called upon to respond to a radiological emergency situation and the NRC contractor, Pacific Northwest Laboratory. This report is divided into two volumes. Volume 1 discusses the theoretical and mathematical basis for the dispersion and dose calculations. Volume 2 describes the MESORAD computer code and includes flowcharts, program and variable listings, and sample input and output for use in checking the basic operation of the model. This effort represents a significant advancement in radiological assessment aids for use in near real-time operations. The MESORAD capability will continue to be enhanced to provide for added user flexibility as well as to account for advancements in the state-of-the-science.

MESORAD was developed as an emergency response tool that would be used by technically cognizant staff to assess the potential consequences of a radiological emergency situation. Care was taken with the documentation to present an unbiased description of the techniques in the model. The topic of the role of dose assessment and specifically the application of models as an aid in the protective action decision-making process was not addressed.

The modular nature of MESOI was specifically retained in MESORAD to provide users with the flexibility to adapt it to a particular location or application. Much interest has been expressed in MESORAD's utility as an accident assessment aid, as well as in its applicability to probabilistic risk and routine release assessments. The NRC staff believes that this capability can be broadly applied as long as the ultimate users recognize the uncertainties in the dose assessment process. For additional information, the reader is directed to NUREG/CR-3011 (G. Stoetzel et al., "Dose Projection Considerations for Emergency Conditions at Nuclear Power Plants") and NUREG/CR-3955 (J. Martin et al., "General Overview Training Manual for Nuclear Power Plant Incident Response") for a discussion of the role and limitations of dose assessments during severe accidents, and to NUREG/CR-3332 (J. Till and R. Meyer, Eds., "Radiological Assessment - A Textbook on Environmental Dose Analysis") for a generic discussion of dose assessment.

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ABSTRACT

MESORAD is a dose assessment model for emergency response applications. Using release data for as many as 50 radionuclides, the model calculates:

- external doses resulting from exposure to radiation emitted by radionuclides contained in elevated or deposited material,
- internal dose commitment resulting from inhalation,
- and total whole-body doses.

External doses from airborne material are calculated using semi-infinite and finite cloud approximations. At each stage in model execution, the appropriate approximation is selected after considering the cloud dimensions. Atmospheric processes are represented in MESORAD by a combination of Lagrangian puff and Gaussian plume dispersion models, a source depletion (deposition velocity) dry deposition model, and a wet deposition model using washout coefficients based on precipitation rates.

The programs are written primarily in FORTRAN 77 with some use of Digital Equipment Company VAX FORTRAN extensions. The graphics modules make use of DISSPLA graphics. All the programs were developed on a VAX 11/780 computer.

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EXECUTIVE SUMMARY

This report is divided into two volumes. This volume, Volume 1, describes the technical basis for the MESORAD dose assessment model. Volume 2 describes the MESORAD computer code. The MESORAD model was developed by Pacific Northwest Laboratory for use as a part of the Intermediate Dose Assessment System in the U.S. Nuclear Regulatory Commission's Operations Center in Washington D.C.; it is also used as a part of the Emergency Radiological Detection System at the U.S. Department of Energy's Hanford facilities in Washington State.

MESORAD is intended to be used for emergency response applications. Dose pathways represented in the model are those that are most likely to be important during and immediately following a release. The doses computed include: external dose resulting from exposure to radiation emitted by radionuclides in the air and deposited on the ground, internal dose commitment resulting from inhalation, and total whole-body dose. When executed on super-minicomputers, dose estimates can be obtained within 15 minutes.

In MESORAD, atmospheric dispersion and dose computations are made simultaneously. Atmospheric dispersion computations are made using available meteorological data and an advanced version of the MESOI atmospheric dispersion model. Dose computations are made on the basis of release data for as many as 50 radionuclides using a semi-infinite cloud approximation or finite puff model as appropriate. The finite puff model used in the dose computations is an approximation to the point-kernel integration technique used in other dose models and is a significant advance in the state-of-the-art in dose modeling. Using the finite puff model in place of the point-kernel integration, dose computation times have been reduced by a factor of about 100 with a reduction in accuracy of only about 1%.

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INTRODUCTION

MESORAD is a dose assessment model for emergency response applications. It was developed by Pacific Northwest Laboratory (PNL) for use as part of the Intermediate Dose Assessment System in the U.S. Nuclear Regulatory Commission (NRC) Operations Center in Washington, D.C. and is accessible to NRC staff at remote locations. It is also a part the Emergency Radiological Detection System at the U.S. Department of Energy's (DOE) Hanford site facilities in Washington State. The model is designed to be run in an interactive mode on super-minicomputers (for example, Digital Equipment Company VAX-11/780 and Data General MV-6000 computers). When MESORAD is run on these computers, dose estimates can be obtained within 15 minutes.

The MESORAD model was developed from Version 2.0 of the MESOI atmospheric dispersion model (Ramsdell, Athey and Glantz 1983), and MESOI can still be run within MESORAD. MESORAD, however, is more than a simple extension or add-on to MESOI. Dose assessment calculations occur simultaneously with the atmospheric dispersion and deposition calculations. In most atmospheric dispersion/dose assessment codes, the air and ground concentrations are integrated over the duration of a scenario, and these time-integrated concentrations are used for the dose calculations. In MESORAD, air and ground concentrations are calculated following each 15-minute time step, and these values are used for dose calculations. This technique of stepping through the scenario in short time increments allows the user to see the effects of plume movement and changes in dimensions and of other processes such as terrain interactions and removal processes as the scenario develops. Thus a MESORAD run can give decision-makers valuable information about the progression of an accident scenario.

MESORAD is intended to be used for emergency response applications to assess the actual or potential consequences of a radiological emergency condition. The consequences addressed by MESORAD are those that would occur in the immediate time frame of the release (a number of hours) rather than the extended time frame (days or weeks). The dose pathways included therefore are those that are likely to be most significant during the release itself, while most dose pathways that would be important in the long term after the release are not addressed.

Atmospheric processes are represented in MESORAD by a combination of Lagrangian puff and Gaussian plume dispersion models, a source depletion (deposition velocity) dry deposition model, and a wet deposition model using washout coefficients based on precipitation rates. Based on the calculated air and ground concentrations, MESORAD uses release data for as many as 50 radionuclides to determine external doses resulting from exposure to radiation

emitted by radionuclides contained in the elevated material or deposited on the ground, internal dose commitment resulting from inhalation and total whole-body dose.

This report describes the theoretical bases for the MESORAD model. The atmospheric process models included in MESORAD are generally the same as the models used in MESOI. As a result, the atmospheric model descriptions have been condensed from descriptions in the MESOI documentation (Ramsdell, Athey and Glantz 1983) where appropriate. Two extensions to MESOI and two modifications to algorithms in the MESOI code are described in more detail.

Although the atmospheric process models in MESORAD are described first for continuity, primary emphasis of the report is on the models used in dose calculations. The models used in MESORAD for the calculation of internal and external doses are consistent with currently accepted, state-of-the-art models. For the calculation of external dose resulting from exposure to the plume, there are two available models: a semi-infinite cloud approximation and a finite puff model. When the dimensions of a puff become large in comparison with the mean free paths of gamma radiation emitted from radionuclides in the puff, the external doses are computed using the semi-infinite cloud model. For other cases, the finite puff model is used.

MESORAD makes a major contribution to the state of the art in the calculation of external doses for the situation where the dimensions of the plume are not large when compared to the mean free path of gamma radiation. The technique, entitled the discrete-point approximation, was developed to replace point-kernel integration, the traditional technique for performing finite puff calculations. The discrete-point approximation provides a significant savings in computation time, running approximately 100 times faster than the point-kernel integration technique. For the situations present in MESORAD calculations, the two methods produce results typically agreeing within 1%. For near real time applications, the savings in computation time is essential, while the small disagreement is insignificant when compared to uncertainties in the source term and dispersion and dose computations.

MESORAD makes extensive use of external files for data input, although provisions have been made for manual data entry at run time. Data entered through external files include facility specific information such as terrain elevations and nuclide libraries and scenario specific information such as meteorological data and radionuclide release rate estimates. Separate utility programs, not described in this report, can be used to prepare the external files.

This report is divided into three major sections. The first section begins with a brief introduction to atmospheric dispersion models, and includes a discussion of the Gaussian equations as applied in a puff model. This is

followed by discussions of the diffusion, transport, and depletion processes as they are modeled in MESOI Version 2.0 and MESORAD Version 1.0.

The next section describes the enhancements made to the atmosphere model. These include a Gaussian plume model operating on a polar grid close to the source, interpolations of topographic data to fit differing model domain sizes, and an improved technique for estimation of the influence of terrain on the surface wind field.

The last major section of the report discusses the dose calculation models. Three dose pathways are described: external dose resulting from radiation emitted by radionuclides deposited on the ground, external dose resulting from radiation emitted by nuclides in the puff, and internal dose commitments resulting from the inhalation of radionuclides in the puffs. This section also describes the two different models used for calculating external dose: the semi-finite cloud approximation and the finite puff model, and concludes with a discussion of the limitations and uncertainties of the dose models.

This volume also contains four appendices. Appendix A is a discussion of the diffusion coefficient parameterizations used in the atmospheric models. Appendix B is a discussion of the derivation of dose factors used by MESORAD. The specific characteristics of the radionuclides used by MESORAD are listed in Appendix C, and Appendix D contains a brief description of minor modifications made to the MESOI Version 2.0 code which are incorporated in MESORAD.

ATMOSPHERIC PROCESS MODELS

When material is released to the atmosphere, it is dispersed freely. Small-scale atmospheric motions distribute material within plumes, while large-scale motions move plumes about. Atmospheric dispersion models attempt to describe the combined effects of these motions. Since atmospheric motions are random, dispersion models can only describe an average set of effects.

The starting point for development of a dispersion model is a differential equation called the diffusion equation. This equation and its solutions under very specific boundary and initial conditions are described in advanced mathematics texts. The conditions rarely exist in the atmosphere. However a number of approximate solutions, including the Gaussian diffusion models, have been applied to atmospheric diffusion problems with reasonable success. The derivation and application of atmospheric dispersion models is covered in specialized texts, for example Gifford (1968), Csanady (1973), and Pasquill (1979).

Among all the atmospheric dispersion models, the best known and most widely applied is the straight-line Gaussian plume model. When development of the MESOI dispersion model was begun, a Gaussian puff model was chosen over the straight-line model and other models because 1) it is easier to realistically represent spatial and temporal variations in atmospheric conditions in puff models than in straight-line models, and 2) Gaussian puff models retain much of the computational simplicity of straight-line Gaussian models.

One of the basic assumptions in puff models is that a continuous plume can be approximated by a finite number of puffs released in succession. The concentration at a receptor is assumed to be equal to the sum of the concentrations from all of the puffs, that is

$$\chi(x,y,z,t) = \sum_{i=1}^N \chi_i(x,y,z,t) \quad (1)$$

where χ = concentration

x,y,z = position of the receptor in Cartesian coordinates

t = time of the concentration estimate

i = puff index

N = total number of puffs

In practice, computational rules can be established to limit the number of terms included in the summation. How well the puff model approximates the

continuous plume model depends upon the ratio of puff dimensions to the separation between puffs. Increasing the number of puffs used to simulate a plume increases the accuracy of the puff approximation, but this increase is made at the expense of increased computational time.

In the absence of external influences such as the ground, the concentration within puffs in MESORAD is assumed to be Gaussian. With this assumption, the concentration at x, y, z at time, t , resulting from puff, i , is

$$\chi(x, y, z, t) = \frac{Q(t)}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left\{ -\frac{1}{2} \left[\left(\frac{x - x_0(t)}{\sigma_x} \right)^2 + \left(\frac{y - y_0(t)}{\sigma_y} \right)^2 + \left(\frac{z - z_0(t)}{\sigma_z} \right)^2 \right] \right\} \quad (2)$$

where $Q(t)$ = amount of material (radionuclide) in the puff at t
 $\sigma_x, \sigma_y, \sigma_z$ = diffusion coefficients that describe the spread of the puff in the along-wind, cross-wind, and vertical directions, respectively (referred to as sigma x, sigma y and sigma z).
 $x_0(t), y_0(t), z_0(t)$ = the coordinates of the center of the puff at t

The atmospheric modeling problem can now be divided into three parts. The first part is specifying the diffusion coefficients (i.e., modeling diffusion). The second part of the overall problem is specifying the position $x_0(t), y_0(t), z_0(t)$ (i.e., modeling transport). And, the third part is specifying $Q(t)$ (i.e., modeling depletion). The MESORAD models for each of these processes are described in the following sections.

Before examining the models for the individual processes, several simplifying assumptions that have been incorporated in the MESORAD atmospheric process models must be introduced. The first assumption is that along-wind and cross-wind diffusion are equal; that is, horizontal cross-sections through puffs are circular. As a result, sigma x can be replaced by sigma y. A corollary of this assumption is that concentrations in a horizontal plane decrease as a function of increasing distance from the puff center and are independent of the direction in which the distance is increased. Therefore, the coordinate system can be re-oriented without changing the relationship in Equation (2).

The second simplifying assumption is that the height of the puff center above ground is constant. This height is referred to as the effective release height. It is the sum of the stack or vent height plus plume rise. The elevation of the puff center is the sum of the elevation of the terrain immediately beneath the center of the puff and the effective release height. As the puff is transported downwind, it rises and falls, conforming to changes in terrain elevation.

PUFF DIFFUSION

Many experiments have been conducted to measure atmospheric diffusion coefficients. Results from various tests have been combined to develop diffusion coefficient parameterizations. In general, the parameterizations are a function of travel distance or time and atmospheric stability. Four parameterizations are included with MESORAD to provide users with alternatives. One of the parameterizations must be selected when MESORAD is run.

The MESOI parameterizations are 1) the NRC parameterization used in the MESODIF-II, XOQDOQ, and PAVAN models (Powell, Wegley and Fox 1979; Sagendorf, Goll and Sandusky 1982; Bander 1982); 2) the Briggs' 'open country' parameterization (Briggs 1973; Gifford 1975); 3) a parameterization recommended for use by the U.S. Army (Ramsdell, Hanna and Cramer 1982); and 4) the Start and Wendell (1974) approximation to Markee's desert parameterization (Yanskey, Markee and Richter 1966). These parameterizations are described in Appendix A.

The atmospheric mechanism associated with diffusion is wind turbulence. Turbulence is a random fluctuation of wind direction and speed that is caused by flow over and around obstacles on the surface. It may also be caused by differential heating of the atmosphere. The thermal structure of the atmosphere can enhance or suppress turbulence. When the thermal structure tends to enhance turbulence, the atmosphere is unstably stratified; when turbulence is suppressed, the atmosphere is stably stratified. If turbulence is neither enhanced nor suppressed, the atmosphere is neutrally stratified.

Turbulence measurements can be used to estimate diffusion coefficients. However, turbulence measurements are not made at many of the facilities for which diffusion models are required. Consequently, methods of estimating diffusion coefficients have been developed that use more easily obtained meteorological data (e.g., air temperature differences, sky cover, solar radiation, and wind speed) to estimate an atmospheric stability class. Mathematical or graphical relationships are then used to determine diffusion coefficient values using the stability class and distance from the release point. Among the more familiar methods of estimating stability classes are the NRC temperature difference definitions found in Regulatory Guide 1.23 (USNRC 1974), and the Pasquill-Gifford-Turner methods (Gifford 1961 and 1976; Turner 1964).

Note that methods for determining stability classes have been compared in many papers [for example, Luna and Church (1972), Skaggs and Robinson (1976), Lalas, Catsoulis and Petrakis (1979), Weil (1979), Lague, Irvine and Lavery (1980), Sedefian and Bennett (1980), and Mitchell (1982)]. The consensus is that the various methods of determining stability classes give inconsistent results when applied to the common data sets. Horst, Doran and Nickola (1979) and others have shown that better diffusion coefficient estimates can be made using turbulence measurements directly instead of going through the indirect step of determining stability classes. The use of stability classes should be considered to be a source of uncertainty in MESORAD diffusion and deposition computations.

The common relationships used to evaluate diffusion coefficients are families of curves that give coefficient values as a function of distance from the release point. Time after release may be used instead of distance. Each curve in the family is associated with a stability class. In most plume-type diffusion models, the atmospheric stability at the time of release is used to determine the stability class, and concentrations at all distances are estimated using the relationship for that stability class.

One of the advantages of a puff-type model is that the model can take into account changes in atmospheric conditions that occur during transit from the release point to the receptor. However, properly accounting for changes of stability is more complex than simply changing from one relationship to another. Simply changing relationships as stability changes result in unnatural (impossible) instantaneous expansions and contractions of puffs. To avoid these physically unrealistic expansions and contractions, MESORAD uses virtual distances rather than actual distances in its diffusion computations.

At the beginning of each time interval, the stability class for the interval and the diffusion coefficients from the end of the previous interval are used to compute distances to a virtual point source (virtual distances) for the horizontal and vertical coefficients. These virtual distances and the distance moved by the puff during the interval are then used to compute the diffusion coefficients used in the interval. In this scheme, the diffusion rates change when the stability changes, but there are no discontinuities in the diffusion coefficients.

Two constraints are applied to the diffusion coefficients. The first constraint is that neither the horizontal nor the vertical diffusion coefficient is permitted to decrease. The second constraint, applied only to the vertical diffusion coefficient, limits vertical diffusion to the layer of the atmosphere next to the earth's surface. This layer is referred to as the mixing layer. The height of the top of the mixing layer is entered as one of the meteorological variables. The earth's surface and the top of the mixing layer are assumed to be reflecting boundaries. For material released within the mixing

layer, these assumptions lead to concentrations that are uniform in the vertical when the magnitude of the vertical diffusion coefficient equals 80% of the mixing layer thickness. As a result, the magnitude of the vertical diffusion coefficient is not permitted to exceed 80% of the thickness of the mixing layer, unless the mixing layer thickness decreases with time. When the vertical diffusion coefficient is greater than 80% of the mixing layer thickness because the mixing layer thickness has decreased as a function of time, no further increase in the vertical diffusion coefficient is permitted. If material is released above the top of the mixing layer, it is permitted to diffuse downward into the mixing layer, where it becomes trapped. Thus, the top of the mixing layer is similar to a semipermeable membrane.

The treatment of reflection of material at the ground and the top of mixing layer in MESORAD is identical to the treatment in MESOI. It is based on the superposition of contributions from virtual sources located below the ground and above the top of the mixing layer. This approach follows from the discussion in Csanady (1973) and is described in detail in Ramsdell, Athey and Glantz (1983). In essence, the exponential term in Equation (2) is separated into horizontal and vertical parts. The vertical term is then replaced by an infinite sum of exponential terms

$$\exp \left[-\frac{1}{2} \left(\frac{z - z_0}{\sigma_z} \right)^2 \right] + \sum_{n=-\infty}^{\infty} \left\{ \exp \left[-\frac{1}{2} \left(\frac{2nH - h_e - z}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{2nH + h_e - z}{\sigma_z} \right)^2 \right] \right\} \quad (3)$$

where H = the height above ground of the top of the mixing layer
 h_e = the effective release height (above ground)
 z = the height of the receptor above ground.

If the receptor is at ground level, the summation simplifies to

$$2 \sum_{n=-\infty}^{\infty} \exp \left[-\frac{1}{2} \left(\frac{2nH - h_e}{\sigma_z} \right)^2 \right]$$

These summations converge to their limit rapidly, and as a result, are truncated after a few terms.

MESORAD uses differences in elevation between the center of the puffs and the elevations of grid points in diffusion computations. The elevation of the ground beneath the center of the puff at each time step is determined by interpolating from the elevations of the surrounding grid points. The method of interpolation is described in a following section, Topographic Interpolation. One of the steps in applying MESORAD to a specific site is the preparation of a topographic data file that contains the elevation at each grid point. If a topographic data file is not available, MESORAD assumes that the site is flat.

PUFF TRANSPORT

Puff transport is treated in MESORAD just as it was in MESOI Version 2.0. A three-layer wind field model is assumed. The lowest layer extends from the ground to a height of 10 m; the next layer extends from a height of 10 m to the top of the mixing layer, and the top layer extends upward from the top of the mixing layer. The winds in each layer are defined as functions of time.

In the lowest layer, measured or predicted winds for as many as 30 locations are used to determine east-west and north-south components of the transport vectors at nodes on a 16- x 16-node grid. The components are determined using weighted spatial interpolation and extrapolation where the weights used are inversely related to squares of the distances between the wind station locations and the grid nodes. It is permissible for the speed of both components to be zero.

Following the interpolation, the winds at the grid nodes may be modified to account for anticipated terrain effects. If this option is selected, a simple, deterministic procedure is followed. At locations where terrain effects are anticipated, wind components perpendicular and parallel to the face of the responsible terrain feature are computed. The perpendicular component is adjusted by a predetermined multiplicative factor. The parallel component is then adjusted to maintain the magnitude of the original wind vector, and finally, new east-west, north-south components of the transport vector are computed. The details of the adjustment procedure in MESORAD are different from those in MESOI Version 2.0, and are described in the section entitled Terrain Effects on Wind Fields. Preparation of the data file needed for modifying winds to account for anticipated terrain effects is one of steps in customizing MESORAD.

The wind in the top layer is specified as a function of time. It is assumed to be horizontally uniform, and is not adjusted for anticipated terrain effects. The geostrophic or gradient wind may be used in the top layer. Many

meteorological texts (e.g., Holton 1979) describe computation of these winds from surface pressure measurements. Upper-air wind observations can also be used in the model.

Winds at heights between the surface (10 m) and the top of the mixing layer are determined by interpolation between the surface wind field and the wind specified for the top layer. They are computed only when needed for use in puff transport. Each of the two wind components is interpolated separately in two steps. In the first step, the surface layer wind directly beneath the puff center is estimated using the same inverse-square weighted scheme used to determine grid-point transport components. The second step is vertical interpolation to the effective release height. MESORAD currently uses linear interpolation in the vertical as a default because a cursory examination of readily available wind profile data did support the use of any other weighting scheme. However, provision has been made for nonlinear interpolation. Nonlinear weighting might be used to compensate for an anticipated vertical variation in terrain effects.

Puff movement is determined by the transport wind vector components at the height of the puff center. The transport wind vector has a magnitude equal to the wind vector, but its direction is different from the wind direction by 180 degrees. The wind direction is the direction from which the wind blows, while the transport direction is the direction toward which the wind blows.

Two surface transport wind fields and two top-layer transport winds are retained for use in MESORAD. These winds represent the conditions at the beginning of a simulation period, and the winds at the beginning of the next period. The duration of simulation periods is generally one hour or less. For nuclear facilities where average wind data become available at 15-minute intervals, simulation periods typically will be 15 minutes. The wind fields are used to estimate the transport wind at the beginning and end of the advection periods within the simulation period. Simulation periods are subdivided into advection periods. The length of advection period is determined by the number of puffs released each hour and must be an integer factor of the simulation period. When four puffs are released each hour, the advection period is 15 minutes. Thus, in nuclear facility applications, the durations of the simulation period and the advection period will generally be the same. When advection periods are shorter than the simulation periods, the winds at the beginning and end of the advection periods are assumed to vary linearly in time.

Initial estimates of puff movement are made using puff-center winds for the beginning of each advection period. Puff-center winds for the end of the advection period are then estimated using the initial movement estimates. The

two winds are averaged to produce refined estimates of the movement of puffs during the advection period. The wind is assumed to be constant during the advection period.

The $x_0(t)$ and $y_0(t)$ coordinates of the center of a puff at any time t following release are given by

$$x_0(t) = x_0(0) + \int \bar{u}(x,y,z,t) \Delta t \quad (4)$$

and

$$y_0(t) = y_0(0) + \int \bar{v}(x,y,z,t) \Delta t \quad (5)$$

where $x_0(0), y_0(0)$ = coordinates of the release point
 $u(x,y,z,t), v(x,y,z,t)$ = average component speed for the advection period
 Δt = duration of the advection period

The summation is carried out over all advection periods since the puff release.

PUFF DEPLETION

After material is released to the atmosphere, a number of mechanisms reduce the amount of material in the air. The removal mechanisms include dry deposition of material that comes in contact with surfaces, washout of material by precipitation, and radioactive decay. Radioactive decay of the radionuclides initially released and ingrowth and decay of daughter nuclides are described in the discussion of dose computation that follows. This section briefly describes the treatment of dry deposition and washout in MESORAD. These processes are treated as they were in MESOI Version 2.0. A more complete description of the parameterizations is included in Ramsdell, Athey and Glantz (1983).

Basic diffusion computations are performed once in MESORAD assuming a standard release that corresponds to a unit release rate for plume models and a nondepleting radionuclide. Associated with each puff are as many source terms as there are radionuclides being released, and flags indicate whether the radionuclide can be depleted by dry deposition or washout. If a radionuclide can be depleted by these processes, the mass of the radionuclide associated with the puff is reduced as the puff is advected. Masses of radionuclides not depleted by deposition or washout may decrease as a result of radioactive decay during transit from source to receptor.

MESORAD incorporates a source-depletion dry deposition model. Source-depletion dry deposition models are described elsewhere in the literature [for example, Van der Hoven (1968), Pasquill (1974), and Hanna, Briggs and Hosker (1982)]. The essence of the source depletion model is that the flux of material to the surface is proportional to the concentration near the surface. The constant of proportionality is called the deposition velocity because it has units of length divided by time.

The basic formulation of the model is

$$\omega_H(x,y,t) = v_d \chi(x,y,0,t) \quad (6)$$

where ω_H = dry deposition rate at position (x,y)
 v_d = deposition velocity
 $\chi(x,y,0)$ = concentration near the surface

Sehmel (1980) discusses the measurement and uncertainties associated with deposition velocities and summarizes much of the material on them. Considering Sehmel's discussion, a deposition velocity of 0.01 m/s is assumed for all depositing species.

Horst (1977) suggests a more realistic alternative approach to the model used. However, his approach involves more computational time and still has a large degree of uncertainty. As a result, the source depletion model has been included in MESORAD with an implicit assumption that the model will be used to indicate likely areas of high deposition and that quantitative estimates of the amount of material deposited will be made on the basis of in situ measurements.

Dry deposition is a surface layer phenomenon; washout, on the other hand is an integral phenomenon. In washout, the amount of material deposited on the surface and removed from the puffs depends on the concentration of material integrated vertically through the puff, and the precipitation type and rate. Slinn (1978) and Hanna, Briggs and Hosker (1982) discuss the assumptions and limitations of simple washout models of this sort.

In these models, the flux to surface resulting from wet deposition is given by

$$\omega_w(x,y,0,t) = \frac{\lambda_w Q}{2\pi\sigma_y^2} \exp \left[-\frac{1}{2} \frac{|r|}{\sigma_y}^2 \right] \quad (7)$$

where λ_w = washout coefficient
 $|r|$ = distance from puff center

In MESORAD, the washout coefficient is determined by precipitation type and rate. The relationship given in Table 1 was taken from MESOI Version 2.0, and is based on data presented by Engelmann (1968).

MESORAD accumulates material on the surface. Surface contamination is maintained by species, but not by deposition process. At each grid node, the product of deposition rate and time is used to increment the amount of material on the surface at each time step. The total amount of material on the surface is

$$SC(x,y) = \sum_i \sum_j (\omega_d + \omega_w) \Delta t \quad (8)$$

where the summation over the index i represents the contributions of individual puffs during an advection period and the summation over j represents the contribution of all advection periods from the start of the release to the present time.

To compensate for material deposited on the surface by dry deposition, the material associated with the puff is decreased according to

$$Q_{n+1} = Q_n (1 - \lambda_w) \Delta t - 2\pi \sigma y^2 \chi(x_0, y_0, 0) \Delta t \quad (9)$$

where n and $n+1$ denote successive time periods.

Once material is deposited on the surface it is assumed to remain on the surface unless depleted by radioactive decay. Neither the weathering of material into the ground nor the resuspension of material into the atmosphere is treated by MESORAD.

TABLE 1. Washout Coefficients (λ_w) Used in MESORAD (hr^{-1})

Type	Precipitation Rate		
	Light (<1 mm/hr)	Moderate (1 mm/hr - 1 cm/hr)	Heavy (>1 cm/hr)
Liquid	0.79	2.2	4.0
Frozen	0.36	1.2	2.3

MESORAD ATMOSPHERIC MODEL ENHANCEMENTS

Although the basic treatment of atmospheric transport and diffusion is the same in MESORAD and MESOI Version 2.0, there are four areas in which the treatment has been enhanced in MESORAD. These enhancements are: 1) addition of a Gaussian plume model and separate polar grid for computing concentrations and doses near the release point, 2) extension of the expansion and contraction of the model domain to include rescaling topographic and terrain data, 3) revision of the algorithm used in topographic interpolation, and 4) revision of the method used to modify wind fields to represent the expected effects of terrain.

To avoid confusion, the topography and terrain have taken on special meanings in MESORAD. Topography is used when discussing elevations, while terrain is used when discussing the effects of land forms on wind fields. For example, the topography data file contains the elevations for grid points, and the terrain data file contains information used to modify the winds at grid points where terrain effects are expected.

CLOSE-IN GRID

In MESOI Version 2.0, diffusion computations are made for receptors on a 31 x 31 Cartesian grid. The spacing between receptors is large compared to the size of the puffs near the release point. As a result, it is possible for puffs to pass between the grid points undetected, and it is likely that maximum concentrations near the release point will be underestimated. A close-in grid has been incorporated in MESORAD to correct this deficiency. The grid consists of 108 receptors on three circles centered on the release point. The radii of the circles are 800, 1600 and 3200 m; 36 receptors are spaced at 10-degree intervals on each circle. The close-in grid is shown in Figure 1.

Both a straight-line Gaussian plume model and the Gaussian puff model are used in diffusion computations for receptors on the close-in grid. As material is being released, the plume model is used to estimate the exposures (the product of concentration and time) that occur during initial passage of the plume. If a wind direction shift has occurred since the beginning of the release, material released previously may also contribute to exposures at receptors on the close-in grid. These contributions are estimated using the puff model.

FIGURE 1. Close-In Grid Points Affected by Plume at Wind Speeds of 0.5 m/s

The basic Gaussian plume model used to estimate ground-level concentrations at close-in grid receptors is

$$x(r, \theta - \theta_c) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp \left[-\frac{1}{2} \left(\frac{y'}{\sigma_y} \right)^2 \right] \cdot \sum_{n=-1}^1 \exp \left[-\frac{1}{2} \left(\frac{2nH + h_e}{\sigma_z} \right)^2 \right] \quad (10)$$

$$\sigma_z < 0.8 H$$

where θ = the direction angle of the receptor point from grid center
(1 through 36; every 10 degrees)

θ_c = plume centerline azimuth

r = the distance to the grid point from grid center
(800, 1600, and 3200 m are default)

x' = along wind distance where $x' = r \cos (\theta - \theta_c)$

y' = cross wind distance where $y' = r \sin (\theta - \theta_c)$

h_e = effective plume height = $h_r - (h_g - h_c)$

h_r = release height of puff

h_g = topographic elevation at grid point

h_c = topographic elevation along centerline of plume

L = mixing layer thickness

This equation is used when the wind speed is 0.5 m/s or greater and σ_z is less than 80% of the mixing layer thickness. If σ_z equals or exceeds 80% of the mixing layer thickness, the material is assumed to be uniformly mixed in the vertical, and ground-level concentrations are computed using

$$x(r, \theta - \theta_c) = \frac{2Q}{(2\pi)^{3/2} \sigma_y \bar{u}} \exp \left[-\frac{1}{2} \left(\frac{y'}{\sigma_y} \right)^2 \right] \quad (11)$$

for $\sigma_z \geq 0.8 h$

In Equations (10) and (11), the distance used in evaluation of σ_y and σ_z is determined for each grid point by taking the projection of the vector from center of the grid to the grid point on the plume centerline. The restriction on magnitude of the vertical diffusion coefficient was discussed in relation to the diffusion of puffs.

If the wind speed is low (less than 0.5 m/s) or calm, the wind direction is assumed to be variable, and the wind speed is assumed to be 0.5 m/s. These conditions are modeled by assuming that the material is uniformly distributed around the release point. When σ_z is less than 80% of the mixing layer thickness, Equation (10) is replaced by

$$x(r) = \frac{2Q}{(2\pi)^{3/2} r \sigma_z u_d} \cdot \sum_{n=-1}^1 \exp \left[-\frac{1}{2} \left(\frac{2nH + h_e}{\sigma_z} \right)^2 \right] \quad (12)$$

$u_d = 0.5 \text{ m/s}$
 $\sigma_z \geq 0.8 H$

If σ_z is equal to or greater than 80% of the mixing layer thickness, Equation (11) is replaced by

$$x(r) = \frac{Q}{2\pi r H u_d} \quad (13)$$

$$u_d = 0.5 \text{ m/s}$$
$$\sigma_z \geq 0.8 H$$

Dry and wet deposition computations do not involve wind speed. Therefore, they are made in the same manner for both low and high wind speed cases. The amount of material deposited on the ground as a result of dry deposition is calculated using the source-depletion model discussed in the section on puff depletion. Similarly, the washout model described earlier is used to calculate the amount of material removed from the plume by precipitation. Except during heavy precipitation, the material deposited near the source is only a small fraction of the total amount released. Therefore, the source term used with the plume models is not corrected for depletion between the release point and the receptor. The source terms used with the puffs are corrected for depletion. As a result, air concentrations and surface contaminations computed for the close-in grid are only slightly larger than would be expected if depletion were fully treated.

The contributions of puffs to exposures and deposition for close-in grid receptors are computed using the equations given earlier in the discussion of the puff model. During each simulation period, before these computations are made, two checks are made to determine if a puff might contribute to exposures and deposition on the close-in grid.

The first check determines if the time elapsed since puff release is sufficient to have allowed the puff to move beyond the close-in grid. This check is made by comparing the elapsed time with an estimated travel time computed using the wind speed at the time of release. If the elapsed time is less than the estimated travel time, the contribution of the material in the puff is not considered because it is already accounted for in the plume model. If the elapsed time exceeds the travel time, the second check is made.

The second check determines if the wind direction has changed sufficiently since puff release to return the puff to the vicinity of the close-in grid. This check is made using the distance between the release point and puff center. If the distance reached a maximum and has decreased, the puff may contribute to exposures and deposition on the close-in grid, and evaluation of

those potential contributions is begun. If the distance has not decreased, the puff is not considered further relative to the close-in grid.

VARIABLE DOMAIN

MESOI Version 2.0 allowed the user to alter the model domain size by changing the spacing between grid points. MESORAD retains this feature but expands upon it to make the feature compatible with the topography and wind field modification schemes. The user may decrease the domain size, thus increasing the spatial resolution. In this instance, both the topographic data and the wind field modifying terrain features are rescaled to the new spacing. The user may also choose to increase the domain size. In this case the terrain features are rescaled, but the topography is then assumed to be flat. The interpolation schemes used in the rescaling are discussed in the following sections.

TOPOGRAPHIC INTERPOLATION

Topographic data are assumed to be in a 31 x 31 array coincident with the main receptor grid system with a spacing of 2.5 km between grid points. If the default domain size is used, no interpolation of the topographic data is required. If the main grid spacing is increased from than the default spacing, the entire topographic array is set to zeros (i.e., a flat terrain). This choice is made because there are no topographic data for points outside the maximum default distance and thus no way to adequately interpolate the elevations. If the main grid spacing is decreased from the default size, the topography is determined for the 31- x 31-grid array using bilinear interpolation on the original data. A graphical interpretation of this technique is shown in Figure 2. The bilinear interpolation equation used has the form

$$\begin{aligned} T(x,y) = & (1 - \alpha)(1 - \beta)T_{i,j} + \alpha(1 - \beta)T_{i+1,j} \\ & + \beta(1 - \alpha)T_{i,j+1} + \alpha\beta T_{i+1,j+1} \end{aligned} \quad (14)$$

where $\alpha = \frac{x - x_i}{x_{i+1} - x_i}$

$$\beta = \frac{y - y_i}{y_{i+1} - y_i}$$

FIGURE 2. Graphical Interpretation of the Bilinear Interpolation

If topographic data are used for the main grid system, then topography is also used for the close-in grid system. Specific elevations may be defined for the close-in polar grid points. If these data are not available, the model will interpolate points on the polar grid from the elevations defined on the main grid. This is done using a bilinear interpolation as discussed earlier.

In addition to having topographic data at the main grid points and the close-in grid points, the topography directly beneath a puff is also calculated. If the puff center is within the main grid system, then a bilinear interpolation is used to obtain the topographic elevation under the puff center. If the puff is off the main grid system, then the topographic elevation calculated depends on what direction the puff is off the grid (see Figure 3).

If the puff center lies in one of the four corner areas, then the topography at that corner of the main grid is used. If the puff is east, west, north, or south of the main grid system, a linear interpolation of the topographic data between points along the boundary is used.

Terrain Effects on Wind Fields

As discussed earlier, terrain features are defined for MESORAD as those surface features that modify the transport wind field. The method for altering the wind field makes use of a simple description of the orientation and slope of a feature at a wind grid point. There is no explicit process to generate a terrain feature file. The user must experiment with various orientations and slope coefficients to determine a set of data that modifies the wind in an acceptable fashion. Experience with the local meteorology and an understanding of the local terrain influences is necessary. The technique becomes very

FIGURE 3. Calculation of Off-Grid Topographic Elevations

complex in areas of irregular terrain. It is essential to develop the input wind data with insight as to the model treatment, to examine the resultant wind fields under a variety of conditions and to edit the input to best describe the flow over the model domain.

Specifically, the user builds a data file containing terrain descriptors for any wind grid point at which the surface flow would be likely to be affected by the surface features. This data file is input during model initialization, and the information is used to modify each calculated wind field during simulation. The following example illustrates the use of a terrain feature point to modify a wind vector.

This example will illustrate the possible derivation of the terrain descriptors for a single wind grid point. For convenience, assume that the model grid is situated over a site such that a wind grid point lies over a hill. Further assume that the hill is slightly elongated and has a ridge line running southwest to northeast. This feature might be drawn on a topographic map as illustrated in Figure 4.

The first step in creating a terrain descriptor for the point is to decide which two opposing faces of the feature are most likely to influence the surface wind flow. For the hill illustrated, the two surfaces would be either side of a line drawn along the ridge. Such a line would have an angle of 45 degrees from north. This angle is the first element of the terrain descriptor for this wind grid point. This technique requires that topographic features be reduced to these simple geometric terms.

FIGURE 4. Schematic Representation of Terrain

The line defines two main surfaces upon which the wind can impinge, defined as sides A and B in Figure 4. It appears from the topographic information that the slope of the hill on side A is greater than the slope on side B. Thus, it is assumed that side A will provide a greater barrier to flow and would therefore cause a greater change in direction of a wind vector directed toward it.

Each side is assigned a coefficient representing the amount by which the magnitude of a wind vector perpendicular to the surface would be reduced. A value of 1.0 represents no reduction; the feature does not influence the wind at all. A value of 0.0 represents a complete blockage of flow; all flow would be redirected parallel to the surface feature. In the example, assume for convenience that A is 0.5 and B is 0.8. These two coefficients are the remainder of the terrain descriptors for the wind grid point. The process of definition is required for each point at which the wind is to be modified.

To illustrate how the terrain descriptors are used by MESORAD to modify the wind field, consider a wind out of the west which flows into the hill described above. Figure 5 shows the wind vector in relation to the defined line representing the terrain orientation. The components of the wind vector parallel and perpendicular to the hill are determined knowing the angle of both the hill and the wind vector. The parallel component (V) is multiplied by the coefficient for surface A. This simulates the turning of the wind by the terrain feature. Flow increases parallel to the surface and decreases perpendicular to the surface. To maintain the same wind speed of the original wind vector, the magnitude of the parallel component must be increased. When the new components are again added, the new transport vector has rotated in response to the terrain feature (Figure 6).

FIGURE 5. Transport Vector Components Relative to Terrain Feature

FIGURE 6. New Transport Vector

If the parallel component is very small (i.e. wind flowing directly into the hill), there is no way of determining which way to rotate the vector. In this case, the upper-level wind is examined and its components relative to the terrain feature are used to determine the rotation direction.

DOSE CALCULATION MODELS

MESORAD assesses the radiological consequences of a release using three dose pathways: the external dose due to radiation emitted by nuclides deposited on the ground, the external dose due to radiation emitted by nuclides in the puff, and internal dose commitments due to the inhalation of radionuclides in the puff. The dose calculations are performed at the conclusion of each puff advection step, and separate tabulations are made for the contribution of the most recent advection step and for the cumulative effects of the entire scenario.

Since MESORAD uses the air and ground concentrations calculated by the dispersion parts of the code, the dose determinations take advantage of all the sophisticated features of MESOI plus the enhancements previously described in this report. Doses are calculated at all receptor locations, including the 31 x 31 rectangular grid and the close-in polar grid.

This section of the report describes the technical basis for the dose evaluations performed by MESORAD.

RADIONUCLIDES IN THE RELEASE

The principal difference between MESORAD and its predecessor MESOI is the inclusion of a list of radionuclides and the calculation of the effects of the radiation emitted by these nuclides. MESORAD was written to accommodate as many as 50 individual radionuclides in each puff.

The mix of radionuclides and the quantity of each released during the scenario is called the source term. Each puff released onto the grid in MESORAD originally includes a specific quantity of each radionuclide, in units of curies. This original nuclide list is determined by the source term. The source term for MESORAD can be entered as a data file, often one produced by another computer code, or it can be entered by the user.

Decay/Ingrowth During Transport

After a puff is released onto the grid, the quantity of nuclides in each puff is given as a function of time because of the changes resulting from radioactive decay. The radionuclides in each puff experience radioactive decay as the puffs move about the grid, and the production of "progeny" nuclides from the decay of their parent nuclides is also calculated. The equation for

calculating the quantity of a nuclide in a puff at some time, t , after the puff is released is

$$Q_i(t) = Q'_{oi} e^{-\lambda_i t} \quad (15)$$

where $Q_i(t)$ = quantity of nuclide i at time t
 Q'_{oi} = quantity of nuclide i originally released into the puff,
 corrected for puff depletion
 λ_i = radioactive decay constant of nuclide i
 t = time after release of the puff.

Radionuclides in the MESORAD library are grouped into decay groups, where parent nuclides undergo radioactive decay and may produce progeny nuclides. At any time after the release of the puff, the activity of a radionuclide (subscript i) in the puff that may experience an increase from production from a decaying parent nuclide (p) can be calculated by:

$$Q_i(t) = Q'_{oi} e^{-\lambda_i t} + Q'_{op} \frac{f_{pi} \lambda_i}{\lambda_i - \lambda_p} \left(e^{-\lambda_p t} - e^{-\lambda_i t} \right) \quad (16)$$

where Q'_{op} = quantity of parent nuclide, p , originally released into the
 puff, corrected for puff depletion
 f_{pi} = fraction of parent nuclide decays that produce nuclide i
 λ_p = radioactive decay constant of parent nuclide, p .

INTERNAL DOSE COMMITMENT FROM INHALATION

One of the major dose pathways to be considered during the passage of a puff of radioactive material is the internal dose resulting from inhalation of radionuclides in the puff. The radiological hazard which may result from the inhalation of radioactive material is stated in terms of a dose commitment to an organ (in this discussion, the term "organ" will be broadly applied, referring to both anatomical organs and other body tissues). This dose commitment includes the dose to an organ, integrated over the total time that radionuclides could reside in that organ. The dose commitment time period must therefore be long enough to include the time that it takes for radionuclides to be transported from the lungs into that organ, and to allow for the total time that the nuclides reside in the organ. The dose commitment time period used in MESORAD is 50 years.

MESORAD uses the following equation to calculate internal dose commitments from the inhalation of particles in a puff:

$$D_{ho} = \sum_i \frac{E}{Q} Q_i \cdot \dot{B} \cdot DF_{hoi} \quad (17)$$

where D_{ho} = internal dose commitment to internal organ o
 $(E/Q Q_i)$ = time-integrated concentration of radionuclide i in puff, adjusted
 . for radioactive decay and production and for puff depletion
 $\dot{B}$ = breathing rate
 DF_{hoi} = 50-year dose commitment factor for inhaled radionuclide i
 irradiating organ o.

For each advection step, MESORAD calculates the inhalation dose commitments for each grid point using the nuclide concentrations calculated for that grid point. Inhalation dose commitments are calculated for three organs: lung (adult), whole body (adult), and thyroid (child).

The calculation of internal dose commitments is heavily dependent on the mathematical models used to calculate the transport of radionuclides through the body. The inhalation of particles is first treated by the lung model, which determines the retention of inhaled particles in each compartment of the respiratory system, and the subsequent transport of these particles out of the compartments. Additional models treat the transport of the particles from the lung into critical organs and body compartments, calculate the retention of the particles in the organs, and determine the clearance of the particles out of the organs. Clearance from the organs is accomplished by both bodily excretion and radioactive decay. Radioactive decay can also produce progeny nuclides in the organs, and this effect is also handled by the transport models. While radionuclides reside inside organs, the radiation emitted by them can deliver a dose to the organ in which the radionuclides reside and, in the case of long-range radiation such as gammas, to other organs in the body.

The processes of radionuclide deposition in the lungs, transport through the body, clearance from organs and absorption of radiation in the organs are included in the inhalation dose factors. MESORAD uses three inhalation dose factors (one for each organ) for each radionuclide in a release. The inhalation dose factors are taken from standard compilations, modified to make the units compatible with the rest of the calculations. Dose factors are sometimes further modified to account for the radionuclide decay scheme used in MESORAD, or to adjust for the targeted age group.

The dose to the whole body is equivalent to the total energy from emitted radiation absorbed in the body divided by the whole body mass. The whole-body

dose is important because most standards and guidelines used in emergency response are stated in terms of whole body dose. The U.S. Environmental Protection Agency's (EPA) Protective Action Guides (PAG) for example, recommend applying a projected whole body dose of 1 rem to trigger protective responses such as sheltering or evacuation during an accidental release (EPA 1980). Although the PAG for whole body is described in the 1980 report in terms of an external gamma dose to the whole body, the health effects for a 1-rem inhalation dose commitment to the whole body would be similar to those expected to result from a 1-rem external whole body dose. The calculation of whole body inhalation doses is therefore included for completeness.

The calculation of inhalation dose commitment to the thyroid is important because many potential releases could include radioactive isotopes of iodine. Inhaled radioiodines would concentrate in the thyroid and would produce a much higher dose to that organ than other organs would receive. A significant dose to the thyroid could result in adverse health effects. The inhalation dose to thyroid is therefore an important factor in emergency response decisions, and an EPA PAG has been defined for this dose pathway. While inhalation doses to whole body and lung are calculated in MESORAD using parameters applying to an adult body, the thyroid dose is calculated using the parameters for a child's body. The child age group (1 to 11 years old) is the age group receiving the highest dose to the thyroid because of age-dependent biometric parameters (Hoenes and Soldat 1977), so this age group is used for dose calculation.

EXTERNAL DOSE RESULTING FROM EXPOSURE TO A PUFF

The external dose to a person resulting from radiation emitted by radionuclides in a passing puff is an important immediate dose pathway in an accidental release. The organ of interest for this dose pathway is the whole body, as described by the EPA Protective Action Guide (EPA 1980).

MESORAD uses two different models for calculating external dose from the puff. The semi-infinite cloud approximation is appropriate for a ground-level release, when the puff has moved far from the dose point so the concentration sigmas are large. For elevated releases, or for distances near the release point where sigmas are small, the finite puff model is more appropriate.

Semi-Infinite Cloud Approximation

When the sigmas describing the distribution of concentrations in the puff are large compared to the mean free paths of gammas emitted by radionuclides in the puff, the puff can be treated as though it were a cloud with infinite

dimensions. The semi-infinite cloud model uses this assumption, calculating doses according to the following equation:

$$D_p = \sum_i \left(\frac{E}{Q} Q_i \right) DF_{pi} \quad (18)$$

where D_p = external dose to whole body resulting from exposure to the puff
 $(E/Q Q_i)$ = time-integrated concentration of radionuclide i in puff,
 adjusted for radioactive decay and production and for puff
 depletion

DF_{pi} = semi-infinite cloud dose factor for radionuclide i .

Semi-infinite cloud dose factors were determined for all radionuclides and stored in a data library read by MESORAD. Most gammas striking the body surface are attenuated by tissue before depositing energy in the whole body. The alphas and betas emitted by a nuclide are not considered in the external dose calculation because they would not penetrate into tissue, so they would not contribute to the whole-body external dose. These dose factors were therefore calculated using the gamma energies and abundances for each nuclide. The calculations were performed using a specially modified version of the finite puff external dose routine from MESORAD. This utility code performs the same calculations done in MESORAD, using a very large value for σ_y . This calculation ensures compatibility between the two different models used by MESORAD for external dose calculation.

The semi-infinite cloud model is easily implemented, with short computer execution times, so it is widely used for external dose calculations. This model has serious limitations, however, when the puff of radionuclides is poorly approximated by a semi-infinite cloud. If the puff is elevated, the ground concentration may be zero, resulting in a reported dose of zero, which would be a serious underestimate. In another situation, a ground-level plume that has not spread very far could be greatly overestimated by the semi-infinite cloud approximation, because the actual concentrations would decrease within the range of emitted gammas rather than remaining uniform.

Finite Puff Model

The finite puff model used in MESORAD is more generally applicable than the semi-infinite cloud approximation, because it takes into account the actual distribution of radionuclides in a puff of finite size, rather than treating the concentrations as though they were uniform out to infinity. The finite puff external dose calculation uses a 'discrete point approximation' to calculate the dose from a puff.

In the discrete point approximation, the puff is assumed to be a cylinder with a radius of $2\sigma_y$ and a height of $6\sigma_z$ (unless the ground or mixing layer boundary intervenes). This cylindrical puff is then divided, using cylindrical coordinates, into three vertical (z) divisions, between three and eight angular (θ) divisions, and between three and eight radial (r) divisions, as shown in Figure 7. Table 2 summarizes the criteria used for selecting the number of puff divisions.

FIGURE 7. Finite Puff External Dose Calculation: Discrete Point Approximation

TABLE 2. Puff Divisions for Discrete Point Approximation

σ_y (m)	Dose Point to Receptor Distance (m)	Number of z Divisions	Number of θ Divisions	Number of r Divisions
<200	any	3	3	3
>200	<1000	3	8	8
>200	>1000	3	8	5

For each of the differential puff volumes derived by this division process, all of the radionuclides in the volume are treated as though they were located at a point in the center of the differential volume. The dose contribution to each receptor location from each 'discrete point' in the puff is then computed, and the contributions from all discrete points are summed to give the external dose. This calculation is performed using the following equation:

$$D_p = 2.13 \times 10^6 \sum_z \sum_r \sum_\theta \sum_\gamma q_\gamma f_\gamma B_\gamma e^{-\mu_{a\gamma} \rho} \frac{2 r dr d\theta dz}{4 \pi \rho^2} E_\gamma \left(\frac{\mu_{t\gamma}}{\rho t} \right) W_\gamma \quad (19)$$

where

$$2.13 \times 10^6 = (3.7 \times 10^{10} \frac{\text{d/s}}{\text{Ci}})(1.6 \times 10^{-6} \frac{\text{erg}}{\text{MeV}})(0.01 \frac{\text{rad}}{\text{erg/g}})(1 \frac{\text{rem}}{\text{rad}})(3600 \text{ s/hr})$$

D_p = external dose to whole body resulting exposure to the puff

q_γ = time-integrated air concentration of gamma emitters in this gamma energy group

f_γ = number of gammas in this energy group emitted per disintegration

B_γ = buildup factor for air

$\mu_{a\gamma}$ = linear attenuation coefficient for air for this energy group

ρ = distance from source point (center of puff differential volume) to dose point

r = radial displacement of source point from center of puff

θ = angular displacement of source point in the puff

z = vertical displacement of source point in the puff

E_γ = energy of this energy group

$\mu_{t\gamma}/\rho t$ = mass energy absorption coefficient for tissue for this energy group

W_γ = ratio of whole body dose to surface dose.

Equation (19) is written for a monoenergetic source of gammas; whereas, most radionuclides emit gammas with any of several different energies. Equation (19) should therefore be applied for each gamma energy, and the results of all these calculations summed to get a total dose. To improve calculational efficiency, the equation is performed for each of six gamma energy groups, grouped with the following boundaries:

0 - 0.3 MeV
 0.3 - 0.5 MeV
 0.5 - 1.0 MeV
 1.0 - 1.5 MeV
 1.5 - 2.0 MeV
 2.0 - 3.0 MeV

In each MESORAD calculation, all gammas emitted by nuclides in the release are assigned to the appropriate groups. The E_q term is then derived from values for all gammas in the group. The $q_q \times f_q$ term is calculated to represent all gammas emitted in the given energy group by radionuclides present in the differential source volume as the puff passes the dose point.

The buildup factor applies a correction for gammas that are initially taken out of the beam by a scattering reaction with air, then scattered back to the dose point. For air, this factor is a function of the gamma energy and the number of relaxation lengths between the source point and the dose point. The buildup factor values are taken from a tabulation by Goldstein and Wilkins (1954).

The ratios of whole-body to surface dose are energy dependent and are those used by Kocher (1979), based on calculations performed by Poston and Snyder (1974).

The gamma attenuation coefficients for air are the total attenuation coefficients, considering all interactions that a gamma could encounter between the point of emission in the puff and the dose point, thus accounting for any interaction that could prevent radiation from reaching the dose point. The coefficients for tissue are the energy absorption coefficients, accounting for interactions that could deposit energy in tissue to produce a dose. The coefficients were taken from compilations in the Radiological Health Handbook (Bureau of Radiological Health 1970).

The discrete point approximation is efficient and accurate for a wide range of cases, but it does have an inherent limitation: when the σ_y of a puff becomes large, the distance between source points in the puff can be of the order of the mean free path of a photon, and the calculation will yield a poor representation of the dose. To prevent this breakdown in the calculation, the external dose calculation reverts to the semi-infinite cloud approximation when σ_y is larger than 1000 m. At this size, the concentration of nuclides in a puff varies slowly enough that the semi-infinite cloud approximation works well. For puffs smaller than this size, the discrete point approximation is valid.

The implementation of the finite puff model into the close-in grid presents another problem because the finite puff calculations depend on a description of the puff as a cylinder. At distances close to the release point, however, it is important to calculate the external doses using a finite puff model, since the small σ_y values may lead to large inaccuracies using the semi-infinite cloud approximation. The close-in dose calculation therefore uses three cylindrical puffs superimposed on the close-in polar grid. Each puff is centered on the intersection of the plume centerline and one of the polar grid's rings (at either 800, 1600 or 3200 m). Each puff uses the sigma

values and concentrations calculated for the point on the polar grid corresponding to the puff center. The finite puff calculation is then performed using Equation (19) as described for the larger rectangular grid.

EXTERNAL DOSE RESULTING FROM EXPOSURE TO CONTAMINATED GROUND

The external dose to a person resulting from radiation emitted by radionuclides deposited on the ground by a passing puff is an important dose pathway for both the immediate time frame and the long-term time frame following an accidental release. The organ of interest for this pathway, as for the external dose resulting from exposure to the puff itself, is the whole body.

MESORAD calculates both the ground-deposition dose rate and the integrated dose for a person standing on contaminated ground for an assumed residence time of t_r . The whole body dose rate resulting from ground deposition is calculated by

$$\dot{D}_g = \sum_i Q_{gi} DF_{gi}/24 \quad (20)$$

where $\dot{D}_g$ = whole-body dose rate resulting from ground contamination,
 Q_{gi} = quantity of radionuclide i deposited on the ground (Ci/m^2)
 DF_{gi} = whole-body dose factor for radionuclide i deposited on the ground.

The dose rate calculation sums over all radionuclides that reside on the contaminated ground. The MESORAD atmospheric transport models calculate the deposition of radionuclides on the ground. Noble gas radionuclides do not deposit, but if any deposited nuclides decay into noble gas nuclides, the noble gases are assumed to remain on the ground. They can therefore make a small contribution to this dose pathway even though they do not directly deposit.

The dose factors were calculated assuming uniform contamination on a flat surface extending to infinity in all directions (Kocher 1980). Such an assumption ignores the shielding effects that may be caused by surface roughness or vegetation on the ground. The calculation also assumes that after radionuclides are deposited on the ground, the concentrations are altered only by radioactive decay and the ingrowth of progeny nuclides, and that no weathering processes would occur.

The assumptions inherent in this dose calculation will be quite conservative, because surface roughness will often introduce significant attenuation of the emitted radiation. It is difficult for a general code to incorporate these features, so the conservatism is accepted. Ignoring weathering and other removal processes also introduces conservatism in the calculation, but these

features would also be difficult to include in the computer code. Due to these conservative assumptions, the predicted dose rates caused by ground contamination will probably be significantly higher than values that would be assessed by a field monitoring team in an actual release.

The total dose calculated by MESORAD for a person exposed to contamination deposited on the ground is calculated at each advection step. The total dose for any advection step covers the time period from the start of the MESORAD simulation to the end of the current advection step. The dose resulting from ground contamination is therefore calculated by summing each advection step's contribution onto the accumulating total dose:

$$D_g = D_g' + \dot{D}_g \Delta t \quad (21)$$

where D_g = whole body dose resulting from ground contamination
 D_g' = whole body dose resulting from ground contamination at the end of the previous advection step
 $\dot{D}_g$ = whole body dose rate resulting from ground contamination for the current advection step
 Δt = duration of the advection step.

This dose calculation assumes that the person stands at the dose point, with no attempt to evacuate or take shelter, for the entire time from the start of the simulation to the end of the current advection step.

Some dose determinations will apply a sheltering factor for staying inside a building or vehicle. MESORAD ignores the possible dose reduction by sheltering or evacuation because it is designed to project the effects that would result from an accidental release in the absence of precautionary actions. Emergency response decision makers can use these projected doses in deciding whether protective actions should be taken.

TOTAL WHOLE-BODY DOSE

Three different dose pathways in MESORAD are used to find dose to the whole body: internal dose commitment from inhalation, external dose from exposure to the plume, and external dose from exposure to contaminated ground. MESORAD treats these pathways individually and sums these three whole body dose pathways together to provide a 'total whole body dose'.

The two external dose pathways would produce similar health effects for similar doses (unless the residence time were on the order of many years), so it is logical to sum the doses from these two pathways to get a total external whole body dose. There is some controversy among health physicists concerning

the severity of health effects that would result from an external dose delivered over a short period of time compared to a numerically equal 50-year internal dose commitment. The differences in the rate of dose absorption by the body could be significant in producing health effects. The two types of dose equivalent are usually treated similarly, however, as implied by the use of the unit "rem" for both cases. In a typical potential reactor release, most inhaled radionuclides would be cleared from the body within a year or two, so that the internal dose commitment would not be greatly dissimilar from an external dose from the puff. The total whole body dose is therefore presented as an option to be used by those who are interested in this type of analysis.

MESORAD LIMITATIONS

The MESOI, version 2.0, report (Ramsdell, Athey and Glantz 1983) thoroughly describes the uncertainties involved in evaluating the air concentrations and ground concentrations calculated by MESOI and the limitations of the models and the code. These limitations are grouped into mathematical model limitations, uncertainties in the data used by MESOI, and numerical limitations of the implementation of the models in a computer code. All of the MESORAD dose calculations are based on the concentrations calculated by the MESOI methodology, so the MESORAD results are subject to the same limitations and uncertainties as the MESOI results.

In addition to the air and ground concentration uncertainties, a number of uncertainties and limitations result from the attempt to calculate doses to human beings. These uncertainties and limitations are added to those resulting from the calculation of concentrations. Therefore, the user must have a good understanding of the applicability of the code's results and the limitations inherent in using the results.

BIOLOGICAL UNCERTAINTIES

The internal dose pathways are very difficult to precisely evaluate because body types vary from one person to another. The MESORAD calculations depend on values describing the deposition of radionuclides in respiratory compartments, transport of radionuclides from one body compartment to another, retention of nuclides in an organ and clearance from the organ, and the absorption of energy from emitted radiation in an organ or other body compartment. A MESORAD run uses a set of parameters describing a human body considered representative of the entire population at risk. Body and organ sizes and weights and metabolic parameters vary greatly depending on a person's age and body type, and these values can even vary in a single person over time as a result of aging or changes in health, dietary, and exercise patterns.

Because of the variability in the human population, modeling the transport, retention, and clearance of radionuclides in a body has always been a

difficult effort. Several different models have been advanced and the anatomical and physiological data used by the models have constantly been updated. Thus, two sets of inhalation dose factors can differ greatly; an order-of-magnitude difference for the dose from a certain nuclide in a given organ is not uncommon in two dose factor sets using different models or different data bases.

The internal dose models used in MESORAD are consistent with currently accepted, state-of-the-art models, resulting in estimates that are consistent with good health physics practice. The user should be aware that similar calculations using other computer codes, especially those based on different mathematical models or data bases, are expected to give different results from MESORAD.

NUCLEAR DATA UNCERTAINTIES

Most of the data describing nuclear processes involved in the dose calculations of MESORAD are well-defined with small error bounds. For the radio-nuclides that would be expected to occur in accidental releases, the data describing radioactive decay such as half-lives and decay yields and gamma energies are well known; the imprecision in this data is so small that it has no effect on the uncertainty in a dose calculation. Likewise, attenuation parameters, such as the total attenuation coefficients for air and the energy absorption coefficients for tissue, are well-known and do not affect MESORAD's uncertainty.

There is some uncertainty, however, in the buildup factors that are applied to the external dose calculation. Different data sets describing these buildup factors do not always agree, and this uncertainty affects the external dose calculation.

The external dose calculations also have some uncertainty as a result of converting gamma fluxes at the body surface to a whole body dose, which is more meaningful in projecting possible health effects resulting from the radiation exposure. For the external dose resulting from exposure to the puff, the gamma flux is converted by applying a surface-to-whole body dose ratio (Kocher 1979; Poston and Snyder 1974). The same set of ratios also plays an important role in determining the external dose as a result of exposure to contaminated ground. These ratios were determined by sophisticated computer calculations of radiation transport using state-of-the-art codes, but they again depend on a mathematical representation of the structure of the body and on a modeler's definition of 'whole body'. The variability of body types again must be considered, and the user should be aware that this variability affects external as well as internal dose calculations.

UNCERTAINTIES IN THE DISCRETE POINT APPROXIMATION FOR EXTERNAL DOSE

The discrete point approximation was based on a widely used method for calculating gamma fluxes from a radiation source of finite dimensions, the point-kernel integration technique. The point-kernel integration is a method that is widely applicable, but it is very time consuming. The discrete point approximation can be seen as a simplification of the point-kernel integration method that yields a dramatic time savings: an increase by a factor of 100 in computer execution speed. The discrete point approximation was therefore chosen to calculate external dose from exposure to a puff.

The key to the accuracy of a discrete point approximation calculation is the number of source points chosen in the puff. Many points spaced close together give a much better dose determination than few points spaced far apart. In developing the model, a large number of runs was made for each of many different combinations of puff size and elevation and distance to the dose point. These test runs were compared to point-kernel integration calculations, and the test results were used to develop guidelines for the number of source points that must be used to give acceptable accuracy for each condition that could be encountered. The implementation in MESORAD has a worst-case agreement of 10% between the point-kernel calculation and the discrete point approximation. In other words, for the most extreme use of a given number of points, the two methods of calculation agreed to no worse than 10%. For the large majority of cases, however, agreement was within 1%.

COMPATIBILITY BETWEEN EXTERNAL PUFF AND INHALATION DOSES

The external puff dose using the finite puff model is calculated differently than the doses from the inhalation dose pathways. The inhalation doses for a given grid point are calculated essentially by multiplying the ground-level air concentration at the grid point by a dose factor. Thus, the inhalation doses are zero at every grid point with zero concentrations, and greater than zero at every grid point with non-zero concentrations. The calculation of external doses caused by the puff for each grid point are not tied so closely to the grid point's ground-level concentrations, however. Since the two dose pathways are treated differently, a comparison of the calculated internal and external doses at a point far from the puff center could mislead an unknowledgeable observer.

The air concentrations in a puff are assumed to follow a Gaussian distribution, and the algebraic equations describing this distribution never decrease to zero. In a practical implementation on a computer, the values finally fall below the machine's discriminator and are reported as zero, but the concentrations can be non-zero to four or more times σ_y . In the finite puff external dose calculation, however, the puff must have finite boundaries, so the code

will model the puff as a cylinder with a radius of $2 \sigma_y$. This size was chosen to include nearly all the radionuclides in the puff, and to include the areas of significant dose rates.

Putting a sharp edge on the puff, as the finite puff model does, however, has the undesirable effect of ignoring radionuclides that would be predicted by a Gaussian distribution to lie outside the $2 \sigma_y$ puff boundary. The external dose calculation would actually calculate doses to some distance past this boundary, corresponding to gammas emitted from within the puff that could go as far as a photon mean-free-path away from the puff. The Gaussian distribution would predict higher dose rates at points outside the $2 \sigma_y$ puff boundaries, however, because of the radionuclides that would lie outside $2 \sigma_y$.

There are few benefits and considerable penalties in making the cylinder larger than $2 \sigma_y$. The additional points with non-zero doses would have doses so much smaller than the points inside the puff that it would not significantly enhance the dose evaluation. The uncertainty in concentrations at this distance from the puff center would be greater than for points closer to the puff center, so that the evaluated doses at points outside $2 \sigma_y$ would be less reliable than those calculated inside. In order to make the puff size larger, it would be necessary to divide a given puff into more discrete volumes, thus increasing the computing time required to handle a puff. Therefore, little benefit can be gained from increasing the radius of a finite puff.

The user must therefore be prepared to see dose patterns that appear different for the external puff calculation than they do for the inhalation pathways. A contour plot of dose distributions would probably show contour lines for inhalation doses that extend farther from the track of puff passage than the contour lines for the external dose pathway. An additional complication arises when calculating the semi-infinite cloud external doses, because this dose pathway also uses the ground-level air concentrations at each grid point. Because the finite puff calculation is superseded by the semi-infinite cloud method when the puff grows to σ_y greater than 1000 m, a dose plot would abruptly sprout new contour lines for the external dose pathway at the point where a puff crossed this threshold. However, the additional contour lines correspond to doses that are insignificant in relation to the contour lines that are obviously consistent.

MESORAD RECEPTOR ARRAYS

MESORAD maintains a large number of receptor arrays internally that contain the various exposure and dose values. There are 10 specific types of information arrays. These ten types are listed below with a brief description of the array contents and the standard units in which MESORAD outputs the values.

1. Time-integrated ground-level air concentrations assuming no depletion and no radioactive decay. [curie-seconds per cubic meter]
2. The time-integrated ground-level air concentrations considering the depletion processes of deposition, washout, decay, and daughter ingrowth. [curie-seconds per cubic meter]
3. The surface concentration resulting from the depletion processes. [curies per square meter]
4. The 50-year dose commitment to the lung from inhaled radionuclides. [rem]
5. The inhalation dose commitment to the thyroid calculated using parameters for the child age group. [rem]
6. The inhalation dose to the whole body. [rem]
7. The external dose to the whole body from exposure to radionuclides calculated using the semi-infinite cloud approximation. [rem]
8. The external whole body dose resulting from all of the radionuclides that have been deposited on the ground. [rem]
9. The external dose to whole body from exposure to radionuclides calculated using the finite puff (discrete point approximation) model. [rem]
10. The sum of all contributions to whole body dose. Sums the whole body doses from inhalation, ground shine, and cloud shine. [rem]

The arrays for the main receptor grid are all 31 x 31 in size. The arrays for the polar close-in grid are 36 x 3. MESORAD maintains two separate arrays for each of the types listed above. One contains the contribution of only the most recent advection step and the other has the cumulative contribution from the start of the simulation through the most recent advection step.

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APPENDIX A

DIFFUSION COEFFICIENT PARAMETERIZATIONS

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DIFFUSION COEFFICIENT PARAMETERIZATIONS

Four alternative diffusion coefficient parameterizations are provided for use with MESORAD. One of these alternatives, or an alternative provided by the user, must be selected when MESORAD is run.

NRC DIFFUSION COEFFICIENTS

The NRC diffusion models used in licensing applications (MESODIF-II, XOQDOQ, and PAVAN), use diffusion coefficient parameterizations that have been attributed to Eimutis and Konicek (1972). These parameterizations are provided to make MESORAD consistent with the other models.

The NRC parameterizations have the general form

$$\sigma = A x^B + C \quad (A.1)$$

For sigma y, A is a function of stability, and B and C have constant values of 0.9031 and 0.0, respectively. For sigma z, A, B, and C are functions of stability and travel distance. The values of A, B, and C are given in Table A.1. The distance ranges for the sigma z coefficients are: 0 to 100 m, 100 to 1000 m, and 1000 m. It should be noted that the A and C coefficients have dimensions associated with them. The dimensions of A are m^{1-B}, and the dimensions of C are meters.

TABLE A.1. Parameter Values for the NRC Diffusion Curve Formulations

Stability Class	Ay	Az			Bz			Cz		
		Distance Range			Distance Range			Distance Range		
		1	2	3	1	2	3	1	2	3
A	0.3658	0.192	0.00066	0.00024	0.936	1.941	2.094	0	9.27	-9.6
B	0.2751	0.156	0.0382	0.055	0.922	1.149	1.098	0	3.3	2
C	0.2089	0.116	0.113	0.113	0.905	0.911	0.911	0	0	0
D	0.1471	0.079	0.222	1.26	0.881	0.725	0.516	0	-1.7	-13
E	0.1046	0.063	0.211	6.73	0.871	0.678	0.305	0	-1.3	-34
F	0.0722	0.053	0.086	18.05	0.814	0.74	0.18	0	-0.35	-48.6
G	0.0481	0.032	0.052	10.83	0.814	0.74	0.18	0	-0.21	-29.2

BRIGGS' 'OPEN COUNTRY' DIFFUSION COEFFICIENTS

The NRC diffusion coefficient parameterizations are based on early experimental diffusion data. Essentially they are approximations to the Pasquill-Gifford curves (Pasquill 1961; Hilsmeier and Gifford 1962). The Briggs "open country" curves (Briggs 1973) are based on a significantly larger experimental data base. The Briggs' curves are discussed by several authors, including Gifford (1976) and Hanna, Briggs and Hosker (1982). Mathematically, the curves are all of the form

$$\sigma = A \times (1 + B \times x)^C \quad (A.2)$$

where A, B, and C are functions of stability for sigma z; for sigma y, A is a function of stability, and B and C are constants with values of 0.0001 and -0.5, respectively. Table A.2 contains the stability dependent parameter values. The values of B have dimensions of m^{-1} .

Briggs did not include curves for stability class G. The values for A listed for class G were determined from the class F values in accordance with the relationship suggested in Regulatory Guide 1.145 (NRC 1982). For sigma y, the ratio between the G and F curves is 2/3; for sigma z the ratio is 3/5.

ARMY DIFFUSION COEFFICIENTS

Turbulence is directly responsible for diffusion. Recent studies (for example, Hanna et al. 1977, Pasquill 1979, Irwin 1983 and others), suggest diffusion coefficients can be estimated directly using measured turbulence

TABLE A.2. Parameter Values for the Briggs' 'Open Country' Diffusion Coefficient Curves

<u>Stability Class</u>	<u>Ay</u>	<u>Az</u>	<u>Bz</u>	<u>Cz</u>
A	0.22	0.20	0.0	0.0
B	0.16	0.12	0.0	0.0
C	0.11	0.08	0.0002	-0.5
D	0.08	0.06	0.0015	-0.5
E	0.06	0.03	0.0003	-1.0
F	0.04	0.016	0.0003	-1.0
G	0.027	0.011	0.0003	-1.0

statistics. Ramsdell, Hanna and Cramer (1982) developed a diffusion coefficient parameterization for use by the U.S. Army. The parameterization is based on turbulence statistics, but can also estimate the needed statistics from stability classes.

The basic formulation of this parameterization is

$$\sigma = I \cdot F(x) \cdot x \quad (\text{A.3})$$

where I is an intensity of turbulence, $F(x)$ is a function that accounts for changes in the efficiency of turbulence in diffusing material as the travel distance increases, and x is the travel distance.

For σ_y , the intensity of turbulence is the ratio of the standard deviation of the crosswind component of the wind to the mean wind speed. It is approximately equal to the standard deviation of the wind direction, when expressed in radians. For σ_z , the intensity of turbulence is the ratio of the standard deviation of the vertical component to the mean speed. It may be approximated by the standard deviation of the elevation angle of the wind, expressed in radians. Table A.3 gives typical turbulence intensities for stability classes A through G.

TABLE A.3. Turbulence Intensities for Use in
Estimating Diffusion Coefficients

Stability Class	I_y	I_z
A	0.37	0.22
B	0.30	0.20
C	0.20	0.15
D	0.15	0.10
E	0.10	0.05
F	0.10	0.05
G	0.10	0.05

The efficiency of turbulence in causing diffusion is represented by the non-dimensional function $F(x)$. For horizontal diffusion, the function has the forms

$$F(x) = \begin{cases} (x/x_r)^{-1/10} & x < 10,000 \text{ m} \\ 1 & x \geq 10,000 \text{ m} \end{cases} \quad (\text{A.4})$$

where x_r is a reference length used to non-dimensionalize the distance. A unit distance for x_r is more convenient to use; for example, if x is in meters, then x_r should be 1 m. For sigma z, $F(x)$ has the form

$$F(x) = (1 + B x)^C \quad (\text{A.5})$$

This form gives an overall sigma z parameterization that is consistent with the Briggs' sigma z parameterization. As a result, B and C are functions of stability with the values given in Table A-2. Again, B has dimensions of m^{-1} .

DESERT DIFFUSION COEFFICIENTS

Diffusion data collected at the Hanford Site near Richland, Washington and the National Reactor Testing Station (now Idaho National Engineering Laboratory) at Idaho Falls, Idaho in the early 1960's indicated that horizontal diffusion was a lowest during neutral atmospheric conditions and increased in both unstable and stable conditions. As a result, a set of diffusion curves were developed by Markee (Yanskey, Markee and Richter 1966) using these data to represent diffusion in desert climatic conditions. The desert diffusion coefficient parameterization included with MESORAD is an approximation to Markee's curves initially formulated by Start and Wendell (1974). This parameterization was used exclusively in MESOI Versions 1.0 and 1.1. It is not the same as the desert parameterization used in XOQDOQ and PAVAN.

The form of the parameterization for sigma y is

$$\sigma_y(x) = \begin{cases} A_y s^{0.85} & x \leq 20,000 \text{ m} \\ A_y' x^{0.5} & x > 20,000 \text{ m} \end{cases} \quad (\text{A.6})$$

where A and A' are functions of atmospheric stability. The sigma z parameterization is

$$\sigma_z(x) = \begin{cases} A_z \times B_z & \sigma_z/L \leq 0.465 \\ \left[0.465 + 0.335 \left(\frac{x-x_c}{x} \right) \right] L & 0.465 < \sigma_z/L \leq 0.8 \\ 0.8 L & \sigma_z/L > 0.8 \end{cases} \quad (A.7)$$

where B and C are functions of stability, L is the mixing layer thickness, and x_c is the distance at which sigma z becomes equal to 0.0465 L. Table A.4 gives parameter values for the MESORAD desert diffusion coefficient parameterization. The constants A_y , A_y' , and A_z are dimensional with dimensions of $m^{0.15}$, $m^{0.5}$, and m^{1-B} , respectively. Parameters for stability class G have been added to the original Start and Wendell parameterization and have been assumed to have values identical to the class F values.

Table A.5 shows the method used to determine stability classes for the desert diffusion coefficient parameterization.

Diffusion coefficient estimates obtained with the four alternative parameterizations are compared in Figure A.1. The similarity of the sigma y estimates for unstable and neutral conditions reflects a large overlap in the data sets on which the parameterizations are based. Meander of winds in the desert during stable conditions is reflected in large sigma y estimates of the desert parameterization for stable conditions.

TABLE A.4. Parameter Values for the Desert Diffusion Coefficient Curves

Stability Class	A_y	A_y'	A_z	B_z
A	0.718	23.0	0.100	1.033
B	0.425	13.6	0.105	0.975
C	0.349	11.2	0.128	0.891
D	0.267	8.55	0.146	0.824
E	0.299	9.57	0.331	0.567
F	0.401	12.8	0.812	0.307
G	0.401	12.8	0.812	0.307

TABLE A.5. Stability Estimates Using Time of Day, Windspeed, and Cloud Cover for the Desert Diffusion Curves

Time of Day by Season			Windspeed at 8 m (m/s)	Cloud Cover			Insolation	Solar Altitude (degrees)
November Through January	February Through April August Through October	May Through July		D Through 5/10	6/10 Through 10/10	Heavy Overcast		
10 through 12	09 through 11	06 through 09	<6	B	C	D	Slight	15 through 35
13 through 16	14 through 18	17 through 20	06 through 09	C	C through D	D		
			>9	D	D	D		
12 through 13	11 through 14	09 through 11	<6	A	B	C	Moderate	35 through 60
		14 through 17	06 through 09	B	B through C	C		
			09 through 11	C	C	D		
			>11	D	D	D		
		11 through 14	<9	A	A through B	B	Strong	>60
			09 through 11	B	B through C	C		
			>11	C	C	C		
16 through 10	18 through 08	20 through 06	<3	G	F	E	None (night)	<15
			03 through 09	F	E	E		
			09 through 11	E	E	D		
			>11	D	D	D		

A = Extremely unstable
 B = Moderately unstable
 C = Slightly unstable
 D = Neutral
 E = Slightly stable
 F = Moderately stable
 G = Extremely stable

FIGURE A.1. Comparison of the MESORAD Diffusion Coefficient Parameterizations

The relatively large disparity between the sigma z estimates from the four parameterizations not surprising. Relatively few measurements of sigma z exist upon which to base a parameterization. As a result, sigma z data have been estimated using measured concentrations and sigma y's and diffusion models. Sigma y estimates are highly influenced by the diffusion model selection and assumptions made with respect to plume reflection and depletion.

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APPENDIX B

DERIVATION OF DOSE FACTORS USED BY MESORAD

APPENDIX B

DERIVATION OF DOSE FACTORS USED BY MESORAD

RADIONUCLIDES WITH INCLUDED PROGENY

MESORAD was written to accommodate simple decay chains with one parent and one progeny nuclide (a parent nuclide may have more than one progeny). For some important nuclides, this simple decay scheme is insufficient to handle all members of the chain separately. In these cases, the decay schemes were modified to include the effects of additional progeny nuclides that would contribute to a dose but could not be handled by the two-member decay scheme. Progeny radionuclides were included by identifying situations in which secular equilibrium would apply. When a parent radionuclide with a long half life had a progeny nuclide with a much shorter half life, every decay of the parent would also create a decay of the progeny, so that the activities of parent and daughter were equal (assuming a decay yield of 1.0). Thus, a parent-progeny combination that fit secular equilibrium could have dose factors combined according to the progeny's decay yield to have one effective nuclide.

The principle of secular equilibrium was also applied to nuclides with decay schemes that would fit the two-nuclide pattern. If these nuclides had progeny in secular equilibrium, calculations were simplified by treating the pair as one nuclide. There were several nuclides treated in that way.

GAMMA ENERGIES

The gamma energies used in MESORAD were derived from two sources: Kocher (1981) and Lederer and Shirley (1978). To minimize the storage requirements of the data library and to simplify the program execution, the gamma energies were collapsed to five energy groups. Thus, for each radionuclide five gamma energies and fractional yields are listed in the MESORAD data library.

The energy grouping was usually performed by dividing into groups with these boundaries:

- Below 0.3 MeV
- 0.3 to 0.7 MeV
- 0.7 to 1.0 MeV
- 1.0 to 1.5 MeV
- Above 1.5 MeV

These energy boundaries were chosen to give roughly equal numbers of gammas in all groups for nuclides with many gammas, but the boundaries were not

strictly applied in all cases. For radionuclides that emit a small number of gammas, the boundaries were shifted to better accentuate the principal energies. The collapsing method used the following formulae to calculate the representative energy and fractional yield for each group:

$$f_Y = \sum_i f_{Yi} \quad (B.1)$$

$$E_Y = \frac{\sum_i E_{Yi} f_{Yi}}{f_Y} \quad (B.2)$$

where f_Y = fractional yield for this energy group
 f_{Yi} = fractional yield for the i_{th} gamma in this energy group
 E_Y = gamma energy for this energy group
 E_{Yi} = gamma energy for the i_{th} gamma in this energy group.

The gamma energy groupings listed here are not the same as those used by MESORAD's finite puff calculation, which uses a six-bin energy grouping. The five-bin grouping used for data storage is made with flexible boundaries, a method which ensures that the principal gamma peaks will still be dominant in the collapsed scheme. Since the finite puff calculation lumps all the nuclides together, it is most efficient to use a rebinning scheme with fixed boundaries, and the six-bin grouping was most convenient for the calculation. The difference in methods of groupings has no effect on the accuracy of the calculations.

For most nuclides, the collapsed gamma energies and yields are listed in the MESORAD data library. For those radionuclides that are treated in combination with decay products, the gamma energies for included progeny nuclides are included with their fractional yields appropriately adjusted to create the gamma energy group.

INHALATION DOSE FACTORS

Lung, thyroid, and whole body inhalation dose factors used by MESORAD were taken from several data sets:

1. INREM-II: These dose factors were calculated using the computer code INREM-II (Killough, Dunning and Pleasant 1978) and compiled in two volumes (Killough et al. 1978; Dunning et al. 1979). Their calculation was based on internal models using the ICRP Task Group Lung Model, multiple exponential retention functions for organ clearance, and cross-organ dose commitments. The dose factors were

originally compiled in units of rem per microcurie inhaled. For use in MESORAD, the dose factors were converted to units of rem per curie inhaled by multiplying by 10^6 .

2. NUREG-0172 (Hoenes and Soldat 1977): These dose factors were used in MESORAD for noble gas radionuclides, using the model assumptions for noble gases described previously. The dose factors were published in units of mrem per picocurie inhaled. These units were converted to rem per curie inhaled by multiplying by 10^9 .
3. ICRP-30 (ICRP 1979): The mathematical models used to calculate these dose factors are similar to those in the INREM-II computer code, using the ICRP Task Group Lung Model, with multiple exponential organ retention functions and cross-organ contributions to dose commitment. These dose factors are published in units of sievert per bequerel of inhaled activity. The dose factors are therefore multiplied by a conversion factor of 3.7×10^{12} to obtain the units of rem per curie used in MESORAD.

Table B.1 summarizes the source of each radionuclide's inhalation dose factors.

When calculating lung and whole body inhalation doses in MESORAD, the dose factors for individual radionuclides are found by simply multiplying by the appropriate conversion factor to adjust the units. For most nuclides, these converted values are used in MESORAD. For some nuclides, however, several members of a decay chain are lumped together into one dose factor. For these combinations, the individual nuclide dose factors can be combined with the others to make the MESORAD dose factor.

For thyroid dose factors, the values taken from the references must be further modified for use in MESORAD. These modifications are necessary to make the dose factors applicable to the child age group rather than adults. Adult thyroid dose factors are converted to child thyroid dose factors by applying the following equation:

$$DF_{hti} = UF_{hTi} \frac{BR_c}{BR_A} \left(\frac{df_t}{df_T} \right) \quad (B.3)$$

TABLE B.1. References for Inhalation Dose Factors

<u>Nuclide</u>	<u>Lung</u>	<u>Whole Body</u>	<u>Thyroid</u>
^3H	INREM-2	INREM-2	INREM-2
^{60}Co	INREM-2	INREM-2	INREM-2
$^{83\text{m}}\text{Kr}$	NUREG-0172	NUREG-0172	NUREG-0172
$^{85\text{m}}\text{Kr}$	NUREG-0172	NUREG-0172	NUREG-0172
^{85}Kr	NUREG-0172	NUREG-0172	NUREG-0172
^{86}Rb	INREM-2	INREM-2	INREM-2
^{87}Kr	NUREG-0172	NUREG-0172	NUREG-0172
^{88}Kr	NUREG-0172	NUREG-0172	NUREG-0172
^{89}Kr	NUREG-0172	NUREG-0172	NUREG-0172
^{89}Rb	NUREG-0172	NUREG-0172	NUREG-0172
^{89}Sr	INREM-2	INREM-2	INREM-2
^{90}Sr	INREM-2	INREM-2	INREM-2
^{91}Sr	INREM-2	INREM-2	INREM-2
^{91}Y	INREM-2	INREM-2	INREM-2
^{95}Zr	INREM-2	INREM-2	INREM-2
^{95}Nb	INREM-2	INREM-2	INREM-2
^{103}Ru	INREM-2	INREM-2	INREM-2
^{106}Ru	INREM-2	INREM-2	INREM-2
^{127}Sb	INREM-2	INREM-2	INREM-2
$^{127\text{m}}\text{Te}$	INREM-2	INREM-2	INREM-2
^{127}Te	INREM-2	INREM-2	INREM-2

TABLE B.1 (contd)

<u>Nuclide</u>	<u>Lung</u>	<u>Whole Body</u>	<u>Thyroid</u>
^{129}Sb	N/A	ICRP-30	N/A
$^{129\text{m}}\text{Te}$	INREM-2	INREM-2	INREM-2
^{129}Te	INREM-2	INREM-2	INREM-2
^{129}I	INREM-2	INREM-2	INREM-2
$^{131\text{m}}\text{Te}$	INREM-2	INREM-2	INREM-2
^{131}I	INREM-2	INREM-2	INREM-2
$^{131\text{m}}\text{Xe}$	NUREG-0172	NUREG-0172	NUREG-0172
^{132}Te	INREM-2	INREM-2	INREM-2
^{132}I	INREM-2	INREM-2	INREM-2
^{133}I	INREM-2	INREM-2	INREM-2
$^{133\text{m}}\text{Xe}$	NUREG-0172	NUREG-0172	NUREG-0172
^{133}Xe	NUREG-0172	NUREG-0172	NUREG-0172
^{134}I	INREM-2	INREM-2	INREM-2
^{134}Cs	INREM-2	INREM-2	INREM-2
^{135}I	INREM-2	INREM-2	INREM-2
$^{135\text{m}}\text{Xe}$	NUREG-0172	NUREG-0172	NUREG-0172
^{135}Xe	NUREG-0172	NUREG-0172	NUREG-0172
^{135}Cs	INREM-2	INREM-2	INREM-2
^{136}Cs	INREM-2	INREM-2	INREM-2
^{137}Xe	NUREG-0172	NUREG-0172	NUREG-0172
^{137}Cs	INREM-2	INREM-2	INREM-2

TABLE B.1 (contd)

Nuclide	Lung	Whole Body	Thyroid
^{138}Xe	NUREG-0172	NUREG-0172	NUREG-0172
^{138}Cs	NUREG-0172	NUREG-0172	NUREG-0172
^{140}Ba	INREM-2	INREM-2	INREM-2
^{140}La	INREM-2	INREM-2	INREM-2
^{141}Ce	INREM-2	INREM-2	INREM-2
^{144}Ce	INREM-2	INREM-2	INREM-2
^{147}Pm	INREM-2	INREM-2	INREM-2
^{234}U	INREM-2	INREM-2	INREM-2

where DF_{hti} = inhalation dose factor to child thyroid
 DF_{hTi} = inhalation dose factor to adult thyroid
 BR_C = breathing rate for child, 13 liters/min
 BR_A = breathing rate for adult, 20 liters/min
 (df_t/df_T) = ratio of child to adult thyroid dose factors from NUREG-0172.

The difference between the child and adult thyroid dose factors found in NUREG-0172 is due to different organ sizes and masses, and different clearance rates from the thyroid. These differences affect the energy deposition in the organ and the amount of time the radionuclides remain in the organ, thus affecting the calculated doses. For nuclides with thyroid dose factors listed in NUREG-0172, the ratios of child-to-adult dose factors for the nuclide were applied to obtain the MESORAD dose factors. For nuclides not listed in NUREG-0172, an average of all ratios listed there was applied.

One drawback to this method of modifying the thyroid dose factors is the mixing of different models that were not intended to be entirely compatible with each other. In Equation (B.3), the DF_{hTi} term is usually derived from either ICRP-30 or INREM-II calculations, while the ratio of (df_t/df_T) was derived from NUREG-0172, which used an earlier (and less sophisticated) modeling of body processes. Some of the data used in the terms of Equation (B.3) are consistent for all models: organ sizes and masses and breathing rates for different age groups. The different models use different clearance rates for

transport among organs, and it is here that the difference could cause problems. Any discrepancy should be minimized, however, since Equation (B.3) uses a ratio of NUREG-0172 dose factors, so the correction determined by this equation should represent a better estimation to the dose to a child's thyroid than the uncorrected value of DFhTi.

The MESORAD dose factors needed to be adjusted by the ratio of child-to-adult breathing rates because adult breathing rates are used in the code calculation. Multiplying by this ratio therefore automatically adjusts for age-specific breathing rates.

EXTERNAL WHOLE-BODY DOSE RESULTING FROM EXPOSURE TO A SEMI-INFINITE CLOUD

These dose factors were calculated using a modification of the finite puff model used in MESORAD. A computer code called MESOINF was written to perform this calculation. MESOINF was based on the MESDRAD routines CYLIN, QUADn, and ARG (with appropriate utility routines), with modifications to make the puff look like a semi-infinite cloud. The bottom of the puff was chosen to be ground level, the top was 1000 m; the puff radius was 2000 m and the nuclide concentrations were chosen to be uniform in the puff rather than varying by a normal distribution in the vertical and radial dimensions. The dose factor for each nuclide was then calculated by reading the gamma energies from the MESORAD library and running MESOINF.

The use of MESOINF to calculate dose factors rather than using previously tabulated values ensures compatibility between the two models used in MESORAD for calculating external doses. The 2000-m puff radius corresponds to the puff radius that triggers the use of the semi-infinite cloud rather than the finite cloud calculation. The dose factors used by MESORAD are compiled in Table C.5, and this table also lists a comparison of the dose factors used by MESORAD and factors compiled in two other data bases.

WHOLE-BODY DOSE DUE TO GROUND DEPOSITION

The dose factors for the whole-body external dose caused by radionuclides deposited on the ground were taken from the compilation by Kocher (1980). These values were listed in units of mrem/yr per mCi/cm². The published values were multiplied by a conversion factor of 2.74×10^{-4} to convert them to units of rem/d per Ci/m² for use in MESORAD. Where necessary, the dose factors were also adjusted to account for the effects of other radionuclides in its decay chain not treated separately by MESORAD.

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APPENDIX C

SPECIFIC RADIONUCLIDE CHARACTERISTICS

APPENDIX C

SPECIFIC RADIONUCLIDE CHARACTERISTICS

MESORAD is designed to accommodate up to 50 radionuclides. Various physical properties of the nuclides must be defined for use in the dose calculations. The model reads a data file during initialization to enter these definitions. Any nuclide that is entered as part of the source term and has not been predefined will be ignored.

The following tables list the decay schemes, gamma energy groups and the dose factors of the nuclides that have been used in the various implementations of MESORAD. In some cases, information was not available or has not yet been calculated. These values are reported as N/A or 'Not Available'.

TABLE C.1. Radionuclide Decay Scheme

<u>Nuclide</u>	<u>Half Life (days)*</u>	<u>Parent* ID</u>	<u>Fraction Yield* from Parent</u>
^3H	4485.3		0
^{60}Co	1925.2		0
$^{83\text{m}}\text{Kr}$	0.07625		0
$^{85\text{m}}\text{Kr}$	0.1867		0
^{85}Kr	3915	$^{85\text{m}}\text{Kr}$	0.211
^{86}Rb	18.66		0
^{87}Kr	0.0530		0
^{88}Kr	0.118		0
^{89}Kr	0.00219		0
^{89}Rb	0.01072	^{89}Kr	1.00
^{89}Sr	50.55	^{89}Rb	1.00

* Data from Kocher (1981).

TABLE C.1. (contd)

Nuclide	Half Life (days)*	Parent* ID	Fraction Yield* from Parent
$^{90}\text{Sr}/^{90}\text{Y}$	10446		0
$^{91}\text{Sr}/^{91\text{m}}\text{Y}$	0.3958		0
^{91}Y	58.51	^{91}Sr	1.00
$^{95}\text{Zr}/^{95\text{m}}\text{Nb}$	64.02		0
^{95}Nb	35.06	^{95}Zr	1.00
$^{103}\text{Ru}/^{103\text{m}}\text{Rh}$	39.35		0
^{106}Ru	368.2		0
^{127}Sb	3.85		0
$^{127\text{m}}\text{Te}/^{127}\text{Te}$	109	^{127}Sb	0.169
^{127}Te	0.3896	^{127}Sb	0.831
^{129}Sb	0.1833		0
$^{129\text{m}}\text{Te}/^{129}\text{Te}$	33.6	^{129}Sb	0.166
^{129}Te	0.04833	^{129}Sb	0.834
^{129}I	5.734E+9		0
$^{131\text{m}}\text{Te}/^{131}\text{Te}$	1.25		0
^{131}I	8.040	$^{131\text{m}}\text{Te}$	1.000
$^{131\text{m}}\text{Xe}$	11.84	^{131}I	0.01086
^{132}Te	3.26		0
^{132}I	0.0958	^{132}Te	1.00
^{133}I	0.867		0

* Data from Kocher (1981).

TABLE C.1. (contd)

Nuclide	Half Life (days)*	Parent* ID	Fraction Yield* from Parent
^{133m}Xe	2.19	^{133}I	0.0288
^{133}Xe	5.245	^{133}I	0.9712
^{134}I	0.0365		0
^{134}Cs	753.1		0
^{135}I	0.275		0
^{135m}Xe	0.01067	^{135}I	0.165
^{135}Xe	0.380	^{135}I	0.835
^{135}Cs	8.401E+8		0
^{136}Cs	13.16		0
^{137}Xe	0.00266		0
^{137}Cs	1.102E+4	^{137}Xe	1.00
^{138}Xe	0.00981		0
^{138}Cs	0.0224	^{138}Xe	1.00
^{140}Ba	12.79		0
^{140}La	1.676	^{140}Ba	1.00
^{141}Ce	32.50		0
^{144}Ce	284.3		0
^{147}Pm	958.20		0
^{234}U	8.930E+7		0

* Data from Kocher (1981).

Notes on Table C.1:

^{88}Kr includes ^{88}Rb , assumed to be in equilibrium with ^{88}Kr

^{90}Sr includes ^{90}Y , assumed to be in equilibrium

^{91}Sr includes $^{91\text{m}}\text{Y}$, assumed to be in equilibrium

^{95}Zr includes $^{95\text{m}}\text{Nb}$, assumed to be in equilibrium

^{103}Ru includes $^{103\text{m}}\text{Rh}$, assumed to be in equilibrium

^{106}Ru includes ^{106}Rh , assumed to be in equilibrium

$^{127\text{m}}\text{Te}$ includes ^{127}Te , assumed to be in equilibrium

$^{129\text{m}}\text{Te}$ includes ^{129}Te , assumed to be in equilibrium

^{129}I is not treated as a daughter of $^{129\text{m}}\text{Te}$ or ^{129}Te

$^{131\text{m}}\text{Te}$ includes ^{131}Te , assumed to be in equilibrium

$^{133\text{m}}\text{Xe}$ includes contributions from ^{133}Xe

$^{135\text{m}}\text{Xe}$ includes contributions from ^{135}Xe

^{125}Cs is not treated as a daughter of ^{135}Xe

^{137}Cs includes $^{137\text{m}}\text{Ba}$, assumed to be in equilibrium

^{144}Ce includes $^{144\text{m}}\text{Pr}$ and ^{144}Pr , assumed to be in equilibrium

TABLE C.2. Gamma Energies and Yields

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^3H	0	0
^{60}Co	1.1732 1.3325	1.000 1.000
^{83}mKr	0.01097	0.2334
^{85}mKr	0.1456 0.30487	0.6214 0.02954
^{85}Kr	0.51399	0.00434
^{86}Rb	1.07663	0.0878
^{87}Kr	0.402578 0.81371 1.32574 2.4022	0.495 0.10267 0.02774 0.19269
^{88}Kr	0.1468 0.3863 0.8706 1.43022 2.1972	0.40 0.04 0.3048 0.22499 0.86728
^{89}Kr	0.21684 0.4274 0.722898 1.4178 2.6172	0.23174 0.206 0.5212 0.38418 0.2957
^{89}Rb	0.27722 0.7964 1.1351 2.3726	0.0196 0.19362 1.0372 0.3067

* Data from Kocher (1981).

TABLE C.2. (contd)

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^{89}Sr	0	0
^{90}Sr	0	0
^{91}Sr	0.2709	0.01685
	0.5750	0.6812
	0.77516	0.28827
	1.0443	0.34863
	1.6772	0.00439
^{91}Y	1.2049	0.0030
^{95}Zr	0.016185	0.00336
	0.2357	0.00195
	0.724184	0.437
	0.756715	0.553
^{95}Nb	0.3892	0.0003
	0.76579	0.99808
$^{103}\text{Ru}/^{103\text{m}}\text{Rh}$	0.01613	0.13003
	0.29498	0.00249
	0.4969	0.8932
	0.55704	0.0083
	0.61033	0.056
^{106}Ru	0.5531	0.3152
	1.0505	0.0173
	1.3054	0.01133
^{127}Sb	0.18552	0.1667
	0.45968	0.34424
	0.66756	0.486
	0.781816	0.17404
	1.2147	0.0071
$^{127\text{m}}\text{Te}$	0.02464	0.43244
	0.36030	0.00132
	0.41790	0.00970

* Data from Kocher (1981).

TABLE C.2. (contd)

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^{127}Te	0.1727	0.0013
	0.36030	0.00134
	0.41790	0.00988
^{129}Sb	0.20356	0.0539
	0.55319	0.41017
	0.85044	0.882
	1.1243	0.21818
	1.7330	0.1138
$^{129\text{m}}\text{Te}$	0.02836	0.35435
	0.46393	0.0529
	0.70118	0.02019
	1.0917	0.003938
^{129}Te	0.03324	0.23688
	0.45960	0.071
	0.48739	0.0131
	0.70304	0.00557
	1.0917	0.00626
^{129}I	0.02870	0.8592
$^{131\text{m}}\text{Te}/^{131}\text{Te}$	0.1300	0.6090
	0.39426	0.1863
	0.78794	0.88225
	1.1608	0.23364
	1.92007	0.04157
^{131}I	0.1437	0.1493
	0.36436	0.81451
	0.502991	0.00361
	0.6371	0.0748
	0.722893	0.01803
$^{131\text{m}}\text{Xe}$	0.03120	0.6436
^{132}Te	0.033789	0.8849
	0.22816	0.88

* Data from Kocher (1981).

TABLE C.2. (contd)

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^{132}I	0.21337	0.03329
	0.42448	0.0322
	0.71232	2.65567
	1.26634	0.24763
	1.99485	0.0329
^{133}I	0.08305	0.03049
	0.46404	0.01286
	0.52951	0.8872
	0.81124	0.09197
	1.24395	0.04657
$^{133\text{m}}\text{Xe}$	0.0366	1.0954
	0.233221	0.103
^{133}Xe	0.04985	0.909
^{134}I	0.3192	0.25754
	0.625741	0.517
	0.86695	1.7761
	1.2108	0.4011
	1.8213	0.10656
^{134}Cs	0.32382	0.02254
	0.56717	0.2381
	0.604699	0.976
	0.79641	0.9413
	1.24844	0.584
^{135}I	0.18797	0.08191
	0.41920	0.05412
	0.72617	0.1787
	1.2678	0.88943
	1.84472	0.15095
$^{135\text{m}}\text{Xe}$	0.02952	0.2122
	0.249794	0.899
	0.3891	0.00578
	0.52976	0.841

* Data from Kocher (1981).

TABLE C.2. (contd)

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^{135}Xe	0.0347	0.0604
	0.249794	0.899
	0.35839	0.0022
	0.40799	0.00358
	0.61334	0.031
^{135}Cs	0	0
^{136}Cs	0.12653	0.78899
	0.34358	0.5008
	0.81840	1.0003
	1.0481	0.796
	1.2353	0.197
^{137}Xe	0.13983	0.00287
	0.4552	0.31138
	0.8826	0.00816
	1.4567	0.01859
	2.11002	0.00591
^{137}Cs	0.02946	0.07833
	0.661649	0.8512
^{138}Xe	0.19567	0.51978
	0.42245	0.29377
	0.77969	0.04083
	1.15686	0.06003
	1.9320	0.41345
^{138}Cs	0.15263	0.0519
	0.45317	0.36512
	0.65762	0.17448
	1.3207	1.1299
	2.3658	0.24501
^{140}Ba	0.0434	0.3905
	0.37288	0.0985
	0.53732	0.25

* Data from Kocher (1981).

TABLE C.2. (contd)

Nuclide	Energies* (MeV)	Yields* (0<y<1)
^{140}La	0.11062	0.03694
	0.43764	0.6894
	0.84212	0.4403
	1.5948	0.9591
	2.48897	0.04415
^{141}Ce	0.03248	0.1984
	0.14544	0.484
^{144}Ce	0.03899	0.13288
	0.69649	0.0146
	1.48915	0.003
	2.1857	0.0076
^{147}Pm	0	0
^{234}U	0.01385	0.1066

* Data from Kocher (1981).

TABLE C.3. Inhalation Dose Factors

Nuclide	Dose Factor Adult Lung* (rem/Ci**)	Dose Factor Adult Whole Body* (rem/Ci**)	Dose Factor Child Thyroid* (rem/Ci**)
^3H	125	125	155
^{60}Co	1.32E+5	1.71E+4	1.44E+5
$^{83\text{m}}\text{Kr}$	0.519	0	0
$^{85\text{m}}\text{Kr}$	2.91	0	0
^{85}Kr	2.41	0	0
^{86}Rb	7680	6690	2.64E+4
^{87}Kr	15.3 [†]	0	0
^{88}Kr	55.4 [†]	0	0
^{89}Kr	21.3 [†]	0	0
^{89}Rb	0	21.2 [†]	0
^{89}Sr	1.75E+5	1.09E+3	0
^{90}Sr	4.92E+4	2.42E+5	3.70E+4
^{91}Sr	4380.	357	946
^{91}Y	1.98E+5	5670	1740
^{95}Zr	1.31E+5	5560	8490
^{95}Nb	3.10E+4	1940	3240
^{103}Ru	5.85E+4	1.98E+3	2.37E+3
^{106}Ru	3.85E+6	6.18E+4	2.20E+4

* Data from Dunning et al. (1979) and Killough et al. (1978).

** Inhaled.

† Data from Hoenes and Soldat (1977).

TABLE C.3. (contd)

Nuclide	Dose Factor Adult Lung* (rem/Ci**)	Dose Factor Adult Whole Body* (rem/Ci**)	Dose Factor Child Thyroid* (rem/Ci**)
^{127}Sb	2.82E+4	879	889
$^{127\text{m}}\text{Te}$	1.20E+5	2470	6100
^{127}Te	2480	51.3	126
^{129}Sb	N/A	3330	N/A
$^{129\text{m}}\text{Te}$	1.54E+5	3.21E+3	1.13E+4
^{129}Te	1060	18.0	42.1
^{129}I	788	2050	1.19E+7
$^{131\text{m}}\text{Te}$	1.10E+4	656	2.71E+5
^{131}I	2.401E+3	613.1	2.16E+6
$^{131\text{m}}\text{Xe}$	1.40	0	0
^{132}Te	2.79E+4	1710	6.26E+5
^{132}I	1200	78.0	6.05E+4
^{133}I	3170	203	5.98E+5
$^{133\text{m}}\text{Xe}$	2.68 [†]	0	0
^{133}Xe	1.57 [†]	0	0
^{134}I	642	34.3	2.28E+4
^{134}Cs	3.38E+4	4.55E+4	1.25E+5
^{135}I	2480	142	1.81E+5

* Data from Dunning et al. (1979) and Killough et al. (1978).

** Inhaled.

† Data from Hoenes and Soldat (1977).

TABLE C.3. (contd)

Nuclide	Dose Factor Adult Lung* (rem/Ci**)	Dose Factor Adult Whole Body* (rem/Ci**)	Dose Factor Child Thyroid* (rem/Ci**)
^{135m}Xe	6.27	0	0
^{135}Xe	4.05	0	0
^{135}Cs	641	4400	1.79E+4
^{136}Cs	6980	6000	1.52E+4
^{137}Xe	17.4	0	0
^{137}Cs	1.62E+4	3.26E+4	1.07E+5
^{138}Xe	24.4	0	0
^{138}Cs	6.07	40.6	0
^{140}Ba	9740	2080	4720
^{140}La	2.01E+4	1050	68.9
^{141}Ce	6.31E+4	1150	226
^{144}Ce	2.92E+6	4.68E+4	1970
^{147}Pm	2.87E+5	5300	297
^{234}U	9.07E+7	3.80E+6	7.20E+5

* Data from Dunning et al. (1979) and Killough et al. (1978).

** Inhaled.

TABLE C.4. Dose Rate Factors to Whole Body
Resulting From Contaminated Ground

<u>Nuclide</u>	<u>Dose Rate Factor*</u> <u>(rem/d per Ci/m²)</u>
³ H	0
⁶⁰ Co	695
^{83m} Kr	0.264
^{85m} Kr	54.5
⁸⁵ Kr	0.693
⁸⁶ Rb	26.0
⁸⁷ Kr	213
⁸⁸ Kr	675
⁸⁹ Kr	213
⁸⁹ Rb	559
⁸⁹ Sr	0
⁹⁰ Sr	0
⁹¹ Sr	290
⁹¹ Y	1.00
⁹⁵ Zr	215
⁹⁵ Nb	221
¹⁰³ Ru	146.0
¹⁰⁶ Ru	61.6
¹²⁷ Sb	207
^{127m} Te	3.50

* Data from Kocher (1981).

TABLE C.4. (contd)

<u>Nuclide</u>	<u>Dose Rate Factor*</u> (rem/d per Ci/m ²)
¹²⁷ Te	1.56
¹²⁹ Sb	N/A
^{129m} Te	21.4
¹²⁹ Te	17.8
¹²⁹ I	0
^{131m} Te	442.0
¹³¹ I	123
^{131m} Xe	5.80
¹³² Te	77.5
¹³² I	660
¹³³ I	185
^{133m} Xe	14.1
¹³³ Xe	15.3
¹³⁴ I	742
¹³⁴ Cs	458
¹³⁵ I	433
^{135m} Xe	233
¹³⁵ Xe	83.3
¹³⁵ Cs	0
¹³⁶ Cs	619

* Data from Kocher (1981).

TABLE C.4. (contd)

<u>Nuclide</u>	<u>Dose Rate Factor*</u> <u>(rem/d per Ci/m²)</u>
¹³⁷ Xe	55.6
¹³⁷ Cs	168
¹³⁸ Xe	304
¹³⁸ Cs	643
¹⁴⁰ Ba	46.8
¹⁴⁰ La	635
¹⁴¹ Ce	26.1
¹⁴⁴ Ce	15.3
¹⁴⁷ Pm	0
²³⁴ U	0.116

* Data from Kocher (1981).

TABLE C.5. External Whole Body Dose Factors for
Exposure to a Semi-Infinite Cloud

Nuclide	Mesorad Dose Factor* (rem/s per Ci/m ³)	Kocher, 1979 Dose Factor (rem/s per Ci/m ³)	Reg. Guide 1.109 Dose Factor (rem/s per Ci/m ³)
³ H	0.00E+00	0	0
⁶⁰ Co	4.05E-01	4.60E-1	5.56E-1
^{83m} Kr	0.00E+00	1.28E-5	3.42E-6
^{85m} Kr	1.36E-02	2.86E-2	3.61E-2
⁸⁵ Kr	3.68E-04	3.90E-4	6.11E-4
⁸⁷ Kr	1.28E-01	1.48E-1	3.61E-1
⁸⁸ Kr	3.93E-01	4.97E-1	5.83E-1
⁸⁹ Kr	3.15E-01	3.49E-1	1.05E+0
⁸⁶ Rb	1.37E-02	1.65E-2	2.22E-2
⁸⁹ Rb	3.18E-01	3.87E-1	5.83E-1
⁸⁹ Sr	0.00E+00	2.34E-5	5.83E-4
⁹⁰ Sr	0.00E+00	1.76E-8	6.67E-5
⁹¹ Sr	1.54E-01	1.74E-1	2.47E-1
⁹¹ Y	5.67E-04	6.56E-4	8.61E-4
⁹⁵ Zr	1.22E-01	1.27E-1	1.89E-1
⁹⁵ Nb	1.27E-01	1.31E-1	1.78E-1
¹⁰³ Ru	7.92E-02	8.18E-2	1.14E-1
¹⁰⁶ Ru	3.40E-02	3.58E-2	4.72E-2
¹²⁷ Sb	1.09E-01	1.19E-1	1.86E-1

* (Calculated by the code MESOINF, using gamma data derived from Kocher (1980)).

TABLE C.5. (contd)

Nuclide	Mesorad Dose Factor* (rem/s per Ci/m ³)	Kocher, 1979 Dose Factor (rem/s per Ci/m ³)	Reg. Guide 1.109 Dose Factor (rem/s per Ci/m ³)
^{127m} Te	8.67E-04	1.35E-3	3.33E-5
¹²⁷ Te	8.49E-04	8.52E-4	3.33E-4
¹²⁹ Sb	2.33E-01	---	---
^{129m} Te	7.76E-03	1.17E-2	2.61E-2
¹²⁹ Te	8.62E-03	9.89E-3	2.42E-2
¹²⁹ I	1.98E-03	1.54E-3	5.00E-3
^{131m} Te	1.94E-01	2.68E-1	2.78E-1
¹³¹ I	6.56E-02	6.72E-2	8.61E-2
^{131m} Xe	5.99E-04	1.56E-3	7.78E-4
¹³² Te	3.09E-02	3.93E-2	5.00E-2
¹³² I	3.79E-01	3.96E-1	5.56E-1
¹³³ I	1.01E-01	1.07E-1	1.22E-1
^{133m} Xe	6.32E-03	8.37E-3	7.50E-3
¹³³ Xe	7.93E-03	6.02E-3	6.94E-3
¹³⁴ I	4.17E-01	4.60E-1	5.56E-1
¹³⁴ Cs	3.62E-01	2.69E-1	3.61E-1
¹³⁵ I	2.59E-01	2.89E-1	4.17E-1
^{135m} Xe	1.15E-01	1.20E-1	9.72E-2
¹³⁵ Xe	4.28E-02	4.47E-2	5.83E-2
¹³⁵ Cs	0.00E+00	0	7.78E-6

* (Calculated by the code MESUINF, using gamma data derived from Kocher (1980)).

TABLE C.5. (contd)

Nuclide	Mesorad Dose Factor* (rem/s per Ci/m ³)	Kocher, 1979 Dose Factor (rem/s per Ci/m ³)	Reg. Guide 1.109 Dose Factor (rem/s per Ci/m ³)
¹³⁶ Cs	3.30E-01	3.77E-1	5.28E-1
¹³⁷ Xe	3.20E-02	3.23E-2	3.33E-2
¹³⁷ Cs	9.29E-02	9.72E-2	1.31E-1
¹³⁸ Xe	1.91E-01	2.09E-1	8.33E-1
¹³⁸ Cs	3.91E-01	4.41E-1	5.00E-1
¹⁴⁰ Ba	3.01E-02	2.55E-2	6.11E-2
¹⁴⁰ La	3.74E-01	4.25E-1	5.28E-1
¹⁴¹ Ce	1.04E-02	1.32E-2	1.64E-2
¹⁴⁴ Ce	5.80E-03	9.10E-3	1.11E-2
¹⁴⁷ Pm	0.00E+00	6.27E-7	9.17E-6
²³⁴ U	0.00E+00	2.52E-5	1.44E-4

* Calculated by the code MESOINF, using gamma data derived from Kocher (1980).

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APPENDIX D

MESOI VERSION 2.0 MODIFICATIONS

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MESOI VERSION 2.0 MODIFICATIONS

Since MESOI Version 2.0 was originally released, there have been several corrections and modifications to the code. To maintain continuity between MESORAD and MESOI, these changes are listed below.

- 1) In the main program (MESOI), after CALL DATRD, the line

```
LDEPTH = LDEPTH * 10
```

was changed to

```
LDEPTH = LDEPTH * 10 + 1.
```

This change was required to avoid dividing by zero when there is an elevated release and LDEPTH = 10 meters.

- 2) In subroutine GRIDIN, after line 160 FORMAT..., the line

```
IF ( DELXY .LT. 0 ) THEN
```

was changed to

```
IF ( DELXY .LE. 0 ) THEN
```

and the line

```
PRINT *, 'NEGATIVE VALUES ARE NOT ACCEPTED'
```

was changed to

```
PRINT *, 'NEGATIVE VALUES AND ZERO ARE NOT ACCEPTABLE'
```

These changes were made to avoid dividing by zero and because a grid spacing of zero (DELXY = 0) does not make sense. Users may wish to place a more restrictive limitation on the acceptable range of DELXY.

- 3) In subroutine LOCATE, between lines 120 FORMAT... and 130 FORMAT..., the line

```
IF ( DAY .GT. SDAY .AND. SDAY .GT. 2 ) GOTO 620
```

was changed to

```
IF ( DAY .GT. SDAY .AND. (IYR+1) .LT. SYR ) GOTO 620
```

This change was required to permit the model to run correctly when the meteorological data base starts in one year and the simulation is to start in the following year.

- 4) In subroutine TERRA, the line used to determine if the wind is approaching the terrain from the east

```
IF ( ANGD .GE. 90.0 .OR. ANGO .LT. 270.0 ) THEN
```

was changed to

```
IF ( ANGO .GE. 90.0 .AND. ANGO .LT. 270.0 ) THEN
```

This change corrects the logical IF statement.

- 5) In the subroutine CLEAN, the following statement was added

```
INCLUDE 'CONST.INC'
```

This was necessary to define the variable DELXY in the subroutine. The addition of the statement brings the CONST common block into CLEAN.

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13. ABSTRACT (200 words or less) MESORAD is a dose assessment model for emergency response applications. Using release data for as many as 50 radionuclides, the model calculates: <ul style="list-style-type: none"> o external doses resulting from exposure to radiation emitted by radionuclides contained in elevated or deposited material, o internal dose commitment resulting from inhalation, o and total whole-body doses. <p>External doses from airborne material are calculated using semi-infinite and finite cloud approximations. At each stage in model execution, the appropriate approximation is selected after considering the cloud dimensions. Atmospheric processes are represented in MESORAD by a combination of Lagrangian puff and Gaussian plume dispersion models, a source depletion (deposition velocity) dry deposition model, and wet deposition model using washout coefficients based on precipitation rates.</p>			
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