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**A Preliminary Assessment of
Selected Atmospheric Dispersion,
Food-Chain Transport, and Dose-To-Man
Computer Codes for Use by the DOE
Office of Civilian Radioactive
Waste Management**

K. J. Riggle
J. W. Roddy

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Chemical Technology Division

A PRELIMINARY ASSESSMENT OF SELECTED
ATMOSPHERIC DISPERSION, FOOD-CHAIN TRANSPORT,
AND DOSE-TO-MAN COMPUTER CODES FOR USE BY THE
DOE OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

K. J. Riggle*
J. W. Roddy

*ORAU Fellow, U.S. DOE Radioactive Waste Management
Graduate Fellowship Program

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A Preliminary Assessment of Selected
Atmospheric Dispersion, Food-Chain Transport,
and Dose-to-Man Computer Codes For Use By The
DOE Office of Civilian Radioactive Waste Management

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ABSTRACT

This work is part of the ongoing Systems Modeling Program at Oak Ridge National Laboratory, which is assisting the DOE Office of Civilian Radioactive Waste Management in selecting appropriate computer codes for the process of licensing a high-level radioactive waste repository or a monitored retrievable storage facility. A preliminary study of codes for predicting dose to man following airborne releases of radionuclides is described. These codes use models for estimating (1) atmospheric dispersion of activity and deposition onto the ground surface, (2) exposures via external irradiation, inhalation of airborne activity, and ingestion following transport through terrestrial food chains, and (3) the dose per unit exposure for each exposure mode. A set of criteria is given for use in choosing codes for further examination. From a list of over 150 computer codes, five were selected for review. In the area of atmospheric dispersion, AIRDOS-EPA, MESORAD, and MATHEW/ADPIC are described. Under the heading of food-chain transport, AIRDOS-EPA and RAGTIME are discussed. AIRDOS-EPA and MESORAD are reviewed in the area of dose-to-man. The federal regulations which apply to the allowable dose to the public from high-level waste management operations are discussed. Pending a more complete assessment, AIRDOS-EPA is recommended for calculating doses from the atmospheric and food-chain pathways, largely because it is mandated by the Environmental Protection Agency for demonstrating compliance with 40 CFR Part 61. An extensive bibliography is added to assist the reader in obtaining more specific information.

1. INTRODUCTION

The work described here is part of the Systems Modeling Program (SMP) underway at Oak Ridge National Laboratory. The purpose of the SMP is to assist the Office of Civilian Radioactive Waste Management (OCRWM) in selecting appropriate computer codes for the process of licensing a high-level radioactive waste repository, or a monitored retrievable storage (MRS) facility, should one be authorized. These codes should: (1) produce desired results in usable form, (2) produce results that are sufficiently accurate, and (3) have been judged against an adequate quality assurance plan such that they will withstand licensing scrutiny. Previous computer code assessments have been performed in the areas of thermal analysis, shielding, criticality, and radionuclide generation and depletion. This work is concerned with codes for predicting dose to man following airborne releases of radionuclides. They consider models and data bases for estimating (1) atmospheric dispersion of activity and deposition onto the ground surface, (2) exposures via external irradiation, inhalation of airborne activity, and ingestion following transport through terrestrial food chains, and (3) the dose per unit exposure for each exposure mode.

The first step was to identify codes which fall in these categories and are presently being used in OCRWM programs by subcontractors, national laboratories, and field offices. In addition, codes which are not presently being used, but which show good capabilities for certain OCRWM applications, will be discussed. To accomplish this task, a draft compendium of technical computer codes¹ completed for OCRWM in July 1987, was used to determine codes in present use, and a literature search was undertaken to identify other promising codes. This step resulted in a list of over 150 computer codes, which is shown in Appendix A.

The next step was to develop a set of criteria to be used in choosing codes for more detailed inspection. Of particular importance was the ability of the code to deal with postulated airborne release scenarios for operations at a geologic repository or MRS facility. In addition, the code should be nonproprietary and have thorough documentation. Other criteria included the relevance of the mathematical model used for calculation and whether the code input parameters or data libraries were up-to-date. Emphasis has been placed on code capabilities as they relate to OCRWM needs. A set of general guidelines for selection are given in Sect. 2, and criteria that are specific to each group of codes are given in the following sections.

Using these criteria, two or three codes in each group were chosen for more thorough investigation. Since some codes fell in more than one area, they are discussed more than once. Preliminary recommendations were made based on the outcome of those evaluations.

In view of the fact that dose to man is the primary end result of these calculations, the federal regulations concerning dose limits for members of the public from operations at high-level waste facilities have been summarized. The applicable regulations are contained in 40 CFR Part 61 and 40 CFR Part 191.

The purpose of this report is not to provide detailed theoretical information about the codes or the models incorporated into them. This information may be found in many available references, some of which have been listed for the reader's convenience. It is assumed that the code user will have access to expertise in the appropriate areas. This report will focus on the practical capabilities of each code which may make it more or less appropriate for a specific application.

1.1 REFERENCE FOR SECTION 1

1. Compendium of Technical Computer Codes Used in Support of Civilian Radioactive Waste Management: Draft Technical Report, Science Applications International Corporation, 1-147-03-342-00 (1987).

2. GENERAL ASSESSMENT CRITERIA

In choosing the codes to review in this study, particular attention was paid to codes that are presently in use within the OCRWM program. These codes were identified using a recent compilation of technical computer codes used by subcontractors, national laboratories, and field offices in the OCRWM system.¹ This code list was supplemented by a literature search to identify other promising codes that could be recommended for future use.

An attempt has been made to choose codes for study that represent different mathematical models, so that the models as well as the codes could be compared. This criterion was used to help choose alternate codes for review in cases where all of the current OCRWM codes used essentially the same model and were therefore very similar in their capabilities.

Codes that are not generally available or which are proprietary may not be useful in the program, and so were disregarded, as were codes for which thorough documentation could not be readily obtained. These codes are difficult to revise or enhance, and the information needed for quality assurance may not be easy to acquire.

The degree to which a code has been documented was a very important assessment criterion. Proper documentation allows the new user to implement the code correctly and understand its purposes and limitations. It also aids in the quality assurance process, which is an extremely important part of any licensing effort.

The NRC has published some guidelines for proper documentation of computer codes to be used in the high-level waste program.² Each code will need a detailed description of the mathematical models and numerical methods that are used to solve the given problem, along with the capabilities and limitations of the code. There should also be a user's manual that is complete enough to allow the new user to install and run the code and also to utilize the generated output. A document should be provided which highlights all reviews and assessments of the code, including validation studies by the code developer and other independent users. If a code is updated or there are major changes, these revisions should also be thoroughly documented. All of these steps will be necessary if a code is to be used to provide data in support of a repository license.

A good code should be compatible with generally available computer systems, and should not require excessive computer run time. If a code has to be adapted to work on a new computer, not only will there be a waste of man-hours; but the chance of introducing errors is increased.

The quantity of input data needed to run a code, as well as the sensitivity of the code to input value changes, is also an important factor in choosing a code for any particular application. Some codes include their own data libraries, which may or may not be easy to access and update. The user should be aware of the sources of the values included in these data libraries, and know whether they are reliable.

2.1 REFERENCES FOR SECTION 2

1. Compendium of Technical Computer Codes Used in Support of Civilian Radioactive Waste Management: Draft Technical Report, Science Applications International Corporation, 1-147-03-342-00 (1987).

2. S. A. Silling, Final Technical Position on Documentation of Computer Codes for High-Level Waste Management, NUREG-0856 (1983).

3. ATMOSPHERIC DISPERSION CODES

Many previous reports are available which contain compilations and assessments of atmospheric dispersion codes.¹⁻⁵ These compilations were used, along with computer database searches, to complete the list of codes shown in Appendix A. These codes were then subjected to the general assessment criteria to determine the codes to be examined in depth.

One code presently in use within the OCRWM program, AIRDOS-EPA, will be examined along with MESORAD and MATHEW/ADPIC, which are representative of other dispersion models. AIRDOS-EPA utilizes the familiar Gaussian plume model, while MESORAD represents the Gaussian puff model and MATHEW/ADPIC represents the particle-in-cell (PIC) model. These codes were chosen because they are all nonproprietary and well-documented. They also will run on generally available computer systems, although some revisions may be necessary in order to switch between systems. They are also suitable for the release scenarios postulated for a geologic repository. AIRDOS-EPA and MESORAD follow through with a calculation of dose-to-man, which is desirable but not necessary since the air concentration values from ADPIC may be used as input to a dose calculation code.

3.1 ATMOSPHERIC DISPERSION CODE CRITERIA

One very important requirement for an atmospheric dispersion code in the OCRWM program is that the code be suitable for the release scenarios possible for a high-level waste handling or repository facility. These scenarios will

depend on the actual design of the facility, and thus will be determined in more detail later in the repository development program. They may include small chronic stack releases as well as large accidental releases. Some proposed accident scenarios for the preclosure period have been given for a conceptual design of a geologic repository at Yucca Mountain, Nevada.⁶ These include flooding, earthquake, tornado, aircraft impact, underground nuclear explosive testing, fuel assembly drop in a hot cell, and transportation accidents on site. Most of the incidents would lead to an elevated or stack release. Some would include release of heated material, which would involve thermal buoyancy of the plume. The flood scenario would result in dispersion from an area source at ground level. All of these types of releases will need to be dealt with by the atmospheric dispersion codes used in the repository licensing process.

Another very important distinction is whether the code deals with chronic or short-term radionuclide releases. The codes which are based solely on the Gaussian plume model are only able to calculate air concentrations for chronic releases, not from accidental bursts of material. These models calculate annual average air concentrations using annual frequency distributions of meteorological data. Codes which incorporate a "puff" model are generally better suited to accident conditions. Since both chronic and acute releases may occur from a waste-handling or repository facility, codes in both areas will be needed.

The ability of a code to represent dispersion in the presence of buildings and in areas of complex terrain is rather important, especially under accident release conditions where topographic features may divert a plume in a direction different from what annual average conditions would predict. There are many different ways of modeling complex terrain, and much research is presently being performed on this topic under the Atmospheric Studies in Complex Terrain

(ASCOT) program⁷ funded primarily by the Department of Energy. Many of the ASCOT findings have been incorporated into the MATHEW/ADPIC code, which will be discussed later.

There is some question concerning whether centerline or sector-averaged concentrations are most appropriate for radiological assessments. If the dose to the "maximally exposed" individual is desired, the centerline concentration is used; whereas, if average population doses are the end result, one should use sector-averaged air concentrations. Many experts feel that the use of centerline values is overly conservative; since, in real situations, even small wind direction fluctuations will tend to even out the sector distribution of air concentrations. Since both values may be useful, it is desirable that an air dispersion code calculate and report both values.

Care should be taken when using parameters that account for plume depletion by dry or wet deposition or gravitational settling. Often, the parameters for these calculations are not well known; and the use of generic values, which are generally large, may lead to an underestimation of ground-level concentrations downwind. If these parameters are not well-known, it may be better to run the code both with and without deposition, so that the ground-level concentrations may be compared.

One plume depletion mechanism that should be incorporated in the dispersion codes is radioactive decay and ingrowth of daughter products during plume travel. This becomes mainly a bookkeeping task, but could be very important, since the dose to man will depend on the nature and quantity of nuclides present at the exposure point. However, since the high-level waste involved in the source term is assumed to have decayed for at least five years, most short-lived nuclides will have already been depleted; and changes in the plume radionuclide composition during travel may be relatively unimportant.

Other criteria involve the specific capabilities of the codes, such as whether the output air concentrations are represented on a polar or a Cartesian grid. The merit of these capabilities will be better judged by the user of the code and the specific application for its use.

3.2 AIRDOS-EPA

The AIRDOS-EPA code was developed at Oak Ridge National Laboratory for use by the U. S. Environmental Protection Agency.⁸ It employs a modified Gaussian plume model for air dispersion, and follows the calculation through various exposure pathways to dose to man. Annual average ground-level air concentrations at various distances for a continuous source are estimated and are averaged over sixteen 22.5-degree sectors. As an option, the data may be displayed on a 20 X 20 Cartesian grid. As many as 36 radionuclides may be traced simultaneously from up to six stacks or area sources. This code has been used widely for many years, and has the approval of the U. S. Environmental Protection Agency and the Nuclear Regulatory Commission.

3.2.1 Gaussian Plume Model

The Gaussian plume model used in AIRDOS-EPA is the standard atmospheric dispersion model in use today. Its theory and derivation of equations may be found in many references.⁹⁻¹¹ In these derivations, there are some important assumptions and boundary conditions which limit the strict application of the Gaussian plume model.¹¹ These include:

1. stationary, homogenous turbulence conditions;
2. steady-state pollutant concentrations;
3. sufficiently long diffusion time;

4. non-zero wind speed (at least 0.5 m/s);
5. continuity condition holds true
(free atmosphere has no sources or sinks); and
6. total reflection of the plume at the ground surface.

Due to the conditions of long diffusion time and steady-state pollutant concentrations, the Gaussian plume model is best suited for chronic, steady radionuclide releases. In satisfying the condition of steady-state turbulence and the implied need for constant wind speed and direction, the model generally uses some form of average meteorological data. This is often put in the form of a joint frequency distribution of hourly-averaged wind speed, wind direction, and atmospheric stability derived from at least one year of data.

3.2.2 Input Data

The meteorological data needed as input to AIRDOS-EPA includes a joint frequency distribution of reciprocal-averaged wind speed, wind direction, and atmospheric stability class. Wind speeds are categorized to reduce computer run time. Wind direction is divided into sixteen sectors of 22.5 degrees each. Atmospheric stability categories include the standard six Pasquill categories A to F, plus a seventh category, G, for extremely stable conditions during which a plume may travel a great distance. Meteorological input data must also include average rainfall, mixing height, and air temperature.

Other input parameters include release height and annual average release rate for up to 36 radionuclides. If the source is a stack, release velocity, heat release rate, and stack dimensions must be given. For more detailed analysis of input parameters, see refs. 2, 8, and 12.

A code named PREPAR has been developed to aid in the organization of input parameters for use by AIRDOS-EPA.¹³ PREPAR provides default values for all variables, so only the values which need to be changed must be entered. It will then write a data file in the proper format for AIRDOS-EPA, and will print a report of the data values. The report contains warning flags for any apparent mistakes or inconsistencies in the data entered by the user.

3.2.3 Atmospheric Dispersion Capabilities

The dispersion parameters, σ_y and σ_z , used in AIRDOS-EPA are those suggested by Briggs.¹⁴ These curves are the result of a combination of several sets of curves at different distance ranges which were developed by Pasquill and Gifford, Brookhaven National Laboratory, and the Tennessee Valley Authority. Briggs does not recommend these curves for use beyond a distance of 10 km, though some have extended them out to 20 or 30 km. Stability category G has been added to reflect extremely stable conditions which rarely occur in the environment, but which may produce the most conservative air concentration estimates for situations where the maximally exposed individual is far downwind of the source.

The ground-level air concentrations may be averaged for each sector. The method used for averaging compresses the plume within the sector, which may or may not be accurate depending on the atmospheric stability and many other factors. The averaged cross section is shaped as a chord instead of an arc, which does not have a large effect on the output until large downwind distances are reached. The air concentrations may also be listed for the plume centerline.

Plume rise may be calculated according to momentum effects or thermal buoyancy effects, or the value may be input by the user. This can help the user account for the many factors, including (1) wind shear, (2) calm winds, or

(3) building wake effects, which may cause plume rise values to vary over a wide range. Plume rise values may even be input as a negative value to account for downwash, or may be zero to give a more conservative air concentration at close range.

Vertical spread of the plume is limited by the average mixing height which is input by the user. This lid does not affect the plume until the downwind distance, x , equals $2x_L$, where x_L is the value of x for which σ_z equals 0.47 times the lid height. From this point outward, the air concentration is assumed to be uniform between the ground and the mixing lid.

Plume depletion is included in the calculation by the source depletion method which substitutes a new reduced release rate at each downwind distance. The ratio of reduced rate to original rate is calculated for depletion by dry deposition, scavenging (wet deposition), and radioactive decay. Dry deposition is based on a deposition velocity, which may include gravitational settling for larger particulates. This deposition velocity is subject to much uncertainty, since it depends on variables such as soil type, vegetation type, and the specific physical and chemical form of each radionuclide. Wet deposition is based on a scavenging coefficient, which is also subject to the same kinds of uncertainty. Radioactive decay uses well-known effective decay constants which include factors such as parent-daughter equilibrium and ingrowth of daughter products.

3.2.4 Strengths and Limitations

One of the main strengths of AIRDOS-EPA is its relatively long history of use. This has resulted in extensive documentation and several validation studies. One such study^{15,16} compared values calculated by AIRDOS-EPA to

measured concentrations of Kr-85 in the vicinity of the Savannah River Plant. The predicted values were consistently higher than measured values by an average factor of 2.4. Another study¹⁷ compared measured and predicted values at five separate sites. The combined results showed that the predicted values were an average of 12% lower than measured concentrations. Therefore, it appears that AIRDOS-EPA predictions are relatively accurate when compared with measured steady-state concentrations.

The fact that AIRDOS-EPA is well-documented and widely used is an important factor in favor of its use in the OCRWM facility licensing process. This code has been used many times to generate data in support of NRC license applications and other environmental impact statements, and so is generally accepted as suitable for these purposes. The Environmental Protection Agency (EPA) also mandates the use of AIRDOS-EPA in 40 CFR Part 61 for determining compliance with emission standards, unless an alternative code is approved by the EPA.

Most of the limitations associated with AIRDOS-EPA as an atmospheric dispersion code are due to the constraints of the Gaussian plume model. These include the assumptions of constant wind speed, no wind shear, flat topography, and no chemical or physical interactions during plume travel. These ideal conditions are rarely satisfied in real situations, since instantaneous changes in wind direction or speed and terrain features often are encountered. However, many of these variations will average out if long-term, steady-state concentrations are desired.

Another limit of the Gaussian model as applied in AIRDOS-EPA is the uncertainty associated with the dispersion parameters σ_y and σ_z . These parameters are determined empirically and generally are described as functions of downwind distance and atmospheric stability class. Since they are somewhat site-specific, it is recommended that,

where possible, they should be determined for each particular site and at more than one release elevation.¹⁸ However, one of several sets of standard curves is usually implemented. In this case, the use of two sets of curves is recommended - one for a ground-level release and one for an elevated release.¹⁹ One must also be careful in selecting an appropriate stability class, since this choice can result in a factor of four difference between highest and lowest air concentrations calculated from a given set of dispersion parameter curves.¹⁸

3.3 MESORAD

The MESORAD code was developed at Pacific Northwest Laboratory (PNL) for use by the Nuclear Regulatory Commission in responding to emergency situations and accidental releases.²⁰ It uses the Gaussian puff model for calculating atmospheric dispersion, and also calculates external and inhalation doses. Food-chain transport is not included as an exposure pathway. The models used in MESORAD are essentially similar to those in MESOI 2.0,²¹ and due to the modular nature of the codes, MESOI may still be run within MESORAD. Both MESOI and MESORAD are descendants of the MESODIF codes, which were also developed at PNL. MESORAD can trace up to 50 radionuclides during each run. Since it is designed for emergency response applications, the time frame that is modeled is on the scale of hours, rather than days or weeks.

3.3.1 Gaussian Puff Model

The Gaussian puff model used in MESORAD is a variant of the Gaussian plume model, and it treats a plume as the sum of a finite number of puffs released in succession. The air concentration at any point downwind is the sum of the contributions from each puff. Puff models represent spatial

and temporal atmospheric variations more realistically than plume models, while retaining much of the computational simplicity of the straight-line plume models. More information on Gaussian puff models may be found in refs. 9 and 22.

The puff model incorporated within MESORAD includes two important simplifying assumptions. The first is that along-wind and cross-wind diffusion are equal ($\sigma_x = \sigma_y$). This implies that horizontal puff cross-sections are circular and symmetric about the center point, and so the horizontal coordinate system may be re-oriented in any direction. The second assumption is that the puff center remains at a constant height above ground. This height is equivalent to the original release height plus puff rise, and is called the effective release height. This implies that the puff follows terrain contours, rising and falling with the underlying surface.

3.3.2 Input Data

The meteorological input data for MESORAD consists of a three layer wind field, which is defined for the beginning of each simulation period. These simulation periods generally cover one hour or less, depending on the available meteorological data. The lowest wind field layer extends from the surface up to 10 m. This layer may be altered to include the effects of terrain features. Measured or predicted wind data for up to 30 locations are used to define the time-dependent surface wind field at nodes on a 16 X 16 Cartesian grid. The top layer winds are also defined as a function of time and are assumed to be horizontal with no terrain effects. This top layer extends upward from the top of the mixing layer, and so the geostrophic or gradient wind may be used. The intermediate layer lies between 10 m and the top of the mixing layer. Data for this layer are not

required, since the code uses interpolation between the top and bottom layers to define the transport vectors in the intermediate level.

Data files containing release data for up to 50 radionuclides must be supplied as input for MESORAD. A library containing decay information is provided. A time-dependent mixing layer height must also be supplied. More information on data input may be found in ref. 20.

3.3.3 Atmospheric Dispersion Capabilities

MESORAD allows the user to choose among four sets of dispersion parameters. These are (1) the NRC parameters used by MESODIF-II, XOQDOQ, and PAVAN; (2) the Briggs' "open country" parameters; (3) the U.S. Army parameters; and (4) the Start and Wendell approximations to Markee's desert parameters. All of these systems relate σ as a function of downwind distance x , and are described in more detail in ref. 20 and other references given in that document.

Given the nature of the puff model used in MESORAD, there are no "sector-averaged" or "centerline" air concentrations as output. One can obtain the position and size of each puff at hourly intervals. Air concentrations are given as time-integrated concentrations, and include contributions from each puff as it passes the given point. These values are initially calculated assuming no deposition or decay and then are corrected for those species that deposit on surfaces or decay to another species. Concentrations are integrated over both the specific advection period and the entire modeling period.²¹

Surface contamination levels are determined from dry and wet deposition rates, and may also be given both for the duration of one advection period, or for the accumulation of the entire modeling period.

Dry deposition is calculated by means of a source-depletion model. This model assumes that the flux of material to the surface is proportional to the air concentration near the surface, with the proportionality constant being the deposition velocity v_d . MESORAD uses a value of $v_d = 0.01$ m/s for all depositing species. This value is considered by many to be conservative for ground-level doses close to the release, but may result in underestimates of ground-level air concentrations farther downwind.

Wet deposition involves not just near-surface concentrations, but all concentrations above the point of interest. In-cloud and below-cloud scavenging are combined into one process called washout. The model assumes that precipitation removes material from the air in proportion to the precipitation rate and the local air concentration. A washout coefficient is used that is a function of precipitation type and rate.

Puff depletion by radioactive decay is included in MESORAD, and is calculated by the standard decay and daughter ingrowth equations.

The puff is assumed to reflect at the ground surface and at the top of the mixing layer. MESORAD treats this phenomenon by using the concept of virtual sources located below the ground and above the mixing layer. If material is released above the mixing lid, it is allowed to diffuse downward into the mixing layer, but is not allowed to diffuse out of this layer.

The effect of terrain on puff dispersion is included by altering the surface-layer wind fields to account for these effects. This process is not described explicitly, and relies heavily on the user's familiarity with local meteorology and terrain. Terrain data are also used to specify the elevation of the puff center. The height of the puff center above the surface remains constant at the

effective release height, so that the puff is assumed to rise and fall with the underlying surface.

MESORAD incorporates two output grids for air concentrations at receptor sites. The main output is a 31 X 31 Cartesian grid, but the spacing between these receptors may be large enough to allow just-released small puffs to pass between them unseen. This may result in a non-conservative underestimation of the maximum concentration near the release point. To correct this problem, a close-in polar grid has been included, with 108 receptor points at 10 degree intervals along three concentric circles at distances of 800, 1600, and 3200 m. The straight-line Gaussian plume model is used to obtain time-integrated concentrations during the initial passage of the released material. The puff model is used if wind direction shifts occur during this initial transport. Deposition in the close-in polar grid is calculated by the same methods already described.

The size of the domain represented by the Cartesian grid may be increased or decreased by the user to better serve a particular application. Decreasing the grid size will increase the resolution capabilities, but may only be useful if adequate meteorological data are available.

3.3.4 Strengths and Limitations

MESORAD, although relatively recent, is the result of the progression of MESODIF and related codes, which began in 1974. Therefore, there is adequate documentation of the theoretical basis and practical applications of the code. Validation studies involving MESOI and MESODIF have shown the usefulness of those codes, but the studies may be applied only to the transport and diffusion sections of MESORAD. These studies include a comparison of dispersion data from the Idaho National Engineering Laboratory with the output values of MESODIF, MESOI, and MESOJ. The first two codes

overpredicted air concentrations at short range from an elevated release because they both assume surface release. This condition would not be a problem for MESORAD, because it allows the elevation of the release to be specified. All three predictions, however, were in qualitative agreement with the observed data.²³ Future validation studies will be needed to properly document the dose calculation output of MESORAD.

The puff model incorporated in MESORAD has the advantage of being able to represent meteorological variations more accurately than plume models. This is important for modeling accident scenarios and short-term air concentrations. However, several locations for sampling of meteorological data are needed to obtain accuracy that is better than that of the straight-line Gaussian plume codes.

The limitations associated with the atmospheric dispersion section of MESORAD are discussed in detail in the MESOI documentation.²¹ They include the usual uncertainties associated with mathematical modeling of complex realities and with input parameters. The modular nature of MESORAD allows changes to be made within the mathematical models when they are indicated by changes in the state-of-the-science. However, input parameter uncertainties are unavoidable, and they contribute extensively to the available limit of accuracy. Some compromises were also made in order to keep the computer run time for MESORAD low, which is important for accident response applications. These compromises are related to the resolution of the output grid and to the interval used in the time-integration. These factors may be changed by the user if run time is not a major consideration.

3.4 MATHEW/ADPIC

The codes MATHEW and ADPIC were developed at Lawrence Livermore National Laboratory (LLNL),^{24,25} and have been

coupled because of their complimentary capabilities. MATHEW produces a mass-adjusted, three-dimensional wind field which is used as input for ADPIC, which calculates time-dependent air concentrations by the particle-in-cell (PIC) model. Dose calculations are not performed by these codes. MATHEW/ADPIC is particularly suited for dispersion in areas of complex terrain, since the wind field is determined for each specific site to include terrain influences. MATHEW/ADPIC forms the core of the Atmospheric Release Advisory Capability (ARAC) system which was also developed at LLNL.²⁶ ARAC is a real-time emergency response system designed to assess the potential environmental consequences of radiological accidents, and provides services to state agencies, the Department of Energy, and the Department of Defense.

3.4.1 Particle-in-Cell (PIC) Model

The particle-in-cell model used in ADPIC is a mathematically sophisticated representation of gradient transport or K-theory,⁹ in which the theoretically estimated diffusivity coefficient, K , replaces the empirically determined diffusion parameter, σ . The three-dimensional advection-diffusion equation is solved in its flux-conservative form for a given mass-consistent advection field, which, in this case, is provided by MATHEW. The solution is performed by the finite-difference approximation method for a Cartesian coordinate system. The pollutant concentration is represented by Lagrangian "particles," which represent air parcels, imbedded in an Eulerian grid. This procedure is what gives it the name particle-in-cell. Each "particle" is subject to a "pseudo-velocity," which is the sum of the actual advection velocity field vector and the diffusivity velocity; this is determined at each time step based on the cell concentration at the beginning of the time step. Each "particle" is traced independently as it moves

under the effect of this pseudo-velocity, and the concentration at the end of each time step is determined by counting the "particles" in each volume element. This discrete particle concept allows for the straightforward treatment of plume depletion by deposition or decay.

For a more complete description of the theory behind the PIC method, the reader is referred to refs. 9, 25, and 27.

3.4.2 Input Data

In order for ADPIC to perform three-dimensional, time-dependent dispersion calculations, it must have a three-dimensional space-and time-varying wind field, which is supplied by MATHEW. MATHEW divides the region of interest into rectangular volumes, which are set on the lowest topographic point in the area. Terrain features are allowed to extend upwards into the volume. This volume is further subdivided at intervals which are determined by the regional topography, application requirements, and computer storage limitations. These subdivision intervals represent (x,y,z) grid positions at which wind vectors will be specified, if the grid point is above the ground surface. All available meteorological data are used to determine the wind vectors, including ground and elevated measurements. The rest of the grid points are determined by interpolation or extrapolation based on an inverse-square distance weighting scheme. The resulting wind field is then transferred to ADPIC for dispersion calculations.²⁴

An initial Gaussian particle distribution is created within ADPIC as a starting point. The user must specify the initial grid size and the beginning position (x,y,z) of the material within the grid. The length of each time step is another input parameter.²⁷

3.4.3 Atmospheric Dispersion Capabilities

The values of the diffusivity parameters, K_h and K_z , used in ADPIC, may be determined by several methods. One may assume that they remain constant, or they may be defined as functions of the grid coordinates (x,y,z) and time. Since diffusion theory is not yet able to define values of K , they are often calculated as functions of the Pasquill diffusion parameter σ_y , the Monin-Obukhov length, or some other empirically determined value.²⁷

The output air concentration is given for each grid-cell volume as a function of time, and from this one can obtain concentration values at the cloud center or at ground level, also as a function of time.

Dry deposition is modeled using a deposition velocity, and wet deposition due to below-cloud scavenging uses a washout coefficient which is defined for a specified precipitation rate over a given surface area. Surface accumulation is represented on a horizontal grid, and values for instantaneous or time-integrated accumulation are available. Radioactive decay corrections are handled using the standard decay constants and equations.

The grid structure within ADPIC may be either fixed or moving and expanding. The fixed grid may be used for either continuous or puff releases which occur at or near the ground surface. The grid range may cover from 5 to 200 km. The moving and expanding grid is especially suited for single puff releases. The puff trajectory may be followed since the grid automatically expands and travels with the puff. Up to five continuous or puff sources may be introduced into the grid during each run. Continuous sources are modeled as sequential puffs, with one puff released during each time step.

Terrain complexity is treated explicitly by MATHEW/ADPIC, since the wind field used in ADPIC is created

by MATHEW specifically for a certain region's terrain and meteorology. Thus, calm winds and wind shear may be included directly in the structure of the advection field.

3.4.4 Strengths and Limitations

MATHEW/ADPIC has been involved in many validation studies, especially due to its use in the ARAC program. Air concentration values generated by MATHEW/ADPIC have been compared with data from the Chernobyl accident,²⁸ the Oresund over-water experiment,²⁹ the INEL field experiment,²³ the Savannah River tests using SF₆,³⁰ the 1980 ASCOT Geysers nocturnal drainage flow experiment,³¹ and many other sets of data.³² The success of these comparisons was highly dependent on the quantity and quality of meteorological data and on the amount of tuning performed on the MATHEW wind field output. In general, the calculated values were within a factor of 2 for 50% of the measured values, and within a factor of 5 for 75% of the values for experiments in areas of relatively simple terrain. When more complex terrain features were modeled, the results showed a decrease in accuracy to where 20% of the calculated values were within a factor of 2 and 35% within a factor of 5.²⁸

These results show that, even though MATHEW/ADPIC has a sophisticated method of dealing with complex terrain, there are practical limitations to the accuracy of the method. These limitations arise from a lack of accurate representative data and from the need for more work on the theory involved with terrain modelling. The Atmospheric Studies in Complex Terrain (ASCOT) program is involved in the effort of advancing the theoretical and practical aspects of terrain modelling, and future improvements will be incorporated in later versions of MATHEW/ADPIC.⁷

At present, the particle-in-cell model is further restricted by the need for a more accurate determination of

values for the turbulent diffusivity coefficients, K_H and K_Z . These values are especially lacking for regions of complex terrain, and this limits the accuracy of MATHEW/ADPIC in such situations. This limitation is similar to the uncertainties associated with σ_y and σ_z , since both σ values and K values must be fit empirically to measured data.

MATHEW/ADPIC requires extensive computer memory capabilities and, depending on the computer, may require long run times. Therefore, some feel that it may not be generally applicable to emergency response uses.³³ However, with sufficient site-specific meteorological data and a well-tuned advection field, it could provide useful information for a facility license application. In order to "tune" any code to a specific site, one must have substantial data on wind, turbulence, and measured air concentrations. This will require multiple measuring towers, higher altitude measuring devices, and tracer releases.

3.5 Summary and Recommendations

All three of the codes discussed above may be very useful, provided the application is appropriate for the model. In comparing the two Gaussian model codes, AIRDOS-EPA is generally applied to emergency planning, while MESORAD is used for emergency response. In emergency planning, simplifying assumptions concerning the stability of atmospheric conditions may be made, which are necessary for a plume model. These assumptions are often chosen in the interest of worst-case scenario planning. Emergency response requires the use of real-time atmospheric data, for which the puff-type model is better suited. The particle-in-cell model in MATHEW/ADPIC may be useful if a large quantity of meteorological data is available for determining the three-dimensional wind field. This is not generally the case at present, but such data could result from site-

characterization activities to be performed at the repository location.³⁴ Because this data will be so essential regardless of the chosen code or codes, it is important for it to be gathered carefully and thoroughly. This will require a network of well-placed measuring stations and many months of data collection. Experts in meteorology should be involved in this effort.

Of course, there are many other available computer codes which use the same types of models as the three codes outlined in this report, as well as other atmospheric models which have been developed for dispersion studies.³⁵ Some of these other codes are listed in Appendix A. They may be equally appropriate for use, provided they are extensively validated and well-documented. In some cases, it may be desirable to use more than one code so that the outputs may be compared. The user will need to be the judge as to which codes are most appropriate for any specific scenario.

The Nuclear Regulatory Commission has given some guidelines on atmospheric dispersion models to be used for light-water reactors in their Regulatory Guide 1.111.³⁶ This guide discusses the three dispersion models outlined in this report. It states that:

"The preferred model is that which best simulates atmospheric transport and diffusion in the region of interest from source to the receptor location, considering the meteorological characteristics of the region, the topography, the characteristics of the effluent source and the effluent as well as the receptor, the availability and representativeness of input data, the distance from source to receptor, and the ease of application."

This places the burden of proof on the user to demonstrate that the codes are utilized appropriately. Since no

Regulatory Guide is available specifically for high-level waste handling facilities, it is assumed here that the guidelines would be similar to those for light-water reactors.

Many feel that the most suitable model is the simplest model which can be acceptably validated.³⁷ This criterion would seem to point to codes which use the Gaussian plume model, but this may not be the case for situations in which validation studies show that plume models are not appropriate, such as in regions of complex terrain. Again, the user must decide, using all available resources, which code or codes to use.

In the future, recent developments in the areas of diffusion theory and complex terrain will require that models and codes be updated. The user should be aware of these updates and what effect they may have on the output of the code. Input data parameters are also subject to revision in light of future studies and measurements. These revisions may be implemented as the code is updated, or it may be the responsibility of the user to be alert to these changes and update his or her own input data files.

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4. FOOD-CHAIN TRANSPORT CODES

The terrestrial food-chain exposure pathway to man via airborne contamination is an important part of the calculation of dose. A review of Appendix A shows that there are not nearly as many codes in this area as in the atmospheric dispersion or dose-to-man areas. Most of the computer codes which are currently in use for the estimation of terrestrial food-chain transport utilize models which are given in the U. S. Nuclear Regulatory Commission's Regulatory Guide 1.109.¹ These models were derived from those used in the HERMES codes, which assume chronic release and equilibrium exposure conditions.² Codes which use these models, or slight variations of them, include AIRDOS-EPA,³ GASPAR II,⁴ PABLM,⁵ and FOOD.⁶ Since all of the current OCRWM codes use this model, the calculations used in AIRDOS-EPA will be examined in this report in the interest of continuity.

In addition, there are models which accommodate time-dependent transport and accumulation of radionuclides in the food chain and which are therefore useful under accident release conditions. These models are used in the TERMOD code⁷ and also in the more recent RAGTIME⁸ and RAGBEEF⁹ codes. The time-dependent model as used in RAGTIME will be reviewed, since it is well-documented and more general in scope than RAGBEEF.

4.1 FOOD-CHAIN TRANSPORT CODE CRITERIA

Since almost all of the presently available codes use essentially the same model, there are few distinctions to be

made. One major variation among food-chain transport codes is whether they assume equilibrium conditions, as in Regulatory Guide 1.109, or are time-dependent. This factor is important for many of the same reasons as for atmospheric dispersion codes, especially when distinguishing codes for routine or for accident release conditions. Equilibrium conditions never quite occur in real situations, but this assumption is often made in order to simplify calculations for chronic releases. In order to account more realistically for accident release conditions, time-dependent codes are needed.

Another distinction that may be made involves the input parameters for uptake and accumulation of radionuclides by various food items. These parameters may be quite simple - e. g., using a generic value for all types of plants - or they may be very sophisticated. Unfortunately, there are little experimental data available; and often a generic value must be used. These input parameters are being continually updated as new research is completed, and it is desirable that a code have a mechanism for updating values as they become available.

4.2 AIRDOS-EPA

As discussed in Section 3.2, AIRDOS-EPA is a radiological assessment code that performs atmospheric dispersion, food-chain transport, and dose-to-man calculations.³ It was developed at Oak Ridge National Laboratory, and has a long history of use and acceptance by the Nuclear Regulatory Commission and the Environmental Protection Agency in generating data for licensing applications and other environmental impact statements. For estimating radionuclide concentrations in meat, milk, and vegetables, AIRDOS-EPA uses the models contained in the Nuclear Regulatory Commission's Regulatory Guide 1.109.

4.2.1 Regulatory Guide 1.109 Model

The models and equations given in Regulatory Guide 1.109 are designed to be used to calculate annual doses from routine releases from nuclear reactors.^{1,10} These calculations are needed for reactors to demonstrate compliance with the design objectives in 10 CFR Part 50, Appendix I. Equations are given to calculate external, inhalation, and ingestion doses from releases to the atmosphere or to water. To support the calculation of ingestion doses, models are given for the estimation of steady-state equilibrium radionuclide concentrations in meat, milk, and vegetables. The Regulatory Guide also lists suggested values of input parameters for these equations. Separate models are given for ^{14}C and ^3H , since they behave quite differently from other radionuclides.

To calculate radionuclide concentrations in and on vegetation, the model considers material that is deposited directly on the plant tissues or taken up by the roots after being deposited on the soil. The model is given in the Regulatory Guide as Equation C-5, and gives the radionuclide concentration as a function of several variables, including deposition rate of the radionuclide at the particular location, an interception fraction for the vegetation, and a concentration ratio for root uptake of the specific radionuclide from soil. The values of these parameters may be varied to account for different crops, soil types, and primary consumers.

For vegetation exposed to ^{14}C in the form of CO or CO_2 , Equation C-8 is given. $^{14}\text{CO}_2$ is assumed to be mixed homogeneously in the atmosphere and to be absorbed by plants at a ratio equal to the ratio of ^{14}C to natural carbon in the surrounding air. The $^{14}\text{CO}_2$ then is used by the plant in photosynthesis and is incorporated into the plant tissue.

Tritium is assumed to be incorporated into water molecules as ^3HOH , which is then absorbed by plant tissues in much the same way as $^{14}\text{CO}_2$. The equation given for ^3H concentrations in vegetation is given in Regulatory Guide Equation C-9.

To calculate radionuclide concentrations in milk, one must have an estimate of the amount and contamination level of the animal's feed. An intake-to-milk transfer coefficient, which gives the average fraction of daily intake that appears in each liter of milk, must also be assumed. Allowances may be made for an intake of a combination of fresh pasture grass and stored feed. These models are given in Equations C-10 and C-11 of the Regulatory Guide.

A similar process is used to estimate radionuclide concentrations in meat products. One must estimate the amount and contamination level of the feed, and an average fraction of daily intake which appears in each kilogram of flesh. This model is given in Equation C-12 of the Regulatory Guide.

4.2.2 Input Data

As is indicated by the numerous and lengthy equations described above, the number of necessary input parameters for food-chain transport calculations using AIRDOS-EPA is quite large. A complete listing is given in Table 6 of ref. 3. These parameters include the number of meat or milk producing animals in the area, the agricultural productivity by unit area, the deposition velocities, the interception fractions, the soil-to-plant transfer factors, and the fractions of daily intake that appear per liter of milk or kilogram of meat.

Other suggested values or ranges of values for these input parameters are given in refs. 10-15. The user must

decide on the most appropriate value to use if the parameter may not be directly measured in the field.

As discussed in Section 3.2.2, the PREPAR code is available to help organize input data for use in AIRDOS-EPA.¹¹ PREPAR is interactive and provides default values for parameters which the user does not want to change. The code then writes a data file in a format appropriate as input to AIRDOS-EPA.

4.2.3 Food-Chain Transport Capabilities

AIRDOS-EPA distinguishes between pasture grass consumed by cattle and fresh produce used directly by man by using different values of the agricultural productivity and the concentration factor for uptake of radionuclides from soil.

It is assumed that radioactive decay is the only process that removes radionuclides from the soil, so physical removal by weathering is not included. However, one may use a washing factor to account for the removal of surface contamination from foods during preparation for consumption by man.

As part of its output, AIRDOS-EPA prints a value for annual ingestion rate in picocuries per year for each radionuclide and environmental location. These values then may be compared with annual intake limits recommended by the ICRP to provide a measure of the relative health risks to the population.

4.2.4 Strengths and Limitations

Some of the strengths of AIRDOS-EPA are discussed in Section 3.2.4. One of its more important strong points is the large body of documentation concerning this code. The wide use and general acceptance of AIRDOS-EPA are other factors in favor of the use of this code for the OCRWM

licensing process. The use of NRC models for food-chain transport also helps make AIRDOS-EPA an acceptable code.

However, these NRC models have some shortcomings of which the user should be aware. The use of annual average deposition rates to calculate crop concentrations does not account for seasonal factors, such as the length of the growing season and the feeding of non-pasture grass to livestock during the winter. There may also exist some positive correlations that could have a significant effect on food-chain concentrations. An example is the possible correlation between deposition rates and crop assimilation when the relationship between rainfall and crop growth is considered.¹⁰ In this case, the use of annual average deposition rates may lead to a non-conservative estimate of radionuclide concentrations.

Another limitation of the NRC equilibrium models is the inability to simulate daughter-product ingrowth during transport through food chains. Equilibrium concentration factors are used to distribute radionuclides between food-chain levels or compartments, and so the dynamic nature of radioactive decay may not be directly incorporated.¹⁰ AIRDOS-EPA attempts to correct this problem by adding the daughter isotopes to the source term at the point of deposition.³

As with the use of most models, the selection of input parameter values is a large source of uncertainty. The literature contains quite a variety of parameter values from which to choose.¹⁰⁻¹⁵ As an example, values of the interception fraction for forage grasses range from 0.02 to 0.82.¹² This wide range may be attributed to several factors, such as seasonal variations and differences between species of grass. The values chosen for a specific application will depend on the needs, interests, and considerations of the user. Someone who is attempting to determine compliance with regulations may choose very

conservative values, while someone who is interested in more representative results may choose values closer to the geometric mean of the given range.¹⁰ The user should be aware of these uncertainties and present them clearly with the results. A helpful discussion of statistical distributions associated with food-chain transport parameters is given in ref. 12.

4.3 RAGTIME

The time-dependent food-chain transport code RAGTIME⁸ was developed at Oak Ridge National Laboratory. The model uses first-order linear differential equations, with time as the independent variable, which are solved by the GEAR package.¹⁶ This method attempts to account for seasonal and other variations that occur in real agricultural situations. However, the model is still in development, and so is presented here mainly as a comparison to the historical equilibrium approach and as an important possible improvement that merits further study.

4.3.1 Time-Dependent Food-Chain Transport Model

The RAGTIME model assumes a known time-dependent deposition rate over a given location with interception by above-ground food crops, the soil below the crops, pasture grass, and the soil or root mat under the grass. Each of these interception fractions may be time-dependent to represent the growth dynamics of crop land or pasture. Since interception is related to the surface area and shape of the intercepting surfaces, plants are placed in one of five categories based on morphological characteristics.

Root uptake is also time-dependent in the RAGTIME code. This allows for variation in uptake related to the growth of the plant, the different physiological stages in the life

cycle of the plant, or changes in the soil concentration due to leaching or radioactive decay. Uptake is also dependent on each specific element, and so is related to the ingrowth of daughter products with time.

Other transfer coefficients, such as the rate of transfer from pasture grass to beef or milk, are time-independent pending further investigation. The values of these coefficients therefore are similar to those for the equilibrium transport model described earlier.

The processes within the model are described by differential equations, which are solved using the GEAR package.¹⁶ These solutions are checked for accuracy by using an explicit solution of the Bateman equations to determine the total quantity of radioactivity in the system. The sum of the activities from each compartment as calculated by GEAR is compared to this total to determine the level of agreement.

4.3.2 Input Data

The input parameters used in RAGTIME are even more complex than those for equilibrium food-chain transport codes, since many of the parameters that had been constant are allowed to be time-dependent. However, there are very few available experimental data to provide time-dependent values for many of the parameters, and so constant values such as those given for the equilibrium model must be used. Representative constant values are given in refs. 10-15. A complete listing of input parameters for RAGTIME is given in Section 6 of ref. 8.

4.3.3 Food-Chain Transport Capabilities

At present, RAGTIME may handle one decay chain during each run with up to fifteen radionuclides per chain. The

values for branching ratios must be input by the user. The input source of radioactivity may be described as a step function for each radionuclide in the decay chain. The time-dependent nature of the model allows for an explicit representation of radioactive daughter ingrowth, which is an important improvement over the equilibrium model.

The output of the code includes concentration values at specific time steps and an integrated value for a given time interval.

4.3.4 Strengths and Limitations

The main advantage of the RAGTIME code, over codes which use an equilibrium model, is the increased ability to represent dynamic seasonal factors and ingrowth of radioactive daughters during transport through food-chain compartments. The use of differential equations as opposed to normal algebraic equations allows these variations to be described explicitly.

These capabilities are not yet utilized fully due to a lack of appropriate parameter values. As discussed in Section 4.2.4, equilibrium values for these parameters are not known with much precision, and time-varying values are even less determinate. However, the option is available for these values to be utilized once they have been determined experimentally.

RAGTIME allows for more specific plant information to be used than in the Regulatory Guide 1.109 equilibrium model. The equilibrium model only distinguishes between food crops and pasture grass, whereas the model used in RAGTIME allows for food crops to be broken down into five categories based on morphological characteristics. Of course, this ability is dependent on the availability of appropriate data.

RAGTIME currently is being evaluated in the Biospheric Model Validation Study (BIOMOVS),¹⁷ where its output will be

compared with food-chain transport data from the Chernobyl accident,¹⁸ and with the results of other codes which use the equilibrium model, such as AIRDOS-EPA.

Since this code is still in development, the available documentation is not yet sufficient to support its use in a licensing effort. However, the advances represented by the time-dependent model warrant future investigation.

4.4 SUMMARY AND RECOMMENDATIONS

Of the models currently available for representing radionuclide food-chain transport, the ones contained in NRC Regulatory Guide 1.109 are most often used for generating dose estimates in support of license applications and environmental impact statements. If one were to choose another model, such as the time-dependent model in RAGTIME, the NRC would need to be convinced that it is an acceptable substitute. Since there are few data at present to define the parameters used in the time-dependent model, the equilibrium concept seems to be the most suitable one for use in the OCRWM site characterization and licensing effort. Future improvements in the time-varying food-chain transport parameter data base may make it feasible to use such codes as RAGTIME to obtain more representative data for situations where acute releases or seasonal variations are involved.

As mentioned before, there are many available codes from which to choose that use essentially the same equilibrium models as given in NRC Regulatory Guide 1.109. The selection of a particular code will depend on the needs of the user. AIRDOS-EPA may be an appropriate choice, especially if atmospheric dispersion and dose calculations are also desired, since it is well-documented and widely accepted. GASPAR II is another possible selection, since it uses the same model, is also very well-documented, and is already in use within the OCRWM program. GASPAR II computes dose-to-

man, but does not perform atmospheric dispersion calculations.⁴

4.5 REFERENCES FOR SECTION 4

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5. DOSE-TO-MAN CODES

As with the previous two sets of computer codes, there are quite a few codes which calculate dose to man, but the number of different models represented is limited. Most codes calculate external dose from immersion in contaminated air by the semi-infinite cloud model and the dose from exposure to a contaminated ground surface by the infinite plane model. Internal dose models are based on recommendations of the International Commission on Radiological Protection (ICRP). These recommendations are updated periodically to reflect advances in internal dose calculations. While our present regulations generally use dosimetry data from ICRP Publication 2 (1960),¹ they are now being revised to reflect the changes represented by ICRP Publications 26 (1977)² and 30 (1979).³ These changes form an important distinction between currently used dose codes.

After applying the general criteria given in Sect. 2, two codes were selected for study. AIRDOS-EPA⁴ is in use within the OCRWM program, and represents the standard models currently being applied. MESORAD⁵ is distinct in using a finite-cloud external dose model, although it does not include a method for calculating an ingestion dose.

5.1 DOSE-TO-MAN CODE CRITERIA

Once values for air concentration and soil or food contamination are known, most codes simply employ usage factors and dose conversion factors to calculate the resulting dose. Usage factors are quantities that determine the amount of exposure to an individual or population, such as breathing rate, ingestion rate, and exposure time. Dose conversion factors give the dose per unit radionuclide concentration (for external doses), or per unit intake (for internal doses). It is important that the code's data libraries of dose conversion factors and usage factors be up-to-date, or that it be relatively easy for the user to update these files. There are DCF's for external irradiation, inhalation, and ingestion exposure pathways, and they may be calculated based on a number of different models.

The dose to the skin, total body, or internal organs from external exposure to radionuclides in the air may be calculated using the semi-infinite or a finite cloud model. The semi-infinite model assumes that the air concentration at the point of exposure is uniform throughout the surrounding air. It therefore is not appropriate for calculating the dose at ground level from an elevated plume. The finite cloud model calculates the dose from each discrete volume of air, whether at ground level or not, and so improves the accuracy of the dose estimate. This is especially true near the point of release, where the plume may be elevated or have

a vertical and horizontal extent comparable to the photon mean free path in air.

The dose from a contaminated ground surface is almost always calculated using the assumption that the surface is an infinite, smooth, and uniformly contaminated plane. This is considered conservative, since ground contours and limited contaminated areas would serve to reduce the dose.

Radioactive decay and/or a weathering model may be included as a means of reducing external dose over time from a contaminated ground surface. However, downward migration of activity into the soil usually is not included explicitly.

For calculating dose from inhaled radionuclides, some codes still employ the lung model from ICRP Publication 2.¹ One of these codes is GASPARI-II, which is currently used in the OCRWM program. This model is very simple, and only distinguishes between soluble and insoluble particles when defining deposition fractions and retention half-times. This model was replaced in 1966 by the ICRP Committee 2 Task Group on Lung Dynamics.⁶ In the Task Group lung model, deposition in the lung takes place in three compartments and retention is represented by ten compartments, each with their own retention fractions and half-times. Particulate deposition depends on the size of the inhaled particle, and clearance rate depends on the site of deposition as well as the physical and chemical properties of the particulates.

The dose resulting from radionuclides deposited internally by ingestion or by absorption from the lung may be calculated using ICRP Publication 2¹ or Publications 26² and 30.³ The model presented in Publication 2 considers only the dose to a target organ from radionuclides in that organ. The later publications include dose to a target organ from radionuclides in other source organs. They also give weighting factors for determining the effective dose equivalent from the dose equivalents in several organs and tissues. While making the calculations much more complex,

these additions improve the realism of the model, and provide a dosimetric quantity which is a surrogate for risk.

Realism is also increased by using age-dependent DCF's. Metabolic and organ-mass differences that occur with age can have a significant effect on the uptake and retention of radionuclides and the resulting dose. An example is the thyroid dose from radioiodine. Children have a much higher uptake of iodine than adults and also have smaller thyroids, which results in a higher dose from the same exposure. The U. S. Nuclear Regulatory Commission's Regulatory Guide 1.109⁷ contains age-dependent DCF's, but they are based only on the differences in organ mass and do not reflect changes in metabolism with age. Present and future research will help to better define age-dependent DCF's, which will further improve dose estimates for members of the general public.

5.2 AIRDOS-EPA

AIRDOS-EPA, as discussed in Sections 3.2 and 4.2, is a widely used and accepted code for estimating atmospheric dispersion, food-chain transport, and dose-to-man.⁴ Doses are calculated for eleven organs, including the total body, from exposure to radionuclides via immersion in air or water, external exposure to contaminated ground surfaces, inhalation, and ingestion of contaminated food. Atmospheric dispersion of up to 36 radionuclides may be performed within the code, or values of air concentration per unit release rate (X/Q) and deposition rate per unit release rate (D/Q) may be input by the user. AIRDOS-EPA uses ICRP models and dose conversion factors for internal exposures.

5.2.1 AIRDOS-EPA Dose Models

The gamma dose to the total body and internal organs from immersion in contaminated air is estimated using the

semi-infinite cloud model. This model assumes a hemispherically infinite cloud of uniform concentration. Dose conversion factors for the skin are supplied to the code as input data for each radionuclide, and these factors are multiplied by external dose correction factors to obtain dose factors for the total body and internal organs.

The gamma dose from contaminated soil is calculated at one meter above the surface assuming an infinite, smooth, uniformly contaminated surface. Allowance is made for time-dependent buildup of radionuclides, but radiological decay is the only removal mechanism. Environmental removal by weathering is not included. Dose-conversion factors and external dose correction factors for the total body and reference organs are supplied as input as they are for the external cloud-dose calculation.

The dose commitment from inhalation of radionuclides is estimated using the ICRP Task Group lung model⁶ and the ICRP Publication 30 dosimetric models.³ These models have been used to compute dose conversion factors for each radionuclide based on the dose commitment from the intake of one microcurie. These dose conversion factors, which are supplied as code input, include contributions from daughter radionuclides which are formed internally due to the decay of the inhaled parent radionuclide. The appropriate breathing rate must also be specified.

AIRDOS-EPA calculations for the concentration of radionuclides in food products are described in Section 4.2.1. They are based on the models of U. S. Nuclear Regulatory Commission Regulatory Guide 1.109.⁷ The annual dose commitment to each organ is calculated using dose conversion factors with units of rem per microcurie ingested. The rates of ingestion for each food product must be specified by the user, and may represent an average individual or a maximally exposed individual. ICRP Publication 30³ dosimetric models are used in the calculation

of the dose conversion factors, which include contributions from daughter radionuclides that grow in after the parent radionuclide has been ingested.

Dose calculations for tritium (^3H) and ^{14}C are performed separately from the other radionuclides because these two nuclides display unique behavior in the environment (see Sect. 4.2.1). Tritium is assumed to become associated with water molecules and to follow water through the environment and the food chain. Therefore, doses from both ingestion of food and from drinking water are calculated. The concentrations of tritium in food and water are assumed to be equal to the concentration in the surrounding air, which is considered to be a highly conservative assumption. Dose conversion factors are then used as before. There are also tritium dose factors for inhalation and skin absorption. ^{14}C ingestion doses are calculated assuming that the specific activity in human tissue is equal to the activity in the surrounding air. Dose conversion factors for each organ are used to calculate the dose.

5.2.2 Input Data

AIRDOS-EPA requires extensive data libraries, some of which have been discussed in Sects. 3.2.2 and 4.2.2. Data libraries which are needed for dose calculations include (1) dose conversion factors, (2) external dose correction factors, (3) usage factors, and (4) population data. These data libraries are always being updated to reflect newly published data, and site-specific values may be added by the user.

Values in present use for external cloud and ground surface dose factors and external correction factors are taken mainly from ref. 8. Inhalation and ingestion dose factors are taken from ref. 9; these data are similar to

those obtained using the dosimetric models in ICRP Publication 30.³

On-going research into better ways of determining age-specific dose conversion factors will result in future updates of these data libraries.

Specific population data may be input for a site so that the population dose may be calculated. The user must provide for each sector (1) the number of people, (2) the number of meat and milk producing animals, and (3) the area of crop production land. Intake parameters, including the fraction of ingested food products that is brought in from uncontaminated areas, must also be provided. A complete listing of input parameters is given in Table 6 of ref. 4.

The code PREPAR may be used to organize data for input to AIRDOS-EPA.¹⁰ PREPAR is an interactive code that contains all the needed data files and allows the user to change any appropriate values. The output from PREPAR is a data file in the necessary format for input to AIRDOS-EPA.

5.2.3 Dose-to-Man Capabilities

AIRDOS-EPA will calculate either the population dose or the dose to the maximally exposed individual. Population doses assume average individual intakes, while maximally exposed individual doses are based on maximum intakes. These doses may be displayed on a 20 X 20 Cartesian grid or a sixteen-sector polar grid.

In calculating ingestion doses, the user has the option of specifying the fraction of food ingested in the assessment area that is actually produced in that area. The concentrations in each food type are weighted averages over the whole assessment region. For an extremely conservative result, the user may specify that no food is imported and that all ingested food products come from the assessment area.

The output from AIRDOS-EPA is often used in conjunction with the codes DARTAB¹¹ and RADRISK.¹² DARTAB is used to calculate doses and predict health effects from the AIRDOS-EPA environmental concentration data. The dose conversion factors are slightly different from the ones in AIRDOS-EPA, since DARTAB generally calculates the 70-year committed dose from internal exposures, while AIRDOS-EPA calculates the 50-year committed dose. The RADRISK code is used to generate a dosimetric and health effects data base for use by DARTAB. Both DARTAB and RADRISK were developed at Oak Ridge National Laboratory for use by the Environmental Protection Agency.

5.2.4 Strengths and Limitations

The strong and weak aspects of AIRDOS-EPA concerning atmospheric dispersion and food-chain transport calculations have been discussed in Sects. 3.2.4 and 4.2.4. Some of these will also apply in the area of dose-to-man, since air and food concentration values are used in the calculation of dose.

Dose calculations from AIRDOS-EPA have been involved in many validation studies. An example is given in ref. 13, which compares observed doses from the TMI incident measured with thermoluminescent dosimeters (TLD's) with doses predicted using AIRDOS-EPA. The predicted doses were within a factor of 2 of the measured doses when a ground-level release was assumed.

There are limitations involved with the use of the semi-infinite cloud approximation for calculating external gamma dose. In cases where the plume has not reached ground level, the air concentration and the external dose are assumed to be zero, even though there may be a significant dose from the elevated plume. In these cases, the AIRDOS-EPA documentation advises that this dose be calculated separately and added to the immersion dose calculated by the code.⁴ In cases of a

ground-level release where the plume does not have much of a vertical extent, the semi-infinite cloud model may overestimate the external immersion dose, since there is actually less radioactivity above the individual than the model assumes.

The most important strength of AIRDOS-EPA lies in its wide acceptance and use, and the fact that it is mandated for use by the Department of Energy and the Environmental Protection Agency for evaluating radiological impacts from airborne releases. It is also extensively documented, which is an important factor in the quality assurance process.

5.3 MESORAD

The MESORAD code⁵ was discussed in Sect. 3.3 in conjunction with its Gaussian puff atmospheric dispersion model. MESORAD was developed at Pacific Northwest Laboratory as an emergency response tool for the Nuclear Regulatory Commission. It is a descendent of the MESOI¹⁴ and the MESODIF codes with the addition of dose calculations for the air immersion, ground-surface exposure, and inhalation pathways. Food-chain transport is not treated by MESORAD.

MESORAD uses a combination of the semi-infinite cloud and the finite puff model for calculating external dose. The dose from contaminated ground assumes a uniform concentration on a flat infinite plane. Inhalation doses are estimated using dose conversion factors from three different models, depending on the nature of the inhaled radionuclide.

5.3.1 MESORAD Dose Models

The external dose to the total body from radionuclides in a passing puff may be calculated by one of two methods, depending on the degree of dispersion of the puff.

For ground-level releases or for puffs that have travelled far enough to have dispersed adequately, the puff is modelled as a semi-infinite cloud with uniform concentration. A puff is considered to have dispersed adequately when σ_y and σ_z are large compared to the mean free paths of the gammas being emitted in the puff. The sum of the time-integrated air concentrations of each radionuclide times a dose factor for that radionuclide gives the total body dose at that receptor location. This model is very easy to implement, but may seriously underestimate the dose at ground level near an elevated release.

For elevated releases and for puffs with relatively small sigma values, the finite puff model is used. To speed the calculations, the discrete point approximation is applied instead of the complete point-kernel integration technique. The puff is confined to a cylinder with radius $2\sigma_y$ and height $6\sigma_z$. The cylinder height is also subject to ground and mixing layer boundaries. The cylindrical puff is then divided into three vertical sections, from three to eight radial sections, and from three to eight angular sections. The number of sections depends on the dimensions of the puff and the distance to the receptor point. The radionuclides contained in each differential volume are assumed to be at the center of the volume, thus the discrete point approximation. The dose at the receptor point from each volume is computed using the point-kernel method including the buildup factor, and these doses are summed to get the total dose at that point. This model better accounts for the actual radionuclide distribution in the puff and for situations where elevated plumes are important.

The external dose to total body from contaminated ground is determined by assuming the ground to be a flat, infinite, uniformly contaminated surface. Since the ground concentration is calculated both for the duration of one advection period and for the duration of the entire modelling

period, the dose from ground contamination may be calculated as a dose rate or an integrated dose. Deposited radionuclides are removed or transformed by decay but not by weathering. Whole-body dose factors are used to calculate dose from the ground concentration of radionuclides.

Dose from inhaled radionuclides is determined as a fifty year committed dose to total body, lungs, and the thyroid. Two different models are used to calculate dose conversion factors. In general, the ICRP Publication 2¹ lung model is used for noble gases that do not tend to deposit or absorb, and so do not contribute to doses other than to the lung. The Task Group lung model⁶ is used for other radionuclides that will be absorbed and contribute to other organ doses. The more sophisticated compartmental approach of the Task Group model is needed to describe this behavior. The dose conversion factors for the total-body and the lung are based on parameters which apply to an adult's body. The thyroid dose factors, however, are based on a child's body, since the iodine uptake of a child's thyroid is significantly higher, and therefore the child's thyroid dose is higher than an adult's under the same exposure conditions.

5.3.2 Input Data

MESORAD contains data files for dose conversion factors and for radionuclide gamma energies and fractional yields. Dose conversion factors for exposure to a semi-infinite cloud were calculated using the MESOINF code and gamma data derived from ref. 15. Dose factors for exposure to contaminated ground were also taken from ref. 15. Inhalation dose factors for noble gases were derived from ref. 16, those for other radionuclides from ref. 17, and the remainder from ref. 3. The radionuclide gamma energies and fractional yields were taken from refs. 18 and 19. The values contained in these data files are listed in Appendix C of ref. 5.

The necessary values of air and ground concentration are calculated earlier in the code sequence. Input parameters for these calculations are described in Sect. 3.3.2.

5.3.3 Dose-to-Man Capabilities

MESORAD dose calculations concentrate on a maximally exposed individual, since the code is designed for accident response applications. The whole body dose to a maximally exposed individual is used in an accident scenario to determine what protective measures may be needed. MESORAD also calculates lung and thyroid doses. The total-body and lung doses are calculated for a standard adult; but the thyroid doses use parameters for a child, since the child's thyroid dose is higher than an adult's under similar exposure conditions. These doses are calculated at each receptor location, both on the 31 X 31 Cartesian grid and the close-in polar grid described in Sect. 3.3.3.

MESORAD is able to accommodate decay chains with one parent and one radioactive daughter. Each parent radionuclide may have more than one daughter. However, if there are more than two radionuclides in a chain, an attempt has been made to combine parents and daughters that occur in secular equilibrium as if they were one radionuclide and assign them one set of dose conversion factors based on this combination. This process would effectively remove one daughter from the decay chain and reduce the number of necessary calculations without affecting the accuracy of the dose estimate. Therefore, it was also used even in instances where there were two-member decay chains, in an effort to reduce computer run time.

5.3.4 Strengths and Limitations

One of the most important strengths of the MESORAD code for dose calculations is the use of the finite puff model for external doses. This model is somewhat more realistic than the semi-infinite cloud model, particularly for estimating doses close to an elevated release. The use of the finite puff model is supported by MESORAD's Gaussian puff atmospheric dispersion model, which gives time-dependent air concentrations of radionuclides in each puff. Both of these models are especially useful for describing accident scenarios.

Some error is introduced by the use of the discrete point approximation instead of the point-kernel integration technique, but this error has been shown to no greater than 10%.⁵ On the other hand, the necessary computer time may be reduced by a factor of 100. Compared to the uncertainties involved with the general process of modelling and choice of parameter values, this 10% error is not significant.

The uncertainties associated with input parameters are complicated by the frequency with which these values are updated and revised. The user must attempt to keep abreast of these revisions and keep the data libraries up-to-date while also maintaining all necessary documentation of these changes.

5.4 SUMMARY AND RECOMMENDATIONS

As mentioned in Sect. 5.1, the calculation of dose from environmental concentrations essentially involves the use of dose conversion factors which are tabulated in the literature (refs. 3, 8-9, 15-17). The choice of a model is therefore included in the choice of a set of dose conversion factors. A good code will be able to keep abreast of the frequent updates in dose factor values.

AIRDOS-EPA and MESORAD have the ability to keep up-to-date with advances in the science of dose calculations, since their data libraries may be accessed and revised. This fact may pose some problems for documentation and configuration control that will need to be handled properly for codes used in the repository licensing effort (see Sect. 7.3). However, it also facilitates the use of the most recently published data, or of site-specific data, which may improve the accuracy of the code output.

In comparing the dose components of AIRDOS-EPA and MESORAD, AIRDOS-EPA has the advantage of handling all of the major atmospheric exposure pathways, including food-chain transport. MESORAD's major strength is the implementation of the finite-cloud external dose model which includes dose from an elevated plume.

5.5 REFERENCES FOR SECTION 5

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6. DOSE LIMIT REGULATIONS

The maximum permissible dose to members of the general public from the management and storage of high-level wastes is defined by the Environmental Protection Agency (EPA) in 40 CFR Part 191.¹ The design criteria needed to meet these

standards are given by the Nuclear Regulatory Commission (NRC) in 10 CFR Part 60.²

The EPA also has promulgated regulations limiting the emission of all hazardous air pollutants in 40 CFR Part 61.³ Subpart I of this document applies to facilities licensed by the NRC, which would include the high-level waste repository as well as the MRS facility. The maximum annual dose equivalent to any member of the public from the emission of radionuclides in the air may not exceed 25 mrem (0.25 mSv) to the whole body or 75 mrem (0.75 mSv) to any critical organ.

The EPA's regulations for the management and storage of spent nuclear fuel, high-level, and transuranic radioactive wastes in 40 CFR Part 191 limit the total dose from all exposure pathways, and they are more restrictive than the limits given in 40 CFR Part 61 for airborne emissions. 40 CFR Part 191 states that the combined annual dose equivalent to any member of the public from such management and storage operations may not exceed 25 mrem (0.25 mSv) to the whole body, 75 mrem (0.75 mSv) to the thyroid, and 25 mrem (0.25 mSv) to any other critical organ.

The NRC regulations in 10 CFR Part 60 cover the design objectives necessary for the high-level waste repository or the MRS facility to meet the dose limits given in 40 CFR Part 191. Both preclosure and postclosure operations are included.

6.1 REFERENCES FOR SECTION 6

1. U. S. Environmental Protection Agency, "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," Code of Federal Regulations, Title 40, Part 191 (1987).

2. U. S. Nuclear Regulatory Commission, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," Code of Federal Regulations, Title 10, Part 60 (1988).
3. U. S. Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants," Code of Federal Regulations, Title 40, Part 61 (1987).

7. FINAL SUMMARY AND RECOMMENDATIONS

7.1 SUMMARY

A selected group of computer codes from the areas of atmospheric dispersion, food-chain transport, and dose-to-man have been reviewed. A list of over 150 such codes was compiled, from which four codes were selected for inspection. Code selection was based on (1) the suitability of the model, (2) the completeness of the documentation, (3) the availability of the code, (4) the present use of the code within the OCRWM system, and (5) the overall usefulness of the code. Code capabilities, especially as related to the needs of OCRWM and its repository development program, have been highlighted. The strengths and limitations of each code were also discussed.

In the area of atmospheric dispersion, AIRDOS-EPA, MESORAD, and MATHEW/ADPIC were reviewed. These codes represent the Gaussian plume, Gaussian puff, and particle-in-cell models, respectively. In general, AIRDOS-EPA is designed for emergency planning and routine emissions and MESORAD is designed for emergency response. MATHEW/ADPIC is limited in its usefulness by the large volume of meteorological data which is required for defining its three-dimensional wind fields, but it has the potential for dealing explicitly with complex terrain effects. All three of these

codes have been involved in validation studies that show their usefulness in various applications.

The codes AIRDOS-EPA and RAGTIME were reviewed in the area of food-chain transport. AIRDOS-EPA incorporates the equilibrium transport model described in the U. S. Nuclear Regulatory Commission Regulatory Guide 1.109,¹ and RAGTIME represents a time-dependent transport model. Both of these models suffer from the uncertainties associated with input values for such variables as the interception fraction for activity deposited on vegetation and plant/soil bioaccumulation factors. These variables are all extremely site- and season-specific, and they represent a potentially large source of uncertainty in the calculation of ingestion dose. AIRDOS-EPA has a long history of use, while RAGTIME is still in the development stage. However, the time-dependent model in RAGTIME shows potential for significantly improving the description of food-chain transport.

In the area of dose-to-man, the codes AIRDOS-EPA and MESORAD were chosen. AIRDOS-EPA represents ICRP models for ingestion and inhalation dose calculations, and it uses the semi-infinite cloud immersion dose model and the infinite plane surface model for external dose calculations. MESORAD is distinct in using the finite-cloud model for external dose calculations, but it does not compute a dose for the ingestion pathway and does not always use ICRP Publication 30 models for calculating inhalation doses.

7.2 CODE RECOMMENDATIONS

Due to the complexities associated with atmospheric modeling and the many models available for dealing with different scenarios, it is unlikely that any one atmospheric dispersion code could be determined to be the best for all applications. The selection of a code will need to be done by experts familiar with the peculiarities of the site to be

modeled. In some cases, it may be beneficial to use more than one code and compare their outputs.

The areas of food-chain transport and dose-to-man are somewhat easier to resolve. Until time-dependent values for food-chain variables are better determined, the model of choice seems to be the equilibrium model given in U. S. Nuclear Regulatory Commission Regulatory Guide 1.109.¹ The fact that it is recommended by the Nuclear Regulatory Commission makes it a particularly good selection for OCRWM activities. The internal dose models given by the ICRP in their Publications 26² and 30³ and in the report of the Task Group on Lung Dynamics⁴ are most often used to calculate dose conversion factors. External dose factors derived from the semi-infinite cloud immersion model and the finite-plane ground contamination model also are chosen most frequently.

Pending a more complete assessment, the present code of choice for calculating dose-to-man from atmospheric and food-chain pathways would seem to be AIRDOS-EPA. This code has a large body of documentation already in place that shows its usefulness and applicability for many release scenarios. AIRDOS-EPA is mandated for use by the Environmental Protection Agency in 40 CFR Part 61, Subpart I,⁵ for demonstrating compliance with the regulations in that document. It also has the endorsement of the Department of Energy, and it has been accepted many times for use in Nuclear Regulatory Commission licensing applications. There are many limitations associated with AIRDOS-EPA, some of which are highlighted in this report. Potential users should be very aware of these limitations and how they might affect the usefulness of the code output in their specific situation. For example, in cases where the external dose from an overhead plume may be important, the writers of AIRDOS-EPA recommend that this dose be calculated separately and added to the overall external dose estimate.

It is important to keep in mind the developing nature of models and codes. Research involving complex terrain modeling and age-dependent dose conversion factors will soon allow models to be improved even further, and these newer models will be incorporated into new and existing codes. Therefore, code assessment should be an on-going effort, and new codes should not be overlooked in the selection process.

7.3 GENERAL RECOMMENDATIONS

The following recommendations are suggested as areas for future work.

1. In order for a code to withstand licensing scrutiny, it must be very well-documented (see Sect. 2.0). In researching the codes in present use within the OCRWM system, many were found to be lacking in this area. If these codes are to continue in use, this problem must be remedied. Thorough documentation is essential for quality assurance and for general code usability.
2. Quality assurance has recently become a very important part of any work related to the OCRWM program. Therefore, any codes used in the OCRWM program will need to be brought into compliance with all relevant quality assurance guidelines.⁶ In order to insure this compliance, it may be advantageous to organize a code distribution center, where codes with the proper quality assurance and configuration control can be distributed for use by OCRWM contractors.
3. On-site validation studies should be performed to help determine the usefulness of a code for the site in question. A large body of data from the Nevada Test Site area already exists, which may be of use if the

Yucca Mountain site remains as the one chosen for the high-level waste repository. These data include lengthy meteorological measurement records and tracer release studies.⁷

4. It is important that ample meteorological data be gathered carefully and thoroughly during site-characterization. Output from a code can be no more accurate than the input values used. Meteorological experts should be involved in this data collection, to help insure that it is done properly. Quality assurance is also an important consideration during this process.
5. This preliminary study should be followed by a more thorough assessment of these code categories. This assessment will need to cover such topics as uncertainty analysis and sensitivity analysis, and it should discuss the practicalities involved with actually running the codes.

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APPENDIX A

OTHER COMPUTER CODES FOUND IN THE LITERATURE

Appendix A

Other Computer Codes Found in the Literature

<u>Code</u>	<u>Atmospheric Dispersion</u>	<u>Food Chain</u>	<u>Dose to Man</u>	<u>Reference</u>
2BPUFF	X	X	X	2
ACRA(I, II, TRIT)	X		X	2
ACRO			X	3
AEOLUS	X		X	5
AERIN			X	2
AIRBORNE	X			3
AIREM	X		X	2
AIRWAY	X		X	2
AISITE2	X		X	2
AMRAW	X	X	X	2
ARCON	X	X	X	6
AREAC	X		X	2
AREAS	X			2
ARTEMOVA*	X			6
ARTRAN	X			2
ATM	X			2
BELCH	X	X	X	2
BETA			X	6
BIOTRAN		X		2
BOOTH*		X		8
BURP(1, 2)	X	X	X	2
BUSH			X	3
CAAC	X	X	X	3
CDCS	X	X	X	5
CEDRIC			X	6
CHARAK*	X			7
CLEARY*	X			5
CLOUD	X		X	2
COMO			X	5
COMPLEX1 #	X			1
COMRADEX(I-IV)	X		X	2
CRAC(I, II)	X		X	2
CUEX/AIRMOD/TERMOD	X	X	X	2
CWMS/INPREP	X		X	5
DACRIN #	X		X	2
DARTAB			X	3
DIFOUT	X		X	5
DINT-YAEC	X		X	3
DOSE	X		X	2
DOSE B	X		X	5
DOSE1			X	3
DOSES	X		X	5
DOSHEM			X	4
DWNWND	X			3
EERIE			X	6

<u>Code</u>	<u>Atmospheric Dispersion</u>	<u>Food Chain</u>	<u>Dose to Man</u>	<u>Reference</u>
EFDOS	X		X	3
EGAD	X		X	2
EMERALD (NORM, REV1)	X		X	3
ENGELMANN*	X			7
ESDORA	X		X	3
EXDOSE	X		X	2
EXGAM	X		X	2
EXREM (I, II, III)			X	2
FOOD		X	X	2
FOODWEB		X		2
GASDOSE/DOSET	X		X	2
GAMMA	X		X	2
GASDOSE #	X	X	X	1
GASPAR #		X	X	3
GAUCHE		X	X	2
GDOS	X		X	6
GRONK	X	X	X	2
HAARM (1, 2, 3B)	X			5
HADOC			X	3
HARAD	X			3
HEFFTER*	X			5
HERMES	X	X	X	2
ICRP		X	X	2
IDC			X	3
IMPACT			X	2
INDOS (1, 2, 3)			X	2
INGDOS		X	X	2
INHDOSE	X		X	2
INHEC	X		X	5
INPUFF (I, II)	X			10
INREM (I, II)			X	2
IODES			X	3
ISOLA (I, II)	X		X	6
KABEL*		X		5
KAO*	X			5
KAROL*	X			5
KRONIC	X		X	2
LENGENMANN*		X		5
LEWELLEN*	X			5
LONGTM	X			5
LOUIS*	X			5
LUDWIG*	X			5
MCGRATH*	X			5
MDW4	X			5
MESO	X			5
MESODIF (I, II)	X			2
METEO (1, H, N)	X			6
MILDOS	X		X	3
MILLS*	X			6

<u>Code</u>	<u>Atmospheric Dispersion</u>	<u>Food Chain</u>	<u>Dose to Man</u>	<u>Reference</u>
MO142	X		X	5
MSDM	X			5
MUNDO	X		X	6
NOWICKI*	X		X	7
NUBE	X		X	2
PABLM #			X	2
PATH1		X	X	2
PAVAN #	X			3
PDIMLUST	X			5
PLUDOS	X		X	3
PLUME	X		X	6
PLUMEX	X		X	3
PREDO	X		X	2
PROTEUS	X			9
PTXXX #	X			5
PUDEQ			X	6
RACER	X		X	2
RADOS	X		X	2
RADRISK #			X	3
RADS/ARADS	X			2
RAMM		X		2
RANDERSON*	X			5
RAR	X			2
REDIQ			X	5
RIDER*	X		X	5
RISC	X		X	5
RPM(I, II)	X			2
RRR	X			3
RSAC(I, II)	X		X	2
RUBY			X	5
SATO*	X		X	6
SAURON			X	6
SCOPE 2.0 #	X		X	1
SDIST	X			5
SEP	X			2
SHEARER*	X			5
SHERMAN*	X			6
SPEEDI	X		X	3
STAREL/RELISH	X			2
STRAPII	X		X	6
SUBDOSA	X		X	2
SUBPOPA	X		X	2
TEM	X			2
THUNDERHEAD			X	2
TIMED			X	3
TIMIN		X		2
TIRION	X		X	3
TRAVIS*	X			6
UDAD	X		X	2

<u>Code</u>	<u>Atmospheric Dispersion</u>	<u>Food Chain</u>	<u>Dose to Man</u>	<u>Reference</u>
UNAMAP	X			5
USNRDL			X	9
UTM	X			2
VADOSCA/GAS	X	X	X	6
VALLEY #	X			5
VITTL5		X	X	2
VOELZ*	X		X	6
WEERIE	X		X	3
WOLGA	X		X	6
WRAITH	X		X	3
WRED	X		X	2
XOQDOQ #	X			2
YIELDS			X	5
ZUCCARO*	X			6

* Refers to author's last name

Codes presently in use in OCRWM programs

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61. D. Livingston, U. S. Department of Energy, Nevada Operations, Waste Management Project Office, P. O. Box 98518, Las Vegas, NV 89193.
62. J. Waddell, Science Applications International Corporation, 101 Convention Center Drive, Las Vegas, NV 89109.
63. W. Colglazier, Waste Management Research and Education Institute, University of Tennessee, 327 South Stadium Hall, Knoxville, TN 37996.

64. F. L. Parker, Professor of Environmental and Water Resources Engineering, Vanderbilt University, 24th Avenue South, Box 1596, Station B, Nashville, TN 37235.
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