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Technical Manual and User's Guide for MILDOS, Version 4.1

Office of Nuclear Regulatory Research

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Technical Manual and User's Guide for MILDOS, Version 4.1

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ABSTRACT

The MILDOS computer code is used to estimate the radiological impacts of airborne emissions from uranium mining and milling facilities. The code allows users to consider both conventional uranium ore operations and operations associated with *in situ* recovery (ISR) facilities. The code is used by license applicants and U.S. Nuclear Regulatory Commission staff to perform routine radiological impact and compliance evaluations for various uranium recovery operations. As part of a major code update, the following improvements and additions were made to the code: (a) revised ISR models, (b) support for ores containing thorium-232 (Th-232) and its daughter radionuclides in addition to the currently supported uranium-238 (U-238) and its daughter radionuclides, (c) a revised area source model, (d) the capability to perform sensitivity analysis on specific input parameters, (e) the capability to use current meteorological data provided by the National Centers for Environmental Information, and (f) an interactive results module.

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ABBREVIATIONS AND ACRONYMS

AMAD   activity median aerodynamic diameter
ASOS   Automated Surface Observing System
AWOS   Automated Weather Observing System

CFR   *Code of Federal Regulations*
CPU   central processing unit
CSV   comma separated value

DB   database
DC   dose coefficient
DLL   dynamic link library
DoD   U.S. Department of Defense

ECL   effluent concentration limit
EPA   U.S. Environmental Protection Agency

FAA   Federal Aviation Administration

GDAL   Geodata Data Abstraction Library
GEIS   Generic Environmental Impact Statement
GIS   geographical information system
GUI   graphical user interface

HTML   HyperText Markup Language

ICRP   International Commission on Radiological Protection
IDE   integrated development environment
ISHD   integrated surface hourly data (also ISD, ISH, TD-3505, DS3505, DSI-3505)
ISR   *in situ* recovery
IX   ion exchange

JFD   joint frequency distribution

MPC   maximum permissible concentration

NCDC   National Climatic Data Center
NCEI   National Centers for Environmental Information
NRC   U.S. Nuclear Regulatory Commission
NWS   National Weather Service

ORNL   Oak Ridge National Laboratory
OS   operating system

PC   personal computer

QA   quality assurance
QC   quality control

SFC	AERMET surface file (*.SFC)
SRDT	solar radiation/delta-T
SSP	site-specific
STAR	STability ARray (format)
TGLM	Task Group on Lung Dynamics
UDAD	uranium dispersion and dosimetry
USGS	U.S. Geological Survey
UTC	universal time coordinated
UTM	universal transverse Mercator
VB.NET	Visual Basic .Net
WL	working level
WLM	working level month

1 INTRODUCTION

The MILDOS (MILDOS4) computer code is used to estimate the radiological impacts from airborne emissions from uranium milling and mining facilities. It provides the capability to consider both conventional uranium ore operations and operations associated with *in situ* recovery (ISR) facilities. The code is used by license applicants and U.S. Nuclear Regulatory Commission (NRC) staff to perform routine radiological impact evaluations for various potential uranium recovery operations. This manual reflects changes in the code through version 4.1.

1.1   Background

The original MILDOS program (Strenge and Bander, 1981) estimated the air emission releases from uranium ore milling operations and the resulting human exposure. The program incorporated source term release, media concentration, and human exposure models found in the NRC's *Final Generic Environmental Impact Statement on Uranium Milling* (GEIS; NRC, 1980). The GEIS used the dispersion models in the Uranium Dispersion and Dosimetry (UDAD) program, version IX (Momeni et al., 1979), and the radionuclide media concentration and exposure models found in UDAD and draft NRC guidance (Draft RH 802-4) published in May 1979. MILDOS was the direct outgrowth of an earlier version of the UDAD code, UDAD IV. Draft RH 802-4 was subsequently published as NRC Regulatory Guide 3.51, *Calculational Models for Estimating Radiation Doses to Man from Airborne Radioactive Materials Resulting from Uranium Milling Operations* (NRC, 1982). In 1987, the recommended methods used in estimating source term releases as originally used in the GEIS (NRC, 1980) were published as NRC Regulatory Guide 3.59, *Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations* (NRC, 1987).

Models were included in MILDOS to consider both point sources (stacks, vents) and area sources (ore pads, tailing areas). Releases of particulates explicitly considered were limited to the radionuclides U-238, Th-230, Ra-226, and Pb-210. Other radionuclides were implicitly accounted for under the secular equilibrium assumption. Gaseous releases were limited to consideration of Rn-222 plus in-growth of decay products.

The external, inhalation, and ingestion dose coefficients (DCs) used in MILDOS were taken from the GEIS (NRC, 1980), and they, in turn, were the factors used in UDAD (Momeni et al., 1979). The external DCs were adopted primarily from Trubey and Kaye (1973). The inhalation DCs had been calculated by the UDAD computer code (Momeni et al., 1979) in accordance with the Task Group on Lung Dynamics (TGLM) lung model of the International Commission on Radiation Protection (ICRP) (ICRP, 1966, 1972). Ingestion DCs were based on the ingestion models in ICRP Publications 2 and 10A (ICRP, 1959, 1971), with the DCs taken from Hoenes and Soldat (1977). The dose to exposed individuals was calculated for comparison to the requirements of both the U.S. Environmental Protection Agency's (EPA's) Environmental Standards for the Uranium Fuel Cycle (40 CFR Part 190) and the NRC's Standards for Protection against Radiation (10 CFR Part 20).

MILDOS-AREA (Yuan et al., 1989) became the next iteration of MILDOS in 1989. Primary changes to the code (a) allowed it to run on a personal computer (PC) rather than a mainframe computer of the time; (b) included a new, large, area source model; and (c) used more up-to-date DCs. The internal DCs were calculated by using the methodology from ICRP

Publications 26 and 30 (ICRP, 1977, 1979) and the NUREG/CR-4628 report prepared by Oak Ridge National Laboratory (ORNL) for the NRC (Cristy et al., 1986).

By 1998, MILDOS-AREA version 3 was available. A graphical user interface (GUI) had been added to facilitate user input, and ISR sources had been added to the code. The 1989 version of MILDOS-AREA compared the annual average air concentrations to the maximum permissible concentrations (MPCs) in 10 CFR Part 20. On January 1, 1994, a revision to 10 CFR Part 20 (revised Part 20) went into effect. The revised Part 20 updated its dosimetry to the ICRP 1977 recommendations. The changes led to a revision of the calculated allowable concentrations for unrestricted areas, with MPCs being replaced by the term "effluent concentrations." Those changes were incorporated into version 3 of MILDOS-AREA.

1.2   Revisions to MILDOS

As of version 4.1, MILDOS-AREA is now known once again simply as MILDOS. Versions 4.02 and later of the code are 64-bit applications written to be executed on PCs running on Windows 7 through 10 operating systems (OSs). The components used in the code to enhance program operation and performance were selected based on, when possible, minimizing potential installation problems on user machines and promoting code longevity (i.e., using stable components or methods that would not likely be affected by near-term changes in the OS or related functions).

Since the introduction of *in situ* leach uranium recovery facility calculations into MILDOS-AREA, the code's Visual Basic GUI performed preparatory calculations for input to the main FORTRAN calculations written for the original uranium ore calculations. All MILDOS4 calculations are now performed together, in Visual Basic .Net (VB.Net); they are separate from the user input.

1.2.1   Maintained Features

Along with the new features and updates discussed in the next section, MILDOS4 maintains the functionality of version 3 of the code to assist the NRC with uranium recovery evaluations. Figure 1-1 presents the structure of the exposure pathway calculations performed. Uranium-238 and its daughters are explicitly analyzed. Exposures (inhalation/external/ingestion) can be calculated for both individuals and the population in the surrounding 80-km area. Exposure calculations are specific to four different age groups: infant, child, teenager, and adult. Particulate emissions, air dispersion, and uptake can be broken down into and evaluated for different particle size groups. Time steps and adjustment factors are available for the evaluation of different phases of mining/milling operation. Checks against regulatory standards are performed. One minor feature not carried forward into the new version is discussed in Section 1.2.3.

1.2.2   New Features and Updates

A number of new features and updates were applied to the program, in addition to upgrading it to run on the latest Windows operating systems. These features and updates are discussed in Sections 1.2.2.1 through 1.2.2.9. They include: (a) revised ISR models, (b) support for ores containing Th-232 and its daughter radionuclides, (c) a revised area source model, (d) the capability to perform sensitivity analyses on specific parameters, e) the capability to use current meteorological data provided by the National Centers for Environmental Information (NCEI) or from other sources, and (f) an interactive results module.
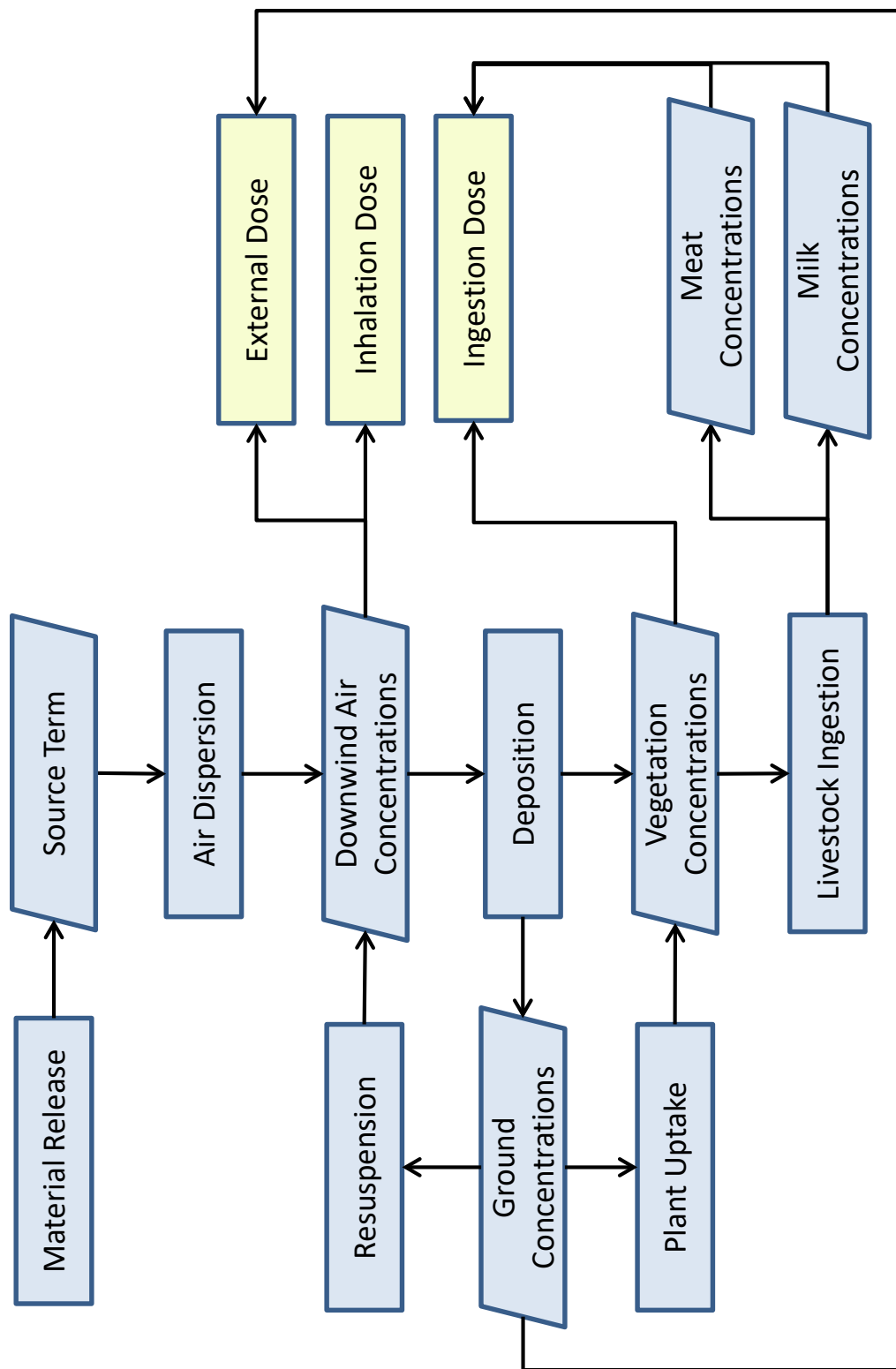
Figure 1-1 Structure of Exposure Pathway Calculations in MILDOS4

This section also addresses other improvements to the program, which include more robust data management with the use of a database for data input/output, the use of a geographical information system (GIS) module to replace the current graphic display, expanded user access to key model parameters, and updated program Help features.

1.2.2.1 Revised ISR Models

The original ISR release models in MILDOS-AREA for new, production, and restoration well fields were treated as point sources. As of version 4.1, these sources are now modeled as true area sources. In addition, the radon vent release as part of the production and restoration well field sources is now the basis for the well field source type; the production and restoration designations are no longer used as source type definitions. The purge (bleed) radon release formerly included in the production and well field sources is now a separate point source release type. Similarly, the radon release from the ion exchange process formerly included in the production well field source is now a separate point source release type. These changes were made so that ISR scenarios could more accurately represent the geometry (location) of radon releases in the vicinity of nearby receptors because well fields are area sources and the purge and ion exchange components are generally not at the center of a well field.

1.2.2.2 Thorium Ores

Thorium ores are important as alternate feed sources, with natural Th-232 and its daughter radionuclides presenting hazards similar to those of uranium ores currently considered in MILDOS4. The revised code handles additional radionuclides in a manner similar to that used for U-238 and its daughters. These additional radionuclides include Th-232, Ra-228 (assumed to be in equilibrium with short-lived Ac-228), and Th-228 (assumed to be in equilibrium with short-lived Ra-224 and Rn-220). Like the hazards presented by the decay products of Rn-222 in the U-238 decay chain, the Rn-220 daughter products are handled in a manner similar to that used for the Rn-220 working level (WL) calculations.

1.2.2.3 Revised Area Source Model

The revised area source air dispersion model is a refined version of the existing chronic Gaussian plume model in MILDOS-AREA 3. The area source model contains adjustments for momentum and buoyant plume releases, plume depletion and deposition, and plume reflection. The virtual point source and finite element analyses for area sources were replaced with a model that automatically divides the area source into multiple point sources and calculates an average air concentration from the individual air concentrations associated with the point sources. The model thus eliminates any assumptions made with regard to the geometry of the area source when the air dispersion calculations are run. Optional dispersion coefficients for releases at ground-level and higher elevations are also available.

1.2.2.4 Meteorological Input Processor

A meteorological data input processor was developed to generate the three-way joint frequency distribution (JFD) of wind speed, wind direction, and atmospheric stability class in STability ARray (STAR) format used by the atmospheric dispersion model. The processor converts meteorological data provided in the current standard format by surface meteorological stations (integrated surface hourly data [also known as ISH, ISD, ISHD, TD-3505, DS3505, or DSI-3505] format). Most surface meteorological data are from the: (a) Automated Surface Observing System (ASOS) program, which is a joint effort of the National Weather Service (NWS), Federal

Aviation Administration (FAA), and U.S. Department of Defense (DoD), and (b) Automated Weather Observing System (AWOS) program, which has been operated and controlled by the FAA in the United States, as well as by state and local governments and some private agencies. These data, which have undergone standard quality assurance/quality control (QA/QC) reviews, are available at stations around the world and at about 1,000 stations in the United States. Other data formats are also supported.

1.2.2.5 Sensitivity Analysis

Sensitivity analysis helps users identify important parameters and understand site issues. Such an analysis examines changes in the results when one parameter is changed slightly. Most input parameters in MILDOS4 are available for use in a sensitivity analysis.

1.2.2.6 Input/Output Data Management

User input for MILDOS4 is contained in a database (DB) file instead of a text file (which was used in previous versions of the program). Using a relational database is well suited to the needs of the MILDOS4 application because it enables an interactive user output format. The program generates a basic output (text) file in HyperText Markup Language (HTML) format as the result of an application run using a given DB input file. The output contains an input echo for QA purposes. Intermediate and final results are stored in the DB file, which the user can further manipulate to obtain different output formats for a given case.

The user DB input file contains the user input parameter values as well as calculated results. A separate program DB contains parameter definitions and the upper- and lower-limit values for each input parameter, if applicable. The upper- and lower-limit values are used as part of the error checking associated with user input that was added for version 4. These values are not intended to be modified by the user.

1.2.2.7 Geographical Information System Module

Previous versions of MILDOS-AREA 3 had a rudimentary graphics display as an aid for problem definition; it provided a view of the relative positions of potential emission sources and potential receptors. A GIS module replaces the previous graphics display. Users can enter source/receptor coordinates through text input, as they did in past versions of MILDOS-AREA, or by clicking on the map in the location desired. MILDOS4 also now offers the ability to define irregularly shaped area sources by using a point-and-click map interface.

1.2.2.8 Expanded Access to Model Input Parameters

Access to more of the parameter values used in the MILDOS models is now available to facilitate a more site-specific analysis of the problem at hand. Individual receptor shielding and occupancy fractions are user-definable. Input values to the wind erosion model are also accessible, if the necessary data are available. Other expanded inputs include particulate densities and deposition velocities, resuspension factors for resuspended material air concentrations, weathering factors, crop growing periods, food transfer factors, and retention factors. The existing values that were used for such parameters in the past versions of the code remain as the default values.

The options for some input parameters have been expanded to afford a more site-specific analysis. The ingestion exposure pathway for population analyses allows for definitions for the

vegetable, meat, and milk production grids that are similar to the definition for the population grid, rather than a single average value for vegetable, meat, and milk production rates for a given area.

1.2.2.9 Updated Program Help

Input parameter definitions and their upper- and lower-limit values are available to the user by pressing a function key when a specific parameter has the input focus.

1.2.3   Discontinued Analyses

Past versions of MILDOS-AREA provided a population dose estimate for the continental United States. Because this calculation was based on previous (outdated) analyses and provides no current regulatory function, a continental U.S. population dose estimate is not calculated in version 4.

1.3   <u>Report Organization</u>

This manual first presents the models necessary to perform the dose calculations, in the order in which they are used. The rest of the document then provides information on using the code and reviewing the results. The various radionuclide sources and their associated air emissions are discussed in Chapter 2. Chapter 3 covers the atmospheric dispersion of the emitted material downwind. Media concentrations (air, ground, plant, and food) at the receptor locations are covered in Chapter 4. Potential dose rates are discussed in Chapter 5. Program operation and reviewing results are covered in Chapters 6 and 7, respectively. References are provided in Chapter 8. The appendices provide additional program details (Appendix A); a list of the DCs used by MILDOS4 (Appendix B); details on the new meteorological data conversion option (Appendix C); derivation of the resuspension model (Appendix D); some guidance on using GIS data (Appendix E); input parameter definitions, defaults, and limits (Appendix F); and variable definitions (Appendix G).

2 SOURCE MODELS

Air emission sources emit gases or particulates and can be represented as point or area sources. Section 2.1 discusses the various mining and milling operations that could result in air emissions. The radionuclides in these emissions considered by MILDOS4 are covered in Section 2.2. The different source types used to model these emissions and the methodology behind each one are discussed in Section 2.3.

2.1   Mining and Milling Methods

Two primary recovery methods are currently used to extract uranium from ore. A conventional uranium mill recovers uranium from ore mined from a conventional underground or surface hard rock mine; it is similar to the mills used to mine other metals and coal. ISR, formerly known as *in situ* leach recovery, involves the injection of a chemical solution into the ore body to dissolve and mobilize the uranium for extraction.

2.1.1   Conventional Ore Mining and Milling

Uranium ore is delivered to the mill, where it may be stockpiled before being processed. The ore is loaded into a machine in which it is crushed and/or ground into smaller particles before the uranium is extracted. The uranium is leached from the ground particulates by using sulfuric acid in most cases, although alkaline solutions can also be used as the leaching agent. Approximately 90 to 95 percent of the uranium is extracted from the ore.

The extracted uranium is concentrated and dried to produce yellowcake (U_3O_8). The dried U_3O_8 is packaged and shipped for further processing into enriched uranium and reactor fuel. "Tailings" are a remnant of the leaching process; they are what remains of the ground particulates. They have the consistency of a rough sand and are generally stored outdoors in large piles. These piles remain a source of radon and particulate emissions until they are remediated.

2.1.2   *In Situ* Recovery

In a typical ISR mining site (Hunter, 1996), a licensee uses a series of injection wells that introduce dissolved oxygen and/or hydrogen peroxide along with sodium carbonate/bicarbonate into the ore zone. The uranium becomes mobilized and is extracted through a series of pumping wells. The uranium-rich water is routed through a processing building, where the uranium is removed from the water by ion-exchange (IX) columns. The loaded IX resin is then processed to remove the uranium (elution). The eluted uranium is further processed into a concentrated uranium slurry. The slurry is then dried into yellowcake (U_3O_8). The dried U_3O_8 is packaged and shipped for further processing into enriched uranium and reactor fuel.

Some ISR facilities have smaller processing plants located remotely from the main processing plant. These plants, called satellite facilities, generally collect the uranium in resin tanks and then ship the loaded resin to the main processing plant for elution, drying, and packaging. The satellite facilities let the licensee economically mine uranium located some distance away from the main processing plant. All applicable ISR source types defined in MILDOS4 are discussed in Sections 2.3.3 through 2.3.6.

2.2   Radionuclides

MILDOS4 estimates the human health exposure due to air emissions from uranium recovery operations. The mining and milling of uranium ore specifically involve risks posed by U-238 and its daughter products. Other uranium isotopes are not considered by the program because of their low relative concentrations and thus their negligible contribution to the overall dose. (For example, the next most abundant uranium isotope, U-235, constitutes about 0.72 percent of the uranium present in natural ores. By contrast, U-238 constitutes about 99.27 percent, yet both pose a similar radiological risk.) In addition to uranium minerals, the ore can contain other radionuclides. One such radionuclide, Th-232 (and its daughter products), is often found in uranium ore, and, depending on its concentration, it can pose a radiological risk along with that posed by uranium. MILDOS4 estimates the human health exposure to both U-238 and Th-232 and their decay series.

2.2.1   Uranium-238 Decay Series

The U-238 decay series is shown in Figure 2-1. With the shorter half-lives of Th-234, Pa-234m, and U-234 compared to that for U-238, MILDOS4 considers U-234 to be in secular equilibrium with U-238 for particulate releases from naturally occurring uranium ores. As such, MILDOS4 only accepts values for U-238 concentrations for hard-rock ore source terms in addition to values for Th-230, Ra-226, and Pb-210 concentrations. Section 6.3.2 covers user input for the various source types modeled. Similar to the U-238/U-234 case, Bi-210 and Po-210 are considered separately but assumed to be in secular equilibrium with Pb-210.

Inhalation exposure, as presented in Section 5.2.2, relies on calculated air concentrations (Section 4.2.2) of U-238, Th-230, Ra-226, and Rn-222. For those radionuclides not explicitly considered in the calculations, the contribution of these short-lived isotopes is incorporated into their parent DCs. External exposure from deposited radionuclides (Section 5.2.1) includes ground concentration calculations (Section 4.1) for the longer lived Rn-222 decay isotopes Po-218, Pb-214, and Bi-214 in addition to the particulate release source term radionuclides U-238, Th-230, Ra-226, and Pb-210. Due to the relatively short half-lives of most of the U-238 decay series, only U-238, Th-230, Ra-226, and Pb-210 are explicitly considered in calculating ingestion doses (Section 5.2.3) from human consumption of vegetables, meat, and milk (Sections 4.3 and 4.4).

2.2.2   Thorium-232 Decay Series

The Th-232 decay series is shown in Figure 2-2. Aside from Th-232 itself, its daughter products are generally much shorter-lived than those in the U-238 decay series. For Th-232 particulate release source terms, Th-232, Ra-228, and Th-228 are explicitly evaluated with Ac-228 considered to be in secular equilibrium with Ra-228 and Ra-224 considered to be in secular equilibrium with Th-228.

Uranium-238   Uranium-234

α | 4.5 billion years   α | 240,000 years

β   250,000
1.2 minutes

Protactinium-234m

β
24 days

Thorium-234   Thorium-230

α | 77,000 years

75,000

Radium-226

α | 1,600 years

NOTES:

The symbols α and β indicate alpha and beta decay, and the times shown are half-lives.

An asterisk indicates that the isotope is also a significant gamma emitter.

Uranium-238 also decays by spontaneous fission.

Radon-222

α | 3.8 days

Polonium-218   Polonium-214   Polonium-210

α | 3.1 minutes   α | 160 microseconds   α | 140 days

β   β
20 minutes   5.0 days

Bismuth-214*   Bismuth-210

β   β
27 minutes   22 years

Lead-214*   Lead-210   Lead-206 (stable)

Figure 2-1 Uranium-238 Decay Series

Inhalation exposure is calculated for Th-232, Ra-228, Th-228, and Rn-220. External exposure is calculated for deposited Th-232, Ra-228, Th-228, and the Rn-220 daughter products Po-216, Pb-212, and Bi-212. As is the case for the U-238 series, ingestion exposure considers only those radionuclides with half-lives comparable to or longer than the amount of time associated with crop growth and storage before consumption: Th-232, Ra-228, and Th-228.
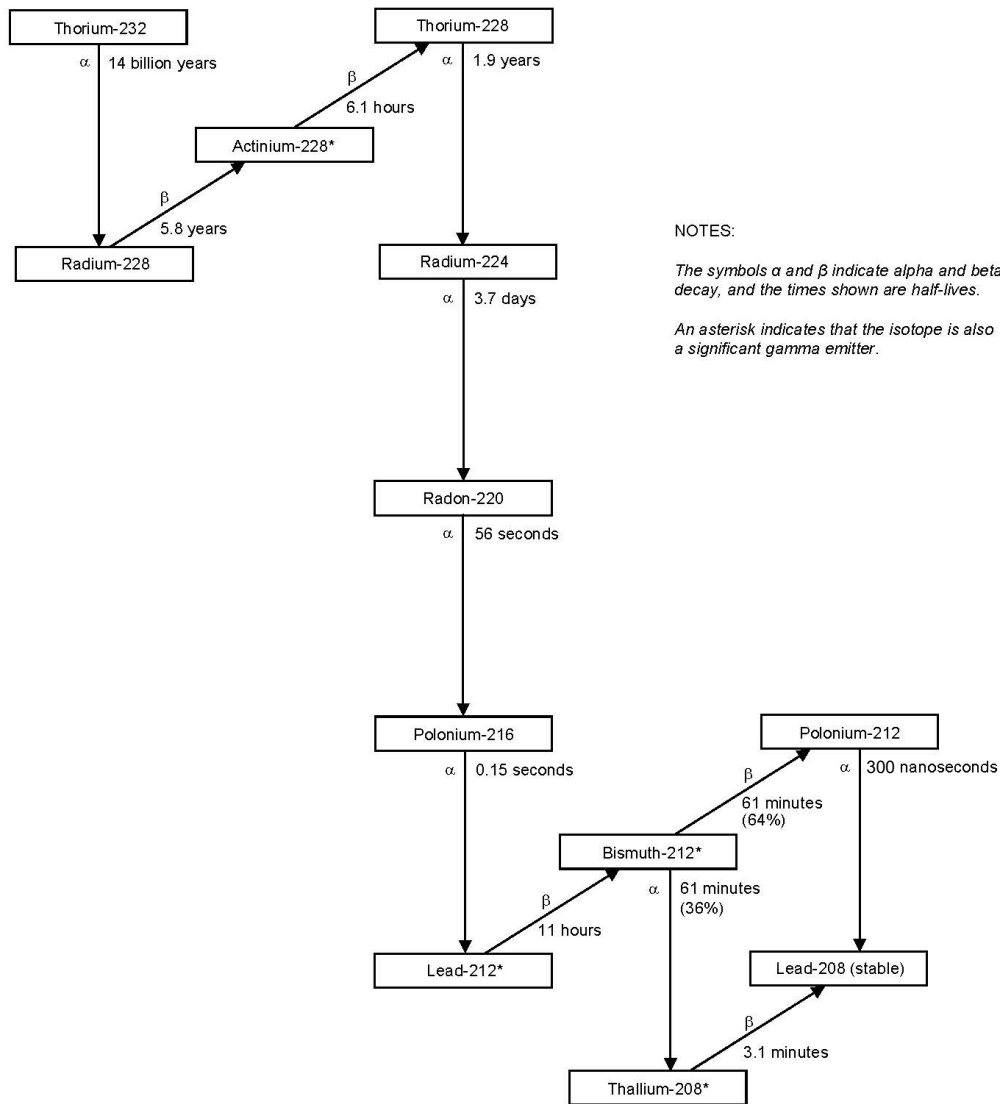
Figure 2-2 Thorium-232 Decay Series

2.2.3   Radionuclides Evaluated

Table 2-1 presents the list of radionuclides in the uranium and thorium series for which user input is required (source release), and media concentrations are specifically calculated. Air concentrations (Section 4.2) are used to estimate doses from inhalation (Section 5.2.2) and external exposure (Section 5.2.1). Ground concentrations are used to estimate resuspended air concentrations (Section 4.2.1), plant concentrations (Section 4.3), and doses from external exposure (Section 5.2.1). Food concentrations (Sections 4.3 and 4.4) are used to estimate ingestion exposure (Section 5.2.3).

Table 2-1 Radionuclides Considered in MILDOS4 Dose Estimate Calculations

Series[a]	Radionuclide	Half-Life	Source Release	Air Concentration	Ground Concentration	Food Concentration
U	U-238	4.5×10^9 yr	X[b]	X	X	X
	Th-234	24 d	—[c]	—	—	—
	Pa-234m	1.2 min	—	—	—	—
	U-234	2.5×10^5 yr	—	—	—	—
	Th-230	7.5×10^4 yr	X	X	X	X
	Ra-226	1.6×10^3 yr	X	X	X	X
	Rn-222	3.8 d	X	X	—	—
	Po-218	3.1 min	—	X	X	—
	Pb-214	27 min	—	X	X	—
	Bi-214	20 min	—	X	X	—
	Po-214	1.6×10^{-4} s	—	—	—	—
	Pb-210	22 yr	X	X	X	X
	Bi-210	5.0 d	—	X	—	—
	Po-210	0.38 yr	—	X	—	—
Th	Th-232	1.4×10^{10} yr	X	X	X	X
	Ra-228	5.8 yr	X	X	X	X
	Ac-228	6.1 h	—	—	—	—
	Th-228	1.9 yr	X	X	X	X
	Ra-224	3.7 d	—	—	—	—
	Rn-220	56 s	X	X	X	—
	Po-216	0.15 s	—	X	X	—
	Pb-212	11 h	—	X	X	—
	Bi-212	61 min	—	X	X	—
	Po-212/ TI-208	3.0×10^{-7} s/ 3.1 min	—	—	—	—

[a] Based on guidance in NRC (1982).

[b] X = the radionuclide is specifically considered under the given heading (e.g., air, ground, and/or food concentrations are specifically calculated).

[c] — = the radionuclide is considered to be in secular equilibrium with its parent; therefore, specific calculations involving the radionuclide are not performed (the value of the parent is used).

2.3   Source Types

The source types represented in MILDOS4 cover the range of scenarios found at mining and milling facilities for conventional hard rock or sandstone uranium ore, as well as those found at ISR uranium mining (recovery) facilities. Seven specific source types are modeled in the code, representing a wide range of emission sources. They are: (1) point, (2) area, (3) new well field, (4) well field, (5) ISR purge, (6) ISR ion exchange, (7) drying and packaging, and (8) land application. Source types 1, 2, and 7 are associated with conventional uranium ore facilities, while types 3 through 8 are associated with ISR facilities. In addition to the generic point source type, source types 5 through 7 are modeled as special cases of point sources, while source types 3, 4, and 8 are modeled as special cases of an area source.

2.3.1   Point Source

Point sources represent a number of emission points at uranium mines and mills. Underground mine surface openings are a source of radon emissions, and so are processing tank venting and well field purge operations at ISR facilities. At uranium ore mills, ore handling, crushing, and grinding are sources of radon and particulate emissions. Yellowcake drying and packaging

operations can also be a source of radon and particulate emissions. Specific point source models are implemented in MILDOS4 to account for radon emissions from ISR facilities; these are discussed further in Sections 2.3.4.2 and 2.3.4.4. Similarly, yellowcake drying and packaging is considered to be a separate source type and is discussed in Section 2.3.5. The general point source type model uses the annual emission rate directly input by the user for each radionuclide, multiplied by the appropriate particulate or radon adjustment factor, as discussed in Section 6.4.

2.3.2 Area Source

Different types of area sources can be found at both conventional and ISR uranium facilities. This section describes a generic area source that can be used to represent ore pads and mill tailings piles at conventional uranium ore milling facilities. Area sources potentially present at ISR facilities are described in Sections 2.3.3, 2.3.4.3, and 2.3.6.

Radionuclide particulate emissions from an area source are estimated by one of two methods. The first method simply multiplies a given radionuclide soil concentration by a given particulate emission rate and a given area to calculate the estimated radionuclide release over the course of time:

$$Q_{0_i} = 10^{-12} C_i q_v A_s ,$$

(2.1)

where

Q_{0_i} = initial amount of radionuclide i released (Ci/s),

10^{-12} = unit conversion factor (Ci/pCi),

C_i = concentration of radionuclide i in the soil (pCi/g),

q_v = emission rate (vertical flux) of particulate material (g/m²-s), and

A_s = area of the source (m²).

The second method is the same as the first, except that the particulate emission rate is estimated by using an erosion model rather than being given by the user. This erosion model (NRC, 1980), which was specifically developed to consider mill tailing piles, calculates the vertical flux (emission rate, also known as the dusting rate), q_v, as follows:

$$q_v = q_h \left(\frac{c_v}{c_h} \right) \frac{1}{u_{*_t}^3} \left[\left(\frac{u_*}{u_{*_t}} \right)^{\left(P_{tm}/3 \right)} - 1 \right],$$

(2.2)

where

q_h = horizontal flux of particulate material (g/m-s),

c_v = coefficient of proportionality for vertical flux (2 × 10⁻⁶ g/m²-s) (Gillette, 1973),

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c_h = empirical constant to relate shear velocity to horizontal flux (1×10^2 g-s^2/m^4) (Gillette, 1973),

u_* = shear velocity (m/s),

u_{*t} = threshold shear velocity (m/s), and

p_{tm} = percent of tailing mass that has a diameter smaller than 20 μm (unitless).

The shear velocity (also called friction velocity), u_*, can be estimated from the wind velocity profile near the surface described by Bagnold (1941) as

$$u_* = \frac{u_z}{2.5 \ln\left(z \big/ z_o \right)}, \tag{2.3}$$

where

u_z = wind velocity at height z (m/s),

z = wind measurement height (m), and

z_o = characteristic surface roughness height (m).

The threshold shear velocity, u_{*t}, for the initiation of saltation is given by Bagnold (1941) as modified by Belly (1964) to consider the influence of moisture:

$$u_{*t} = c_t \sqrt{\frac{\rho_p - \rho_a}{\rho_a} g \, d} \left(1.8 + 0.6 \log_{10} W \right), \tag{2.4}$$

where

c_t = dimensionless coefficient equal to 0.1,

ρ_p = particle density (g/m^3),

ρ_a = density of air (g/m^3),

g = gravitational acceleration (m/s^2),

d = average diameter of saltating particle (m), and

W = water content expressed in weight in percent.

The horizontal flux, q_h, is calculated by the following equation proposed by Lettan and reported by Gillette (1973):

$$q_h = c_h u_*^2 \left(u_* - u_{*t} \right). \tag{2.5}$$

The horizontal flux is taken to be zero when u_* is less than u_{*t}.

Radon emission from an area source is calculated according to:

$$Q_{0_{Rn}} = 10^{-12} q_{Rn} A_s ,$$
(2.6)

where

Q_{0Rn} = initial amount (release rate) of Rn-220 or Rn-222 released (Ci/s),

10^{-12} = unit conversion factor (Ci/pCi), and

q_{Rn} = emission rate of Rn-220 or Rn-222 (pCi/m²-s).

2.3.3   New Well Field Source

Conventional rotary rigs are commonly employed for all drilling activities at an ISR facility. Because high-viscosity bentonitic mud is used to maintain aquifer isolation during the drilling and sealing of exploration drill holes, no particulates are expected to be released during drilling operations. The only sources of radioactive release considered are the ore cuttings temporarily stored in the mud pits with Rn-222 and Rn-220 from radium in the ore. During the period when the ore cuttings are stored in a mud pit while awaiting disposal, the radioactive decay of Ra-226 (Rn-222) and Ra-224 (Rn-220) is producing radon continuously. The amount of Rn-222 or Rn-220 available for release over the well field area, or the maximum release rate, in a year as a result of Ra-226 or Ra-224 decay from ore cuttings in storage is assumed to be given by the following expressions:

$$Rn\text{-}222_{nw} = 10^{-12} E_{Rn222} \lambda_{Rn222} [Ra\text{-}226] t_{pit} M_{ore} N_{pit}$$
(2.7)

and

$$Rn\text{-}220_{nw} = 10^{-12} E_{Rn220} \lambda_{Rn220} [Ra\text{-}224] t_{pit} M_{ore} N_{pit} ,$$
(2.8)

where

$Rn\text{-}222_{nw}$ = Rn-222 release rate from a new well field (Ci/yr),

$Rn\text{-}220_{nw}$ = Rn-220 release rate from a new well field (Ci/yr),

10^{-12} = unit conversion factor (Ci/pCi),

E_{Rn222}, E_{Rn220} = emanating power for Rn-222 or Rn-220 (unitless),

λ_{Rn222}, λ_{Rn220} = Rn-222 or Rn-220 decay constant (1/d),

$[Ra\text{-}226]$, $[Ra\text{-}224]$ = concentration of Ra-226 or Ra-224 in the ore (pCi/g),

t_{pit} = storage time in a mud pit (d),

M_{ore} = average mass of ore material in a mud pit (g), and

N_{pit} = number of mud pits generated per year.

2.3.4   Well Field Sources

No particulate materials are expected to be released from production and restoration well fields because all of the process streams are in a closed-loop circuit. The primary radioactive emission from the process streams of production and restoration well fields is radon gas. Production and restoration well fields may generate radon emissions from up to three sources: (1) potential venting from wellheads and leaking transport piping over the extent of their areas (well field source), (2) "purge," sometimes referred to as "bleed," operations (purge source) and (3) ion exchange processes associated with production well fields (ion exchange source). Section 2.3.4.1 describes the methodology for estimating radon concentrations in well field water and how it is related to the various well field operations. Sections 2.3.4.2 through 2.3.4.4 provide the calculations for determining the radon release rates for purge, well field (venting), and ion exchange sources, respectively.

2.3.4.1 Radon Concentrations in Well Field Water

In the natural environment, radon emanates continuously from the ground and migrates through the rock or soil by both diffusion and convection. The occurrence of radon in water is controlled by the chemical concentration of radium in the host soil or rock and the emissivity of radon into water. Radon enters air-filled pores in the soil mainly because of the recoil of radon atoms upon the decay of Ra-226 or Ra-224. The fraction of radon formed in the soil that enters the pores is called the emanating power; reported values range from about 1 to 80 percent with an average of 20 percent, depending on soil type, pore space, and water content (Mueller Associates, Inc., 1986). It has been found that varying environmental conditions affect the rate of radon emanation. In particular, moisture has been found to have significant effects on the radon emanation rate. For purposes of conservatively estimating the radon release from ISR well fields, the default emanating power is assumed to be 0.25 for Rn-222 and 0.15 for Rn-220.

The movement of radon in groundwater is governed, in most cases, by water transport rather than by diffusion (Hess et al., 1985; Mueller Associates, Inc., 1986). In an ISR production well field, the radon released from the ore body is readily removed by the process water ("lixiviant") moving through the well field by injection and production wells. The 3.8-day half-life of Rn-222 allows it to circulate with the process water in the well field over a long time before it decays. If thorium ore is present, the 56-second half-life of Rn-220 could limit its emission from process water at ISR surface facilities, depending on the rate and distance traveled of the process water in the circulation system.

The basic operating processes of the restoration well field are similar to those of the production well field. Groundwater affected by leaching processes in the production well fields is restored to its pre-mining levels: (1) by the "pump and treat" (groundwater sweep) method and flushing with fresh water injection and (2) by using the permeative stream from reverse-osmosis treatment units. It is expected that, as is the case for the production well field, no particulate materials would be released from the restoration well field operations. The primary source of radioactive release is the radon gas in the process water circulating within and discharged from the restoration operations (purge and venting).

The general equations describing the change in Rn-222 and Rn-220 concentrations over time in the process water of a well field can be expressed as follows:

$$V \frac{dC_{Rn222}}{dt} = f_{Rn} S_{Rn222} - \left(\lambda_{Rn222} + v_{Rn} \right) V C_{Rn222} - \left(F_p + F_{ix} \right) C_{Rn222} \qquad (2.9)$$

and

$$V \frac{dC_{Rn220}}{dt} = f_{Rn} S_{Rn220} - \left(\lambda_{Rn220} + v_{Rn} \right) V C_{Rn220} - \left(F_p + F_{ix} \right) C_{Rn220} , \qquad (2.10)$$

where

V = volume of water in circulation (L),

C_{Rn222}, C_{Rn220} = Rn-222 or Rn-220 concentration in process water (pCi/L),

f_{Rn} = fraction of radon source carried by circulating water (unitless),

S_{Rn222}, S_{Rn220} = Rn-222 or Rn-220 source (pCi/d),

$\lambda_{Rn222}, \lambda_{Rn220}$ = Rn-222 or Rn-220 decay constant (1/d),

v_{Rn} = rate of radon venting from piping and valves during circulation (1/d),

F_p = "purge" rate of treated water (L/d), and

F_{ix} = water discharge rate from resin unloading of IX columns (L/d).

The balance of the fraction of the radon source carried by circulating water accounts for any radon in the mined area that is not swept into the injection-production well loop and remains trapped in the ore zone.

The "purge" or "bleed" in a production or restoration well field is necessary to maintain a hydraulic cone of depression around each well field to prevent leakage of mining solutions outside the well field zone. The radon source terms, S_{Rn222} and S_{Rn220}, can be expressed as follows:

$$S_{Rn222} = 10^6 E_{Rn222} \lambda_{Rn222} [\text{Ra - 226}] \, AD\rho \qquad (2.11)$$

and

$$S_{Rn220} = 10^6 E_{Rn220} \lambda_{Rn220} [\text{Ra - 224}] \, AD\rho, \qquad (2.12)$$

where

10^6 = unit conversion factor (cm^3/m^3),

E_{Rn222}, E_{Rn220} = emanating power for Rn-222 or Rn-220 (unitless),

[Ra-226], [Ra-224] = concentration of Ra-226 or Ra-224 in the ore (pCi/g),

A = active area of the ore zone (m^2),

D = average thickness of the ore zone (m), and

ρ = bulk density of the ore material (g/cm^3).

The water discharge rate from resin unloading, F_{ix}, can be calculated by

$$F_{ix} = N_{ix}V_{ix}P_{ix},$$

(2.13)

where

N_{ix} = number of IX unloadings per day,

V_{ix} = volume content of the IX column (L), and

P_{ix} = porosity of the IX resin (unitless).

Under steady-state conditions, the Rn-222 and Rn-220 concentrations in the process water, C_{Rn222} and C_{Rn220}, respectively, can then be written as

$$C_{Rn222} = \frac{f_{Rn}10^6 E_{Rn222}\, \lambda_{Rn222}\, [\text{Ra - 226}]\, AD\rho}{\left(\lambda_{Rn222} + v_{Rn}\right)V + F_p + F_{ix}}$$

(2.14)

and

$$C_{Rn220} = \frac{f_{Rn}10^6 E_{Rn220}\, \lambda_{Rn220}\, [\text{Ra - 224}]\, AD\rho}{\left(\lambda_{Rn220} + v_{Rn}\right)V + F_p + F_{ix}}.$$

(2.15)

2.3.4.2 Purge Source

When pressure is reduced during purging or when water is aerated during irrigation, radon is readily released to the atmosphere. The amount of radon available for release from the purge depends on the water volume purge rate, F_p, and the radon concentration in the purged liquid, C_{Rn222} or C_{Rn220}. By conservatively assuming that all available radon in the purge water is released, the annual radon emission is

$$Rn222_w = 1 \times 10^{-12}C_{Rn222}F_p d_{op}$$

(2.16)

and

$$Rn220_w = 1 \times 10^{-12}C_{Rn220}F_p d_{op}$$

(2.17)

where

$Rn222_w$, $Rn220_w$ = Rn-222 or Rn-220 release rate from purge water (Ci/yr),

d_{op} = number of well field operating days per year,

and

1×10^{-12} = unit conversion factor (Ci/pCi).

2.3.4.3 Well Field (Vent) Source

The annual radon releases from potential venting from wellheads and leaking transport piping are as follows:

$$Rn222_v = 1 \times 10^{-12} v_{Rn} C_{Rn222} V d_{op}, \qquad (2.18)$$

and

$$Rn220_v = 1 \times 10^{-12} v_{Rn} C_{Rn220} V d_{op}, \qquad (2.19)$$

where $Rn222_v$ and $Rn220_v$ are the annual Rn-222 and Rn-220 releases, respectively, from venting (Ci/yr).

2.3.4.4 Ion Exchange Source

The annual radon discharges from the unloading of the IX column contents are

$$Rn222_{ix} = 1 \times 10^{-12} F_{ix} C_{Rn222} d_{op} \qquad (2.20)$$

and

$$Rn220_{ix} = 1 \times 10^{-12} F_{ix} C_{Rn220} d_{op} \qquad (2.21)$$

where $Rn222_{ix}$ and $Rn220_{ix}$ are the annual Rn-222 and Rn-220 releases, respectively, from unloading the IX column content (Ci/yr).

2.3.5   Yellowcake Drying/Packaging Source

It is noteworthy that particulate releases from the yellowcake production step occur almost entirely in drying and calcining operations. If the yellowcake product were to be packaged as a slurry or as a damp filter-cake product, particulate emissions from this operation would be negligible (NRC, 1987).

For facilities using rotary vacuum dryers for processing yellowcake, no particulate emissions are expected under normal operating conditions. For facilities using thermal drying, stack releases may be estimated on the basis of information provided by a number of operating ISR uranium recovery facilities. Although more data are needed, it has been estimated that the stack release

of yellowcake is about 0.05 percent of the amount produced. However, because the day-to-day variations of particulate release rates can vary by several times, the assumption is that 0.1 percent of the uranium produced escapes as particulates into the atmosphere, as suggested in the *Final Generic Environmental Impact Statement on Uranium Milling* (NRC, 1980).

The particulate release of nuclides other than uranium isotopes is estimated by grab samples reported by ISR facilities (e.g., semiannual reports for Highland Uranium Project, Irigaray and Christensen Ranch Projects, Crownpoint, and others). On the basis of the field measurements, the conservative assumption is that the activities of thorium (0.15–0.4 percent of measured values), radium (0.2–0.3) percent, and the lead and polonium decay progeny are 0.5 percent of the U-238 activity in the yellowcake. Furthermore, it may be assumed that the fraction of this activity being released is the same as the fraction of uranium (0.1 percent) released. Because isolated yellowcake (U_3O_8) is modeled, no thorium ore radionuclides are considered in MILDOS4 for this type of source.

The amount of uranium-238 released in particulate form from a drying/packaging source is calculated in MILDOS4 as

$$U238_{dp} = 3.0973 \times 10^5 R_{yc} f_s U238_{sa},$$

$$(2.22)$$

where

$U238_{dp}$ = U-238 release rate from the facility stack (Ci/yr),

R_{yc} = daily production rate of yellowcake at the facility (kg U_3O_8/d),

f_s = fraction of production released through the facility stack (unitless),

$U238_{sa}$ = specific activity of U-238 (3.3×10^{-7} Ci/g), and

3.097×10^5 = conversion factor, 0.8480 g of U/g of U_3O_8 × 1,000 g/kg × 365.25 d/yr (g-d/kg-yr).

Releases of the uranium-238 daughter products in particulate form are calculated as

$$TH230_{dp} = f_{Th} U238_{dp},$$

$$(2.23)$$

$$RA226_{dp} = f_{Ra} U238_{dp},$$

$$(2.24)$$

and

$$PB210_{dp} = f_{others} U238_{dp},$$

$$(2.25)$$

where

$TH238_{dp}, RA226_{dp}, PB210_{dp}$ = Th-230, Ra-226, and Pb-210 release rates from the facility stack (Ci/yr) and

f_{Th}, f_{Ra}, f_{others} = Th-230, Ra-226, and Pb-210 release fractions relative to the release amount for U-238 (unitless).

2.3.6 Land Application Area Source

Treated water from production or restoration well fields could be used for irrigation or other land area application purposes (e.g., fugitive dust suppression). The low levels of radionuclides in the water could become adsorbed to the soil, creating a source term for radioactive material release through wind erosion processes. The soil concentration of a given radionuclide, i, due to water application can be expressed by:

$$C_{sw}(i,t_1) = \int_0^{t_1} \frac{C_{iw}(i,t_1)R_w F_s}{A_s D_s \rho_s 10^6} \exp\left(-(\lambda_i + \lambda_e)t\right) dt \qquad (2.26)$$

where

$C_{sw}(i,t_1)$ = soil concentration of radionuclide i after water irrigation for time t_1 (pCi/g),

10^6 = unit conversion factor (cm^3/m^3),

$C_{iw}(i,t_1)$ = concentration of radionuclide i in irrigation water during time t_1 (pCi/L),

R_w = water application rate (L/yr),

t = time (yr),

F_s = fraction of radionuclides retained in the soil (unitless),

A_s = area of land application (m^2),

D_s = depth of soil penetration (m),

ρ_s = soil bulk density (g/cm^3),

λ_i = radioactive decay constant for radionuclide i (1/yr), and

λ_e = decay constant to account for environmental loss from soil (1/yr).

The fraction of radionuclides in the applied water in the soil F_s is given by

$$F_s = 1 - \frac{1}{R_d},$$

$$(2.27)$$

where

R_d = retardation factor, which is calculated as:

$$R_d = 1 + \frac{\rho_s K_d}{w},$$

(2.28)

where

K_d = radionuclide distribution coefficient (cm³/g) and

w = soil volume water content (unitless).

An evaluation of Equation 2.26 to estimate the soil concentration gives:

$$C_{sw}(i,t_1) = \frac{C_{iw}(i,t_1)R_w t_1 F_s}{A_s D_s \rho_s 10^6}\left(\frac{1 - \exp\left(-\left(\lambda_i + \lambda_e\right)t_1\right)}{\lambda_i + \lambda_e}\right).$$

(2.29)

In MILDOS4, the exposure timeline is broken up into time steps (see Section 6.4); the number and duration of each is defined by the user. To evaluate the irrigated soil concentrations at the end of a given time step (i.e., for use as the source term for that time step), water application during the previous time steps must be taken into account. The soil concentration at a given time step, n, therefore includes the sum of the concentration buildup during each of the previous time steps, multiplied by their respective decay terms, to give:

$$C_{sw}(i,t_{s_n}) = \left(\frac{C_{iw}(i)R_w F_s}{A_s D_s \rho_s 10^6}\right)\left[\sum_{j=1}^{n-1} P_{Aj} t_{s_j} \exp\left(-\left(\lambda_i + \lambda_e\right)\left(t_n - t_j\right)\right) + P_{An} t_{s_n}\left(\frac{1 - \exp\left(-\left(\lambda_i + \lambda_e\right)t_n\right)}{\lambda_i + \lambda_e}\right)\right],$$

(2.30)

where

$C_{sw}(i,t_{Sn})$ = soil concentration of radionuclide i from water irrigation at the end of time step n (pCi/g),

$C_{iw}(i)$ = concentration of radionuclide i in irrigation water as input by the user (pCi/L),

P_{Aj} = particulate adjustment factor for the source for time step j (unitless).

t_j = length of time from the start of the evaluation period to the end of time step j (yr).

Thus the concentration of radionuclide i in irrigation water during time step j is given by

$$C_{iw}(i,t_{S_j}) = P_{Aj} C_{iw}(i),$$

(2.31)

where

t_{sj} = length of time assigned to time step j (yr).

Given the soil concentration calculated by using Equation 2.30, the radionuclide release rate from a land application area is determined by multiplying the soil concentration by the particulate wind erosion rate for the land area. The default particulate emission rate used is 3.1×10^{-5} g/m^2-s.

3 ATMOSPHERIC DISPERSION

The atmospheric dispersion model used in MILDOS4 is a Gaussian plume dispersion model for both point and area source releases that evaluates the downwind transport of radionuclide contaminants released to the atmosphere from a continuous (chronic) source. The model preserves mass balance and accounts for depletion of the plume from dry and wet deposition processes. Radionuclides released from emission sources described in Chapter 2 are transported by the wind and are dispersed as a result of atmospheric turbulence. If applicable, plume-rise models developed by Rupp et al. (1944) and Briggs (1969) are used to estimate the momentum-driven and buoyancy-induced rise, respectively, of the release. Depending on the circumstances, either the standard Pasquill-Gifford dispersion coefficients (Slade, 1968; Eimutis and Konicek, 1972) or the Briggs (1974) dispersion coefficients can be used. The former are suitable for ground-level releases; the latter are better for elevated releases. For vapor or particulate radionuclides, dry and wet deposition of plume content is also considered for any user-specified receptor location.

Radioactive decay is not considered during the atmospheric transport of particulates because transport times are relatively short in comparison with the radionuclide half-lives. However, because of the relatively short half-lives of radon and its daughters, their decay is taken into account during atmospheric transport. For particulates, separate calculations are performed for different particle size groups to account for the variability in deposition and plume depletion.

3.1 Effective Release Height

Material released from a source area may rise above the release point as a result of thermal buoyancy or the momentum out of a vent or stack. An effective release height, H, is used in the atmospheric dispersion equations to account for the additional height of the release. The effective release height is the sum of the actual physical release height, h, and the thermally and/or momentum-induced plume rise, Δh, with an adjustment for terrain height and vertical settling of the plume:

$$H = \max(h + \Delta h - h_v, 0) - (1 - P_c)[\min(\max(h + \Delta h - h_v, 0), \max(0, E_r - E_p))], \qquad (3.1)$$

where

    H = effective release height (m),

    h = physical release height (m),

    Δh = plume rise (m),

    h_v = vertical (gravitational) settling of the plume (m),

    P_c = plume-path coefficient (unitless),

    E_r = receptor elevation (m), and

    E_p = release elevation, the reference point for the release height (m).

3.1.1 Terrain Height Adjustment

Rising terrain downwind from an area emission source requires that the release height derived for flat terrain be adjusted accordingly. Stability-dependent plume-path coefficients are used in MILDOS4 to estimate the effects of terrain elevation on the height of the plume centerline. The correction to the release height for downwind elevations involves the second term in Equation 3.1, as given in Ross et al. (1985).

An increase in receptor elevation downwind effectively reduces the release height if the release height is greater than zero. This condition is embodied in the [min (max (h + Δh - h_v,0), max (0,E_r - E_p)] portion of Equation 3.1. On the other hand, the plume will not travel straight into a hillside but will follow air currents part way up the hill on its approach. The portion of Equation 3.1 with the plume-path coefficient, (1 – P_c), partially defines the amount of the effective reduction in release height and assures that the terrain height adjustment is not too extreme. For unstable and neutral conditions (stability classes A, B, C, and D), P_c is set to 0.5 so that the plume height remains at least one-half the distance aboveground, as it would be if no adjustment was made. Similarly, for stable conditions (stability classes E and F), P_c is set to 0.3 so that the plume height remains at least one-third the height above the ground, as it would be if no adjustments were made. A plume-path coefficient of 1 represents a nonterrain-lifted plume.

3.1.2 Plume Rise

Plume rise is used in MILDOS4 to estimate the effective release height of an emission source, as shown in Equation 3.1. Plume rise can be the result of the effluent momentum from a stack release or due to the thermal buoyancy of the effluent. For point source releases as described in Sections 2.3.1 and 2.3.6, the option of calculating the plume rise of a momentum-driven plume is available. A buoyant plume rise option is available for all source types.

3.1.2.1 Momentum-Driven Plume

A simple empirical formula was found by Rupp and coworkers (Rupp et al., 1944) to characterize the plume rise of momentum-driven plumes. The effective induced plume rise, Δh, was found to be:

$$\Delta h = 1.5 \frac{v_s d_s}{u_H}$$

(3.2)

where

v_s = exit velocity of effluent from emission stack (m/s),

d_s = inside diameter of the emission stack (m), and

u_H = wind speed at the effective release height (m/s).

3.1.2.2 Buoyant Plume Rise

Buoyant plume rise is estimated in MILDOS4 with the formulas derived by Briggs (1969) for buoyant plumes. The rise from thermal buoyancy is seen to depend on stability class, wind speed, and receptor distance. For stability classes A, B, C, and D, the plume rise is given by

$$\Delta h = \frac{1.6 F^{1/3} x^{2/3}}{u_H} \quad \text{for } x \leq 10\,h \tag{3.3}$$

and

$$\Delta h = \frac{1.6 F^{1/3} (10h)^{2/3}}{u_H}, \text{ for } x > 10\,h, \tag{3.4}$$

where

$F = 3.7 \times 10^{-5}\, Q_h$ (m^4/s^3),

Q_h = heat flux from radionuclide release area (cal/s), and

x = downwind receptor distance from release area (m).

For stability classes E and F, the plume rise is calculated according to

$$\Delta h = \frac{1.6 F^{1/3} x^{2/3}}{u_H} \quad \text{for } x \leq 2.4 \frac{u_H}{\sqrt{s}} \tag{3.5}$$

and

$$\Delta h = 2.9 \left(\frac{F}{u_H s} \right)^{1/3} \text{ for } x > 2.4 \frac{u_H}{\sqrt{s}}, \tag{3.6}$$

except when the wind is so light that the plume rises vertically. Under such conditions, the final plume rise is given by Briggs (1969) as

$$\Delta h = \frac{5.0 F^{1/4}}{s^{3/8}} \text{ when } u_H \leq u_{test}, \tag{3.7}$$

where

$$s = \frac{g}{T_a} \left(\frac{\partial T_a}{\partial z_r} + l \right), \tag{3.8}$$

$$u_{test} = 0.195 F^{1/4} s^{1/8},$$
(3.9)

s = stability parameter (1/s^2),

g = gravitational acceleration (9.80665 m/s^2),

T_a = ambient air temperature (K),

l = normal adiabatic lapse rate of the atmosphere (0.0098 K/m),

$\dfrac{\partial T_a}{\partial z_r} + l$ = potential temperature lapse rate (0.02 and 0.035 for stability classes E and F, respectively), and

z_r = vertical distance above the release point (m).

As recommended by Briggs (1969), Equations 3.3 to 3.6 contain wind speed in the denominator, which would produce unrealistically high values for very low wind speeds. Because the Briggs equations are applicable only to windy conditions, a minimum wind speed of 0.1 m/s is imposed in the above plume-rise calculations.

3.1.3   Vertical Settling

Airborne particulates exhibit a vertical settling velocity characterized by the influence of gravity, atmospheric characteristics, and particulate characteristics such as particle density and diameter. For larger and denser particulates, vertical settling can become significant and lead to a more rapid descent of the plume toward the ground. This downward drift of the plume due to gravity can be accounted for by using what is sometimes referred to as the "tilted plume" model, in which the vertical settling, h_v, in meters of the plume, is given as

$$h_v = \frac{x V_s}{u_H},$$
(3.10)

where

V_s = gravitational settling velocity (m/s).

The settling velocity can be approximated as (Momeni et al., 1979)

$$V_s = 3 \times 10^{-5}\, d_p^2 \rho_p,$$
(3.11)

where

d_p = particle diameter for particulate p (μm), and

ρ_p = particle density (g/cm^3).

3-4

3.1.4 Wind Power-Law Adjustment

For atmospheric dispersion calculations, the measured average wind speed at the effective release height, u_H, is not always available. MILDOS4 uses a power-law function having the following form to estimate the wind speed at the desired height:

$$\frac{u_H}{u_a} = \left(\frac{H}{z_a}\right)^p ,$$

(3.12)

where

u_a = wind speed at measurement height (m/s),

z_a = height of anemometer for wind speed measurement (m), and

p = power for height ratio (unitless).

The wind speed of u_a from the measurement height z_a is adjusted to the effective release height H of the plume for the dispersion calculations. Values for the exponent p as presented in Table 3-1 were taken from Irwin (1979), as modified by Hanna et al. (1982) for the different population zones and stability classes. MILDOS4 uses the values for the rural population zone.

Table 3-1 Estimates of the Power (p) in Equation 3.12 for Population Zones as a Function of Stability Class

Population Zone	Stability Class					
	A	B	C	D	E	F
Rural	0.07	0.07	0.10	0.15	0.35	0.55
Suburban/urban	0.15	0.15	0.20	0.25	0.40	0.60

3.2 Gaussian Plume

For a discrete puff generated from a point source with an effective release height H above ground level, the Gaussian time-dependent dispersion equation can be written as (Pasquill, 1974)

$$C_a(i,x,y,z,t) = \frac{Q_{x_i}}{(2\pi)^{3/2} \sigma_y^2 \sigma_z} exp\left(\frac{-r^2}{2\sigma_y^2}\right)\left[exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right],$$

(3.13)

where

$C_a(i,x,y,z,t)$ = air concentration of radionuclide i at (x,y,z) from a release at $(0,0,H)$ at time t after release (Ci/m^3),

Q_{xi} = depleted source strength of nuclide i at distance x (Ci/s) [see Equation 3.35],

σ_y = horizontal dispersion coefficient (m) [see Equation 3.42],

σ_z = vertical dispersion coefficient (m) [see Equation 3.40],

$r^2 = (x - u_H t)^2 + y^2$ is the square of the distance from a receptor to the plume center (m^2) [assumes Gaussian symmetry, that is, $\sigma_x = \sigma_y$],

x = downwind receptor distance from the release point (m),

y = crosswind distance from the plume centerline (m),

u_H = average wind speed at the effective release height (m/s) [Equation 3.12],

t = time following release (s), and

H = effective release height (m) [Equation 3.1].

The ground-level air concentration (Ci/m^3) for a discrete puff is obtained by setting $z = 0$ in Equation 3.13.

$$C_a(i,x,y,0,t) = \frac{2Q_{x_i}}{(2\pi)^{3/2}\sigma_y^2\sigma_z}\exp\left[-\left(\frac{r^2}{2\sigma_y^2}+\frac{H^2}{2\sigma_z^2}\right)\right] \tag{3.14}$$

A continuous point source can be considered to be a series of overlapping puff emissions. Thus, integration of Equation 3.14 over time yields the downwind air concentration (Ci/m^3):

$$\overline{C}_a(i,x,y) = \int_0^\infty C_a(i,x,y,0,t)dt , \tag{3.15}$$

which can be shown to be (Slade, 1968)

$$\overline{C}_a(i,x,y) = \frac{Q_{x_i}}{\pi\sigma_y\sigma_z u_H}\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{H^2}{2\sigma_z^2}\right)\right], \tag{3.16}$$

where Q_{xi} is the initial source term for radionuclide i (now in units of Ci/s for a continuous source), corrected for wet and dry deposition from the plume, as shown later in Equation 3.35.

3.3   Plume Reflection and Mixing Height

The existence of a stable air layer at higher altitudes under unstable and neutral atmospheric conditions affects atmospheric dispersion at great distances from the release point. The upward dispersion of the plume is eventually restricted when the plume encounters an elevated stable layer (or lid) or a mixing layer at some height L. In MILDOS4, the plume is assumed to be

reflected by this stable layer at these distances. With vertical distribution limited by reflection, integration of Equation 3.13 over z (0 to L) as well as integration over time yields

$$\overline{C}_a(i,x,y) = \frac{Q_{x_i}}{\sqrt{2\pi}\sigma_y u_H L} \exp\left[-\left(\frac{y^2}{2\sigma_y^2}\right)\right],$$

(3.17)

where

   L = mixing layer height, sometimes referred to as the lid height (m).

The following conditions (Powell et al., 1979) are used to determine which of these two equations, Equation 3.16 or 3.17, is used for the dispersion calculation. Equation 3.16 is used for distances where σ_z is small compared to L; that is, when

$$\frac{\sigma_z}{L} \leq \frac{\sqrt{1 - \frac{H}{L}}}{1.2}.$$

(3.18)

Equation 3.17 is used when σ_z is of the same order as L and a uniform distribution can be assumed; that is, when

$$0 \leq H/L < 0.5$$

and

$$\frac{\sigma_z}{L} \geq -2.37\left(\frac{H}{L}\right)^2 + 0.489\left(\frac{H}{L}\right) + 0.756$$

(3.19)

or when

$$0.5 \leq H/L < 1.0$$

and

$$\frac{\sigma_z}{L} \geq -2.37\left(\frac{H}{L}\right)^2 + 4.25\left(\frac{H}{L}\right) - 1.13.$$

(3.20)

At downwind distances between the no-mixing (Equation 3.18) and the total-mixing (Equations 3.19 and 3.20) conditions, the concentration is determined by a linear interpolation between the solutions of Equations 3.16 and 3.17.

The value of the mixing height (L) is estimated from the annual average input values for morning and afternoon (Holzworth, 1972). The mixing height is estimated from the following equation for rural conditions (EPA, 1995):

$$L = 1.5\ L_{pm} \text{ for an extremely unstable atmosphere (stability class A).} \qquad (3.21)$$

For other situations (stability classes B, C, and D), L is taken to be equal to L_{pm}, the average mixing layer height in the afternoon (m). The mixing height does not apply to stable atmospheric conditions.

3.4   Chronic Conditions

Equations 3.16 and 3.17 are valid for unchanging weather conditions when the period of release exceeds the time necessary for the airborne material to travel downwind from the release point to the receptor location. However, weather conditions will fluctuate with time (generally on the order of minutes or longer), causing the plume to meander within a sector when the wind is blowing in a particular direction. Thus, for use in estimating human health impacts under such conditions, it is more appropriate to evaluate the sector-average air concentration.

The air dispersion model in MILDOS4 uses a polar grid divided into 16 sectors to specify the wind direction. The sector-average air concentration at a receptor location that is a distance of x meters from the release point (see Figure 3-1) can be estimated as the integral of Equation 3.16 or 3.17 over y, from minus infinity to plus infinity, divided by the width of the sector ($2y_{sec}$) at distance x from the release point. Because of the symmetry of the Gaussian equation, this sector-average concentration for the case in which there is no plume reflection can be written as:

$$\overline{C_{sec}}(i,x) = \frac{1}{y_{sec}} \int_0^\infty \overline{C_a}(i,x,y)\,dy = \frac{1}{y_{sec}} \int_0^\infty \frac{Q_{x_i}}{\pi \sigma_y \sigma_z u_H} \left[\exp\left(-\left(\frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2} \right) \right) \right] dy, \qquad (3.22)$$

where

$$y_{sec} = x\ \tan\!\left(11.25^\circ\right). \qquad (3.23)$$

Equation 3.22 can be rewritten as

$$\overline{C_{sec}}(i,x) = \frac{Q_{x_i}}{\pi \sigma_y \sigma_z u_H y_{sec}} \exp\!\left(\frac{-H^2}{2\sigma_z^2} \right) \int_0^\infty \exp\!\left(\frac{-y^2}{2\sigma_y^2} \right) dy. \qquad (3.24)$$

By using the identity

$$\int_0^\infty \exp\!\left(-a^2 x^2 \right) dx = \frac{1}{2a}\sqrt{\pi}, \qquad (3.25)$$
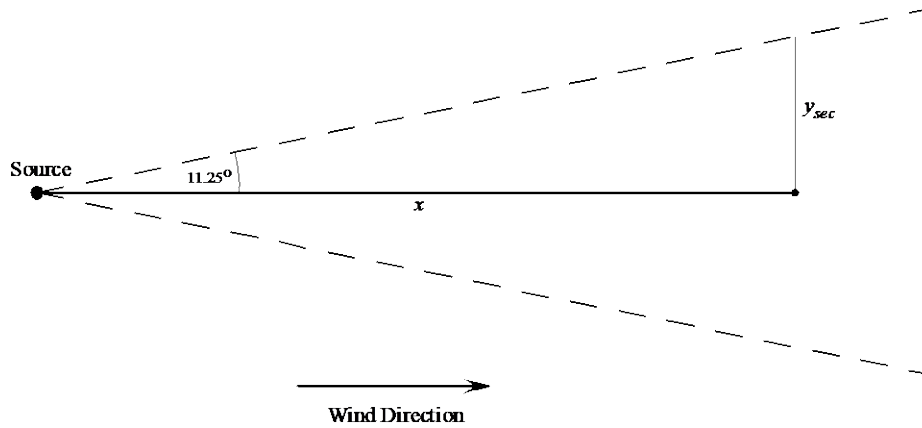
Figure 3-1 Relationships Used in Sector-Average Air Concentration Calculations

Equation 3.24 reduces to

$$\overline{C_{sec}}(i,x) = \frac{Q_{x_i}}{\sqrt{2\pi}\sigma_z u_H y_{sec}} \exp\left(\frac{-H^2}{2\sigma_z^2}\right)$$

(3.26)

to give the sector-average air concentration at a distance of x meters from the source when there is no plume reflection. In the case where there is plume reflection with total uniform mixing, the sector-average air concentration is given as

$$\overline{C_{sec}}(i,x) = \frac{1}{y_{sec}} \int_0^\infty \frac{Q_{x_i}}{\sqrt{2\pi}\sigma_y u_H L} \left[\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\right] dy.$$

(3.27)

By using Equation 3.25, Equation 3.27 can be simplified to give

$$\overline{C_{sec}}(i,x) = \frac{Q_{x_i}}{2y_{sec} u_H L}.$$

(3.28)

In both cases, with and without plume reflection (Equations 3.28 and 3.26, respectively), integrating y to infinity and averaging using the sector width causes the plume to compress to within the sector boundaries.

The term "normalized air concentration," often referred to as χ/Q ("chi over Q"), is used to express the air concentration at a receptor independent of the amount of material released from a given source. It is more formally represented as $\overline{C_{sec}}(i,x)/Q_{0_i}$ in units of s/m³. The original source term or release amount (Q_{0i}) is a component of the downwind depleted source strength (Q_{xi}), as discussed in more detail in Section 3.6 (see Equation 3.35).

The normalized air concentration is unique with regard to the distance between the source and receptor and the direction associated with the source-receptor pair as well as the characteristics of the source material (i.e., particle size and deposition velocity) and the local meteorology. As a practical matter, when it is performing air dispersion calculations, MILDOS4 first calculates the χ/Q value for a source-receptor pair by using Equation 3.26, 3.28, or both, with the original source term (Q_{0i}) set to a unit release (1 Ci/s). Thus, further calculation of the actual downwind air concentration for each time step (see Section 6.4 for the definition of a time step) considered is accomplished by multiplying the normalized air concentration by the release amount for each time step.

3.5   Area Source Model

No area source approximations are used in MILDOS4. Rather, a series of point-to-point calculations are performed by using Equation 3.26 or 3.28, depending on distance. The source area is first partitioned into a grid of 1 × 1-m square resolution or greater. The center point of each grid square is used as the source point representing that small area. Air concentration calculations are performed for emissions from every source grid square, with an average chronic air concentration then calculated for the receptor location (see Figure 3.2). Each point-to-point calculation uses the appropriate wind directions and frequencies for the specific points involved. Thus, the model properly accounts for a receptor that is relatively close to a large area source where the radionuclide air concentration depends on the wind frequency from multiple directions.
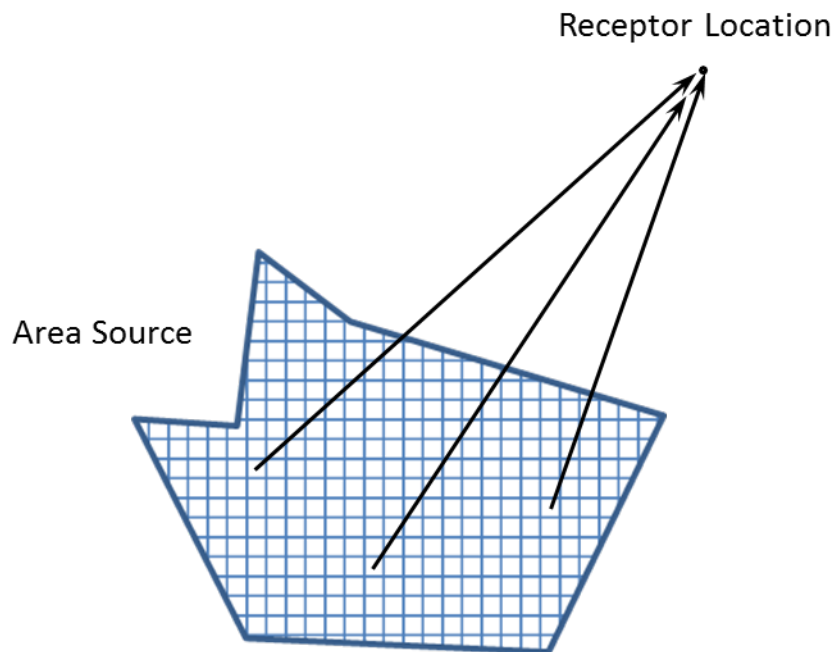
Figure 3-2 Air Concentrations from an Area Source Are Based on an Average Normalized Air Concentration Value Using All Grid Squares within the Area Source

While this method avoids any area source approximations, it does increase computation time. "Point" sources (the size of a grid square [the grid spacing]) larger than 1 m² may be specified to reduce computation time at the sacrifice of some accuracy, as discussed in Section 6.5.1.

3.6   Depletion Correction

As a radioactive plume travels downwind, its radionuclide content decreases as the result of ground deposition. Two deposition mechanisms, dry and wet, account for this radionuclide depletion from the plume. This section describes the methods used in MILDOS4 for calculating plume depletion from radionuclide deposition.

3.6.1 Dry Deposition

Except for the inert gases Rn-220 and Rn-222, most radioactive material emitted from area sources is in particulate form. The particulates with dimensions on the order of a few micrometers or less have vertical movements that largely depend on the vertical turbulence and mean motion of the air; settling of the particles by gravity is minimal where the settling velocity is less than about 0.01 m/s. These small particles are deposited on the ground surface as the result of turbulent diffusion and Brownian motion. Chemical absorption, impaction, and other physical and chemical processes cause the material to be retained at the surface. Such a deposition mechanism depletes the amount of radioactivity in the plume, causing ground contamination and thus affecting potential radiological hazards as the plume travels farther downwind.

Calculation of the dry deposition rate involves the concept of deposition velocity: the ratio of the deposition rate to the air concentration, expressed in units of velocity. The deposition velocity is determined from either field or laboratory measurements of air and ground concentrations. When plume depletion by dry deposition is considered, the initial source term, Q_{0_i}, at the release point can be replaced by a depleted source term, Q_{X_i}, along the downwind sector. In this approach, known as the source depletion model, it is assumed that the depletion reduces only the effective source strength and that the vertical Gaussian profile remains unchanged. In this derivation, total activity has been conserved.

In MILDOS4, the default deposition velocity of particulates is set to 0.01 m/s. In the case of particulates for which the settling velocity is >0.01 m/s, the deposition velocity is set equal to the settling velocity. The deposition velocity of radon daughters is taken to be 0.003 m/s (Momeni et al., 1979).

The reduced source strength Q_{xi} as the result of dry deposition is calculated from the following equation (Slade, 1968):

$$Q_{DRY_{x_i}} = Q_{0_i} \exp\left[-\frac{V_{d_p}}{\sqrt{\frac{\pi}{2}}u_H} \int_0^x F(x)dx \right], \tag{3.29}$$

where

Q_{DRYx_i} = depleted source strength of nuclide i at distance x from dry deposition (Ci/s),

Q_{0i} = initial amount of radionuclide i released (Ci/s),

V_{d_p} = deposition velocity for particle size p (m/s),

$F(x)$ = Equation 3.30 or 3.31 (1/m), and

u_H = average wind speed at effective release height (m/s) [Equation 3.12].

At downwind distances not affected by the presence of a mixing layer,

$$F(x) = \frac{\exp\left(\dfrac{-H^2}{2\sigma_z^2}\right)}{\sigma_z},$$

(3.30)

where

H = effective release height (m) [Equation 3.1], and

σ_z = vertical dispersion coefficient (m) [Equation 3.40].

At downwind distances where total mixing by the presence of a mixing layer can be assumed (Powell et al., 1979),

$$F(x) = \frac{1}{L},$$

(3.31)

where

L = mixing layer height, sometimes referred to as lid height (m).

At downwind distances between the no-mixing (Equation 3.18) and total-mixing (Equations 3.19 and 3.20) conditions, $F(x)$ is determined by a linear combination of the solutions of Equations 3.30 and 3.31.

3.6.2 Wet Deposition

Radionuclides can also be removed from a plume by rain or snowfall. In wet deposition, the depletion mechanism of radionuclides is such that the plume is "washed out" by rain or snow. Thus, the wet deposition rate depends on the total amount of radioactivity contained in the plume, in contrast to dry deposition, for which the depletion is closely related to the air concentration at ground level. The fraction of material removed per unit time by wet deposition is known as the "washout coefficient," V_w, and is defined as follows:

$$V_w = -\frac{1}{C_a}\frac{dC_a}{dt},$$

(3.32)

where

V_w = washout coefficient (1/s), and

C_a = local air concentration (Ci/m^3).

Calculated and measured values of the washout coefficient range from about 1.0×10^{-5} to 1.0×10^{-2} per second (Ritchie et al., 1978; McMahon and Dennison, 1979). The value of the washout coefficient increases with an increasing rainfall rate and is linearly dependent on the rainfall rate:

$$V_w = W_c R,$$ (3.33)

where

W_c = 1×10^{-3} (1/s)(mm/h)$^{-1}$ for stability classes A to D and

1×10^{-4} (1/s)(mm/h)$^{-1}$ for stability classes E and F [Ritchie et al., 1978], and

R = rainfall rate (mm/h).

The depleted source strength from wet deposition, assuming a steady rainfall rate and wind speed, is given by

$$Q_{WET_{x_i}} = Q_{0_i} \exp\left(-\frac{V_w x}{u_H}\right).$$ (3.34)

3.6.3   Combination of Dry and Wet Deposition

Dry deposition is always considered in MILDOS4. When wet deposition is also considered, the depleted source strength at a distance x downwind becomes a function of both dry and wet deposition. The depleted source strength becomes a combination of Equations 3.29 and 3.34 and is calculated according to the following:

$$Q_{x_i} = Q_{0_i} \exp\left\{-\left[\frac{V_w x}{u_H} + \frac{V_{d_p}}{\sqrt{\frac{\pi}{2}}u_H} \int_0^x F(x)dx\right]\right\}.$$ (3.35)

where

Q_{x_i} = depleted source strength of nuclide i at distance x (Ci/s).

3.7   Meteorological Conditions

As presented in the previous sections, the dispersion model in MILDOS4 requires the following meteorological data:

1. Stability class (A through F),

2. Wind speed (m/s),

3. Mixing height (m) (for stability classes A through D),

4. Ambient temperature (K), and

5. Rainfall rate (mm/h).

Either a single stability class and wind speed can be used, or joint frequency data on weather conditions over a period of time (e.g., annual data) can be input manually or read from a STAR format data file.

3.7.1   Dispersion Coefficients

The atmospheric stabilities are classified into six categories (A, B, C, D, E, and F) in order of increasing stability on the basis of criteria established by Pasquill (1974). The dispersion equations in the models used are generic to all stability categories and are empirical in nature. For each stability category, a set of dispersion coefficients, σ_y and σ_z, are initially calculated on the basis of the Pasquill-Gifford curves (Eimutis and Konicek, 1972) and later adjusted for buoyancy-induced dispersion, as discussed in the next section. The Pasquill-Gifford dispersion coefficients are calculated according to

$$\sigma'_y = \left(0.000246\sigma_\theta^2 + 0.00576\sigma_\theta + 0.066\right)x^{0.9031} \tag{3.36}$$

and

$$\sigma'_z = ax^b + c. \tag{3.37}$$

Table 3-2 contains the values for the unitless dispersion parameters σ_θ, a, b, and c as a function of stability class.

Briggs (1974) developed formulas for the dispersion coefficients on the basis of data collected from elevated releases:

$$\sigma'_y \text{ or } \sigma'_z = ax(1 + bx)^c. \tag{3.38}$$

In addition, Briggs coefficients have been derived for rural and urban population zones. See Table 3-3 for values of a, b, and c.

Table 3-2 Pasquill-Gifford Dispersion Parameters for Ground-Level Releases

Applicable Range (downwind distance, *x* in m)	Stability Class	Coefficient			
		σ_θ	a	b	c
x >1,000	A	25	0.00024	2.094	−9.6
	B	20	0.055	1.098	2.0
	C	15	0.113	0.911	0.0
	D	10	1.26	0.516	−13.0
	E	5	6.73	0.305	−34.0
	F	1.5	18.05	0.18	−48.6
100 ≤ *x* ≤ 1,000	A	25	0.00066	1.941	9.27
	B	20	0.0382	1.149	3.3
	C	15	0.113	0.911	0.0
	D	10	0.222	0.725	−1.7
	E	5	0.211	0.678	−1.3
	F	1.5	0.086	0.74	−0.35
x <100	A	25	0.192	0.936	0.0
	B	20	0.156	0.922	0.0
	C	15	0.116	0.905	0.0
	D	10	0.079	0.881	0.0
	E	5	0.063	0.871	0.0
	F	1.5	0.053	0.814	0.0

Source: Data from Eimutis and Konicek (1972)

Table 3-3 Briggs Dispersion Coefficients for Elevated Releases

Weather Conditions	Stability Class	σ_y					
		Rural			Urban		
		a	b	c	a	b	c
Extremely unstable	A	0.22	0.0001	−0.5	0.32	0.0004	−0.5
Moderately unstable	B	0.16	0.0001	−0.5	0.32	0.0004	−0.5
Slightly unstable	C	0.11	0.0001	−0.5	0.22	0.0004	−0.5
Neutral	D	0.08	0.0001	−0.5	0.16	0.0004	−0.5
Slightly stable	E	0.06	0.0001	−0.5	0.11	0.0004	−0.5
Moderately stable	F	0.04	0.0001	−0.5	0.11	0.0004	−0.5
Extremely unstable	A	0.20	0.0	0.0	0.24	0.001	0.5
Moderately unstable	B	0.12	0.0	0.0	0.24	0.001	0.5
Slightly unstable	C	0.08	0.0002	−0.5	0.20	0.0	0.0
Neutral	D	0.06	0.0015	−0.5	0.14	0.0003	−0.5
Slightly stable	E	0.03	0.0003	−1.0	0.08	0.00015	−0.5
Moderately stable	F	0.016	0.0003	−1.0	0.08	0.00015	−0.5

Source: Briggs (1974)

3.7.2 Buoyancy-Induced Dispersion

Buoyancy-induced dispersion is considered in MILDOS4 because emitted plumes undergo a certain amount of growth during the plume-rise phase as a result of turbulent motions associated with plume release conditions and turbulent entrainment of ambient air. Pasquill (1976) suggests that this induced dispersion, σ_{zb}, can be approximated by the following equation:

$$\sigma_{zb} = \frac{\Delta h}{3.5} \, , \qquad (3.39)$$

where

σ_{zb} = buoyancy-induced vertical dispersion coefficient (m).

The effective dispersion coefficient used in MILDOS4 calculations can then be determined by adding variances such as

$$\sigma_z = \left(\sigma_{zb}^2 + \sigma_z'^2 \right)^{1/2}. \qquad (3.40)$$

At the distance of final plume rise and beyond, σ_{zb} becomes constant.

Because the plume can be assumed to be symmetrical around its centerline in the initial growth phases of release, the calculation assumes that buoyancy-induced dispersion in the horizontal direction is equal to that in the vertical direction:

$$\sigma_{yb} = \frac{\Delta h}{3.5} \, ,$$

(3.41)

where

σ_{yb} = buoyancy-induced horizontal dispersion coefficient (m).

This expression is combined with the expression for dispersion that results from ambient turbulence, in the same manner as that described above for the vertical direction, to give the horizontal dispersion coefficient used in the MILDOS4 calculations for estimating air and ground concentrations:

$$\sigma_y = \left(\sigma_{yb}^2 + \sigma_y'^2 \right)^{1/2}.$$

(3.42)

4 ENVIRONMENTAL MEDIA CONCENTRATIONS

Air and ground concentrations of radionuclides are calculated in MILDOS4 for estimating exposure via various pathways, as shown in Figure 1-1. The downwind air transport of the source terms released, as discussed in Chapter 2, was considered in Chapter 3. This chapter considers the models used to estimate the resulting ground, air, vegetation, and livestock concentrations.

4.1   Radionuclide Ground Concentrations

The radionuclide ground concentration over time interval t at a constant deposition rate for particle size p is expressed as follows (see Appendix D, Section D.1, Equation D.3):

$$C_g(i,p,x,t) = V_{d_p} \overline{C_{\text{sec}}}(i,p,x,t) \frac{1 - \exp[-(\lambda_i + \lambda_e)t]}{\lambda_i + \lambda_e}, \tag{4.1}$$

where

C_g(i,p,x,t) = ground concentration of radionuclide i associated with particle size p at a distance x (in m) after time t (Ci/m^2),

V_{d_p} = deposition velocity for particle size p (m/s),

$\overline{C_{\text{sec}}}(i,p,x,t)$ = sector-averaged air concentration of radionuclide i at a distance x (in m) from the source (Ci/m^3) during time t [Equation 3.26 or 3.28 or a combination of the two] (here the dependence on particle size is being explicitly pointed out),

λ_i = radioactive decay constant for radionuclide i (1/s), and

λ_e = decay constant to account for environmental loss from soil (1/s).

The environmental soil loss decay constant, λ_e, accounts for weathering processes, such as downward soil migration, chemical binding to soil, and wind and water erosion. This constant applies to all radionuclides considered to be deposited on the ground.

Equation 4.1 applies in the case in which no previous deposition of radionuclide i on the surface has occurred. In MILDOS4, multiple time steps may be specified (see Section 6.4); in this case, the estimated ground concentration after time step j, where j is ≥2, is given by

$$C_g(i,p,x,t_j) = V_{d_p} \overline{C_{\text{sec}}}(i,p,x,t_{s_j}) \frac{1 - \exp[-(\lambda_i + \lambda_e)t_{s_j}]}{\lambda_i + \lambda_e} + \sum_{k=1}^{j-1} \left(C_g(i,p,x,t_k) \exp[-(\lambda_i + \lambda_e)t_{j-k}]\right), \tag{4.2}$$

where

$C_g(i,p,x,t_j)$ = ground concentration of radionuclide i on particle size p at a distance x (in m) after time step j (Ci/m^2),

$C_g(i,p,x,t_{j-1})$ = ground concentration of radionuclide *i* on particle size *p* at a distance *x* (in m) after time step *j-1* (Ci/m²), and

t_{sj} = length of time assigned to time step *j* (s).

Here, the second term accounts for the previously deposited material. This calculation is performed at each receptor location for each source and particle size group combination in which radionuclide *i* is present, to give the total ground concentration of radionuclide *i*. For a given source, the ground concentration is calculated as follows:

$$C_g(i,x,t_j) = \sum_p C_g(i,p,x,t_j),$$

(4.3)

where

$C_g(i,x,t_j)$ = ground concentration of radionuclide *i* from a given source at a distance *x* (in m) after time step *j* (Ci/m²).

4.2 Radionuclide Air Concentrations

In the case of particulate releases, air concentrations at receptor locations in MILDOS4 account for the downwind air dispersion of the radionuclide sources and resuspension of deposited material. The resuspension model is covered in Section 4.2.1. The model for downwind air dispersion is described in Chapter 3, and the expression used for the combined air concentration as used in the exposure calculations is given in Section 4.2.2. Downwind radon air concentrations are discussed in Section 4.2.2.2. Separate calculations are performed for each size of particulates considered.

4.2.1 Resuspension

Resuspended air concentrations are calculated with a time-dependent resuspension factor (NRC, 1980) given as

$$R(t) = \begin{cases} \dfrac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t), \text{for } t \le t_R \\ \dfrac{V_{d_r}}{V_{d_p}} R_F, \text{for } t > t_R \end{cases},$$

(4.4)

where

$R(t)$ = ratio of resuspended air concentration to ground concentration for a ground concentration at time *t* after deposition (1/m),

V_{dr} = deposition velocity for the reference particle size that corresponds to the values of R_I and R_F (m/s),

V_{dp} = deposition velocity for particle size *p* (m/s),

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R_I = initial value of the resuspension factor for fresh deposits (1/m),

λ_r = resuspension factor decay constant (1/yr) [(ln 2)/resuspension half-life],

R_F = final value of the resuspension factor after time (1/m), and

t_R = time required for the resuspension factor to decrease from its initial to final value (yr), $t = t_R$, when

$$\frac{V_{d_r}}{V_{d_p}} R_F = \frac{V_{d_r}}{V_{d_p}} R_I \exp\left(-\lambda_r t_R\right).$$
(4.5)

Equation 4.5 can be rearranged to solve for t_R to give

$$t_R = -\frac{1}{\lambda_r} \ln \frac{R_F}{R_I}.$$
(4.6)

The inverse relationship with respect to deposition velocity in Equation 4.4 accounts for the decrease in the amount resuspended as the particle size increases.

For a given time step j in MILDOS4, the resuspended air concentration of radionuclide i is the product of the resuspension factor with the radionuclide's ground concentration:

$$C_{air_R}(i, p, x, t_j) = R(t) C_g(i, p, x, t_j).$$
(4.7)

The total resuspended air concentration for radionuclide i at time step j is the sum of contributions from the current and preceding time steps:

$$C_{air_R}(i,p,x,t_j) = \sum_{m=1}^{k-1} \overline{C_{sec}}(i,p,x,t_{s_m}) V_{d_r} R_F \frac{\exp\left[-(\lambda_i + \lambda_e)(t_j - t_m)\right] - \exp\left[-(\lambda_i + \lambda_e)(t_j - t_m + t_{s_m})\right]}{\lambda_i + \lambda_e} +$$

$$\sum_{m=k+1}^{j} \overline{C_{sec}}(i,p,x,t_{s_m}) V_{d_r} R_I \frac{\exp\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_m)\right] - \exp\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_m + t_{s_m})\right]}{\lambda_i + \lambda_e + \lambda_r} +$$

$$\overline{C_{sec}}(i,p,x,t_{s_k}) V_{d_r} \left[\begin{array}{l} R_F\left(\dfrac{\exp\left[-(\lambda_i + \lambda_e)t_R\right] - \exp\left[-(\lambda_i + \lambda_e)(t_j - t_{k-1})\right]}{\lambda_i + \lambda_e}\right) + \\[3ex] R_I\left(\dfrac{\exp\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_k)\right] - \exp\left[-(\lambda_i + \lambda_e + \lambda_r)t_R\right]}{\lambda_i + \lambda_e + \lambda_r}\right) \end{array} \right],$$
(4.8)

where

$$t_j = \sum_{m=1}^{j} t_{s_m}.$$
(4.9)

and

> k = time step of the transition interval where both initial and final resuspension factor contributions occur when t_j is $>t_R$.

Further details and the derivation of Equation 4.8 can be found in Appendix D.

4.2.2   Total Air Concentrations

4.2.2.1 Particulates

The total air concentration for a given particulate size p at a receptor location for a given time step j is the sum of the downwind dispersed source term contribution (as estimated by using Equations 3.26 and 3.28) and the resuspended air concentrations (calculated by using Equation 4.8), which gives:

$$\overline{C_{air}}(i,p,x,t_j)=\overline{C_{\sec}}(i,p,x,t_j)+\overline{C_{air_R}}(i,p,x,t_{j,}),$$

(4.10)

where

> $\overline{C_{air}}(i,p,x,t_j)$ = total air concentration of radionuclide i on particle size p during time step t_j at distance x (Ci/m³),

> $\overline{C_{\sec}}(i,p,x,t_{s_j})$ = sector-averaged air concentration of radionuclide i on particle size p at distance x (in m) from the source during time step j (Ci/m³), by using Equation 3.26 or 3.28 or a combination of the two, and

> $C_{air_R}(i,p,x,t_j)$ = resuspended air concentration for radionuclide i on particle size p at a distance x during time step j (Ci/m³) [Equation 4.8].

The total air concentration for radionuclide i is obtained by summing over all particle sizes:

$$\overline{C_{air}}(i,x,t_j)=\sum_{p}\overline{C_{air}}(i,p,x,t_j),$$

(4.11)

where

> $\overline{C_{air}}(i,x,t_j)$ = total air concentration of radionuclide i during time step t_j at distance x (Ci/m³).

4.2.2.2 Radon and Radon Progeny

Due to the shorter half-lives of Rn-220 and Rn-222 (shown in Figures 2-1 and 2-2), their downwind air concentrations are corrected for decay during transport. For estimating the downwind radon (Rn-220 or Rn-222) air concentrations, the downwind source strength, Q_{xi}, in Equations 3.26 and 3.28, can be expressed as follows:

$$Q_{x\_Rn}=(3.17\times10^{-8}\text{ yr/s})Q_{0\_Rn}\exp(-\lambda_{Rn}\tau),$$

(4.12)

where

Q_{x_Rn} = depleted downwind source strength of Rn at distance x downwind (Ci/s),

Q_{0_Rn} = source strength of Rn at the release point (Ci/yr),

λ_{Rn} = radon decay constant (1/s) [(ln 2)/(Rn decay half-life)], and

τ = transit time between source and receptor, calculated as the downwind distance divided by the average wind speed (x/u_H) (s).

The downwind radon air concentration can then be calculated by multiplying the depleted downwind source strength of radon by the normalized air concentration for a gas:

$$\overline{C_{\text{sec}}}\left(Rn, x, t_j\right) = \left(\frac{\chi}{Q}\right)_{gas} Q_{x\_Rn} \,,$$

(4.13)

where

$\overline{C_{\text{sec}}}(Rn, x, t_j)$ = sector-averaged air concentration of radon at a distance x (in m) from the source during time step j (Ci/m^3), and

$(\chi/Q)_{gas}$ = normalized air concentration for a gas (i.e., a nondepositing molecule), as discussed in Section 3.4, by using Equation 3.26 or 3.28 or a combination of the two (s/m^3).

The concentration of radon daughters at a given downwind distance x depends on their ingrowth during the transit time as calculated by Momeni et al. (1979):

$$\overline{C_{\text{sec}}}\left(i_n, x, t_j\right) = \overline{C_{\text{sec}}}\left(Rn, x, t_0\right)\left(\prod_{i=2}^{n} \lambda_i\right)\left\{\sum_{i=1}^{n}\left[\frac{\exp\left(-\lambda_i \tau\right)}{\prod_{\substack{m=1 \\ m \neq i}}^{n}\left(\lambda_m - \lambda_i\right)}\right]\right\},$$

(4.14)

for n = 2,…,4 for Rn-220 and n = 2,…,7 for Rn-222,

where

$\overline{C_{\text{sec}}}(i_n, x, t_j)$ = sector-averaged air concentration of radon daughter i_n at a distance x (in m) from the source during time step j (Ci/m^3),

λ_i and λ_m = radioactive decay constants for radon daughters (1/s), and

$\overline{C_{\sec}}(Rn,x,t_0)$ = what would be the sector-averaged air concentration of radon at a distance x (in m) from the source (Ci/m^3) without accounting for radioactive decay. Note that the derivation of Equation 4.14 assumes the initial amount of Rn that would be present before decay occurs. This value can be calculated by multiplying the normalized air concentration for a gas at the receptor for a given source multiplied by the amount released (Q_{0_Rn} in Ci/yr) as given by

$$\overline{C_{\sec}}(Rn, x, t_0) = 3.17 \text{ x } 10^{-8} \text{ yr/s} \left(\frac{\chi}{Q}\right)_{gas} Q_{0\_Rn} \;.$$
(4.15)

4.3   Vegetation Concentrations

The ground and air concentrations at each receptor location are used to calculate the radionuclide concentrations in vegetation consumed by humans and livestock. MILDOS4 estimates vegetation concentrations from root uptake from the soil and deposition from air, as shown in the first and second terms, respectively, in Equation 4.16:

$$C_v(i, p, x, t_j) = 10^{12} \frac{C_g(i, p, x, t_j)B_v(i)}{\rho} + 8.64 \times 10^{16} C_{air}(i, p, x, t_j)V_{d_p}F_rE_v \frac{1 - \exp(-\lambda_w t_v)}{Y_v\lambda_w},$$

(4.16)

where

$C_v(i, p, x, t_j)$ = concentration of radionuclide i from particle size p in vegetation type v during time step j (pCi/kg) (wet weight),

10^{12} = unit conversion factor (pCi/Ci),

8.64×10^{16} = unit conversion factor (pCi-s/Ci-d),

$B_v(i)$ = soil-to-plant transfer coefficient for radionuclide i and vegetation type v (pCi/kg [wet] plant per pCi/kg [dry] soil),

ρ = soil areal density for surface mixing (kg/m^2) (dry weight),

F_r = fraction of the total deposition retained on plant surfaces,

E_v = fraction of the foliar deposition reaching edible portions of vegetation v,

λ_w = decay constant accounting for weathering losses [ln 2/plant weathering decay half-life] (1/d),

t_v = duration of exposure while vegetation v is growing (d), and

Y_v = yield density of vegetation v (kg/m^2) (wet weight).

Five categories of vegetation are considered. The first three are for human consumption, and the last two are for livestock consumption: (1) edible aboveground vegetables, (2) potatoes, (3) other edible belowground vegetables, (4) pasture grass, and (5) hay (stored feed). Category-specific input parameters are used in Equation 4.16 in each case.

From a given source, the total concentration of radionuclide i in vegetation type v during time step j is the sum over all particle sizes:

$$C_v(i,x,t_j) = \sum_p C_v(i,p,x,t_j),$$

(4.17)

where

$\quad C_v(i,x,t_j)$ = concentration of radionuclide i in vegetation type v during time step j (pCi/kg) (wet weight).

4.4   Meat and Milk Concentrations

The radionuclide concentrations in meat (beef) and milk are based on livestock consumption of pasture grass and hay (stored feed). The radionuclide concentration in meat is calculated according to

$$C_b(i,x,t_j) = Q F_b(i)\left(F_{pg}C_{v_{pg}}(i,x,t_j) + F_h C_{v_h}(i,x,t_j)\right),$$

(4.18)

where

$\quad C_b(i,x,t_j)$ = average meat concentration for radionuclide i during time step j (pCi/kg),

$\quad Q$ = feed ingestion rate (kg/d) (wet weight),

$\quad F_b(i)$ = feed-to-meat transfer coefficient for radionuclide i (pCi/kg per pCi/d),

$\quad F_{pg}, F_h$ = fraction of the total annual feed requirement that is assumed to be satisfied by pasture grass or locally grown feed (hay), respectively,

$\quad C_{v_{pg}}(i,x,t_j)$ = concentration of radionuclide i in pasture grass [Equation 4.17] (pCi/kg) (wet weight), and

$\quad C_{v_h}(i,x,t_j)$ = concentration of radionuclide i in hay or other stored feed [Equation 4.17] (pCi/kg) (wet weight).

The equation used to estimate milk concentrations from cows ingesting radionuclides in feed is given by

$$C_m(i,x,t_j) = Q F_m(i)\left(F_{pg}C_{v_{pg}}(i,x,t_j) + F_h C_{v_h}(i,x,t_j)\right),$$

(4.19)

where

$C_m(i, x, t_j)$ = average milk concentration for radionuclide *i* during time step *j* (pCi/L), and

$F_m(i)$ = feed-to-milk transfer coefficient for radionuclide *i* (pCi/L per pCi/d).

4.5   Effluent Concentration Limit Ratios

MILDOS4 calculates the ratios of the air concentrations of each radionuclide at each receptor location with the effluent air concentration limits (ECLs) as defined in Table 2 (Column 1) of Appendix B to NRC's *Standards for Protection against Radiation* (10 CFR Part 20).

In the case of Rn-222, the calculated ratio involves consideration of the radon daughter products. The Rn-222 ECL ratio (*ECL*$_{Rn-222}$) is calculated as:

$$ECL_{Rn-222} = \frac{\overline{C_{air}}(Rn222, x, t_j) \times (1 - E_{222\_eq})}{1 \times 10^8} + \frac{\overline{C_{air}}(Rn222, x, t_j) \times E_{222\_eq}}{1 \times 10^{10}},$$

(4.20)

where

$\overline{C_{air}}(Rn222, x, t_j)$ = air concentration of Rn-222 during time step t_j at distance *x* (Ci/m^3) [calculated by substituting Equation 4.12 in Equation 3.26 or 3.28],

E_{222_eq} = equilibrium fraction of radon daughters with Rn-222 in air at the receptor location (unitless) [Equation 4.21],

1 x 10^{-8} = the 10 CFR Part 20 Appendix B Table 2 air concentration value for Rn-222 without daughters (μCi/cm^3 [$\equiv$ Ci/m^3]), and

1 x 10^{-10} = the 10 CFR Part 20 Appendix B Table 2 air concentration value for Rn-222 with daughters (μCi/cm^3 [$\equiv$ Ci/m^3]).

The Rn-222 equilibrium fraction is calculated as:

$$E_{222\_eq} = F_{in} E_{222\_in\_eq} + F_{out} E_{222\_out\_eq},$$

(4.21)

where

F_{in}, F_{out} = indoor and outdoor occupancy fractions, respectively (unitless),

$E_{222\_in\_eq}$ = equilibrium fraction of radon daughters with Rn-222 in indoor air (unitless), and

$E_{222\_out\_eq}$ = equilibrium fraction of radon daughters with Rn-222 in outdoor air [user specified or calculated according to Equation 5.5] (unitless).

The Rn-220 ECL ratio is calculated by dividing the Rn-220 air concentration at the receptor location by the 10 CFR Part 20 Appendix B Table 2 air concentration value for Rn-220 with daughters (3×10^{11} μCi/cm^3). ECL ratios for radon daughters are not calculated on an individual basis.

A demonstration of compliance with 10 CFR 20.1301 using the method in Part 20.1302(b)(2)(i) should be based on annual average effluent concentrations calculated at the boundary of the unrestricted area, and that adjustment of the effluent concentration values in Appendix B for purposes of demonstrating compliance requires prior NRC approval.

5 DOSE ASSESSMENT

This section discusses the exposure models used in MILDOS4. Potential receptors, including individuals and population groups, are considered. Exposure pathways include inhalation of dispersed air and resuspended uranium and thorium ore material, external radiation from ore material in the air and on the ground, and ingestion of ore-associated radioactivity in locally grown foods. Chapter 3 of this manual describes the method for calculating downwind air concentrations; resuspended air concentrations, ground concentrations, and food concentrations are covered in Chapter 4. Figure 1-1 depicts the exposure pathways evaluated.

5.1   Receptors

MILDOS4 estimates doses to individual receptors located near uranium and thorium mining and milling operations as well as the local population group in the surrounding area.

5.1.1   Individual Receptors

Individual receptors include those individuals living and working in the vicinity of uranium and thorium mining and milling operations. Four different age groups are considered by the model: (1) infant, (2) child, (3) teenager, and (4) adult. Age-specific breathing and ingestion characteristics are used in the exposure models (Section 5.2); these are coupled with age-specific DCs, as discussed in Section 5.3.

5.1.2   80-km Population

Collective population doses are assessed by MILDOS4 for the general population living as far as 80 km from uranium and thorium mining and milling facilities. The same age-specific groups used for individual receptors are used in the population exposure models. For the analysis of the area surrounding the facility analyzed, MILDOS4 uses a population grid that partitions a circle with an 80-km radius into 16 directions, with 12 segments in each direction, to give 192 spatial intervals (grid segments). The 12 intervals in each direction are between the following distances in kilometers: 1–2, 2–3, 3–4, 4–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80. This population grid is centered on the first emission source specified by the user. No population analysis is performed for distances within 1 km of the population grid center, but analyses for individual receptors in that distance range may be performed as needed.

5.2   Exposure Pathways

The exposures of individuals and the local population are considered for external radiation from airborne and ground-deposited radioactive material, inhalation of airborne radioactive material, and ingestion of radioactivity in food that is grown locally.

Inhalation and external population exposure calculations are based on an individual located at the midpoint of each population segment. The estimated dose for that individual is multiplied by the number of people in the segment to obtain the collective population dose for that segment.

5.2.1 External

The external dose to an individual receptor is calculated for exposure to ground activity and airborne radiation. Indoor and outdoor exposures are both considered.

$$D_{ext,o}(x,t_j) = 10^{12}\left(F_{in}S_{in} + F_{out}\right)\left(\sum_i \left[DC_{cld,io}\,\overline{C_{air}}(i,x,t_j) + DC_{gnd,io}C_g(i,x,t_j)\right]\right), \qquad (5.1)$$

where

$D_{ext,o}(x,t_j)$ = external dose rate to organ o in individual from outside airborne and deposited activity at distance x and time step j (mrem/yr),

10^{12} = unit conversion factor (pCi/Ci),

F_{in}, F_{out} = indoor and outdoor occupancy fractions, respectively (unitless),

S_{in} = indoor external shielding factor (unitless),

$\overline{C_{air}}(i,x,t_j)$ = total air concentration of radionuclide i during time step t_j at distance x (Ci/m^3) [Equation 4.11],

$C_g(i,x,t_j)$ = ground concentration of radionuclide i from a given source after time step j (Ci/m^2) [Equation 4.3],

$DC_{cld,io}$ = external air immersion dose coefficient for radionuclide i in organ o (mrem/yr per pCi/m^3), and

$DC_{gnd,io}$ = external groundshine dose coefficient for radionuclide i in organ o (mrem/yr per pCi/m^2).

For a given time step j, the total regional population external dose to a given organ o from a given source is calculated as the individual external dose at the midpoint of each population segment multiplied by the number of persons in the segment, n_s, summed over all of the population segments s, as follows:

$$PD_{ext,o}(t_j) = 10^{-3}\sum_s \left(n_s D_{ext,o}(s,t_j)\right), \qquad (5.2)$$

where

$PD_{ext,o}(t_j)$ = total population external dose to organ o from time step j (person-rem/yr),

10^{-3} = unit conversion factor (rem/mrem),

n_s = number of people residing in population segment s, and

$D_{ext,o}(s,t_j)$ = external dose rate to organ o in an individual from a given source from time step j (mrem/yr) [equivalent to Equation 5.1, in which the midpoint of segment

s corresponds to distance *x*]. [For population calculations, 100 percent occupancy (i.e., unity) is assumed for all individuals, with an indoor occupancy of 14 h/day at a shielding factor of 0.7 (that is, F_{in} = 14/24, F_{out} = 10/24, and S_{in} = 0.7) (NRC, 1987)].

5.2.2 Inhalation

Inhalation doses are calculated by using the total air concentrations provided in Section 4.2.2 for particulates and radon and its progeny. The total inhalation dose to an individual in age group *k* from all particle sizes is calculated according to the following:

$$D_{inh,kop}(x,t_j) = 10^{12} \sum_p \sum_i (F_{in}S_{in\_inh} + F_{out})\overline{C_{air}}(i,p,x,t_j)DC_{inh,ikop}IR, \qquad (5.3)$$

where

$D_{inh,kop}(x,t_j)$ = inhalation dose rate to organ *o* in an individual in age group *k* from particulates from time step t_j (mrem/yr),

10^{12} = unit conversion factor (pCi/Ci),

S_{in_inh} = indoor inhalation shielding factor (unitless),

$\overline{C_{air}}(i,p,x,t_j)$ = total air concentration of radionuclide *i* on particle size *p* during time step t_j at distance *x* (Ci/m³) [Equation 4.11],

$DC_{inh,ikop}$ = inhalation dose coefficient for radionuclide *i*, age group *k*, organ *o*, and particle size *p* (mrem/pCi), and

IR = inhalation rate (7,300 m³/yr).

For Rn-222 and its daughters, the inhalation dose is calculated by using the Rn-222 total air concentration according to the following:

$$D_{inh,Rn222}(x,t_j) = 10^{12}\overline{C_{air}}(Rn222,x,t_j)IR[DC_{inh,Rn222}(F_{in}S_{in\_inh} + F_{out}) +$$
$$DC_{inh,Rn222\_D}(F_{in}E_{in\_eq}S_{in\_inh} + F_{out}E_{out\_eq})], \qquad (5.4)$$

where

$D_{inh,Rn222}(x,t_j)$ = inhalation dose rate to an individual from Rn-222 from time step t_j (mrem/yr),

10^{12} = unit conversion factor (pCi/Ci),

$\overline{C_{air}}(Rn222,x,t_j)$ = air concentration of Rn-222 during time step t_j at distance *x* (Ci/m³) [calculated by substituting Equation 4.12 in Equation 3.26 or 3.28],

E_{in_eq}, E_{out_eq} = equilibrium fraction of radon daughters with radon in indoor and outdoor air, respectively (unitless),

$DC_{inh,Rn222}$ = inhalation dose coefficient for Rn-222 (mrem/pCi), and

$DC_{inh,Rn222\_D}$ = inhalation dose coefficient for all Rn-222 daughters (mrem/pCi).

For radon, the dose to the lung is back-calculated by dividing the radon dose to an individual according to Equation 5.4 by the appropriate organ weighting factor. Derivation of the radon DCs is presented in Section 5.3.2.1. Also note that there is no age dependency with regard to radon dose calculations in MILDOS4.

For individual receptors, an option is available to have the code estimate the outdoor equilibrium fraction (E_{out_eq}) for the Rn-222 daughters. All population calculations use this method. The equilibrium fraction can be calculated by dividing the WL at the receptor location by the WL if radon is in equilibrium with its daughters. Here, the WL is calculated according to the methodology in Yu et al. (2001). For Rn-222, the calculation is given by

$$E_{out\_eq} = \frac{1.03 \times 10^{-6} A + 5.07 \times 10^{-6} B + 3.73 \times 10^{-6} C}{1.03 \times 10^{-6} + 5.07 \times 10^{-6} + 3.73 \times 10^{-6}},$$
(5.5)

where A, B, and C are the air concentrations of Po-218, Pb-214, and Bi-214, respectively, relative to the Rn-222 air concentration.

For Rn-220 (unlike for Rn-222), an equilibrium with its daughters is not established because of the Rn-220's short half-life. The inhalation dose is calculated by using the Rn-220 WL according to the following:

$$D_{inh,Rn220}(x, t_j) = (F_{in} S_{in\_inh} + F_{out}) WL_{Rn220}(x, t_j) DC_{inh,Rn222},$$
(5.6)

where

$D_{inh,Rn220}(x,t_j)$ = inhalation dose rate to an individual from Rn-220 from time step t_j (mrem/yr),

$WL_{Rn220}(x,t_j)$ = WL of Rn-220 during time step t_j at distance x (WL) [Equation 5.7], and

$DC_{inh,Rn220}$ = inhalation dose coefficient for Rn-220 (mrem/yr per WL).

The Rn-220 WL is calculated according to Yu et al. (2001) as follows:

$$WL_{Rn220} = 9.48 \times 10^{-10} A' + 1.23 \times 10^{-4} B' + 1.17 \times 10^{-5} C',$$
(5.7)

where A', B', and C' are the air concentrations (pCi/m³), respectively, of Po-216, Pb-212, and Bi-212 at the receptor location.

The total inhalation dose rate to organ o in an individual in age group k from a given source is the sum of the dose rates from particulates and radon, as follows:

$$D_{inh,ko}(x, t_j) = D_{inh,kop}(x, t_j) + D_{inh,Rn222}(x, t_j) + D_{inh,Rn220}(x, t_j),$$
(5.8)

where

$D_{inh,ko}(x,t_j)$ = inhalation dose rate to organ o in an individual in age group k from a given source from time step t_j (mrem/yr).

For a given time step j, the total regional population inhalation dose to a given organ o from a given source is calculated as the individual inhalation dose for each age group at the midpoint of each population segment multiplied by the number of persons of that age group in the segment n_{ks}, summed over all age groups k and over all of the population segments s, as follows:

$$ PD_{inh,o}(t_j) = 10^{-3} \sum_s \sum_k n_{ks} D_{inh,ko}(s,t_j) , $$

(5.9)

where

$PD_{inh,o}(t_j)$ = total population inhalation dose rate to organ o from time step t_j (person-rem/yr),

10^{-3} = unit conversion factor (rem/mrem),

n_{ks} = number of people in age group k residing in population segment s, and

$D_{inh,ko}(s,t_j)$ = inhalation dose rate to organ o in an individual in age group k from a given source from time step t_j (mrem/yr) [equivalent to Equation 5.8, where the midpoint of segment s corresponds to distance x].

5.2.3   Ingestion

Ingestion doses are calculated by using the radionuclide concentrations in agricultural products calculated for vegetables in Section 4.3 and meat and milk in Section 4.4.

5.2.3.1 Individual Ingestion

For individuals, the annual radionuclide intake via ingestion is calculated as

$$ I_k(i,x,t_j) = U_{mk} C_m(i,x,t_j) + U_{bk} C_b(i,x,t_j) + F_{va} U_{vk} \sum_v F_{vck} C_v(i,x,t_j) , $$

(5.10)

where

$I_k(i,x,t_j)$ = ingestion rate of radionuclide i by an individual in age group k during time step t_j (pCi/yr),

U_{mk}, U_{bk} = milk (L/yr) and meat (kg/yr) ingestion rates for age group k,

$C_m(i,x,t_j)$ = average milk concentration for radionuclide i during time step j (pCi/L) [Equation 4.19],

$C_b(i,x,t_j)$ = average meat concentration for radionuclide i during time step j (pCi/kg) [Equation 4.18],

F_{va} = fraction of radionuclide activity remaining in vegetables after food preparation (unitless),

U_{vk} = vegetable ingestion rate for age group k (kg/yr)(wet weight),

F_{vck} = fraction of vegetable category c consumed by age group k (unitless), and

$C_v(i,x,t_j)$ = concentration of radionuclide i in vegetation type v during time step j (pCi/kg) (wet weight).

The ingestion dose for organ o from radionuclide i is then calculated by

$$D_{ing,ko}(i,x,t_j) = I_k(i,x,t_j)DC_{ing,iko} \, , \qquad (5.11)$$

where

$D_{ing,ko}(i,x,t_j)$ = ingestion dose rate to organ o from radionuclide i of an individual in age group k from time step t_j (mrem/yr), and

$DC_{ing,iko}$ = ingestion dose coefficient for radionuclide i in organ o of an individual in age group k (mrem/pCi ingested).

5.2.3.2 Population Ingestion

To estimate the ingestion dose to the regional population, the MILDOS4 model assumes that all of the locally grown food is consumed. Because of this, the population ingestion dose is based on the local agricultural productivity rather than the number of people nearby, because the total activity in the food determines the total collective dose. The amount of each food type grown in each area (grid segment) in the population grid is first calculated in conjunction with the radionuclide concentrations in each food type. Consumption of the total amount of each food type is partitioned among the four age groups. Ingestion doses to each age group are calculated based on the amount of radioactivity consumed and the DCs for each age group. The total ingestion dose to the population is then calculated by summing the doses over all age groups and population grid segments.

The average radionuclide concentration in vegetables in a given population segment is

$$C_{v\_avg}(i,s,t_j) = \sum_v W_{vs} C_{vs}(i,x,t_j) \, , \qquad (5.12)$$

where

$C_{v\_avg}(i,s,t_j)$ = concentration of radionuclide i in vegetables averaged over all vegetable types in population segment s during time step j (pCi/kg) (wet weight),

$C_{vs}(i,x,t_j)$ = concentration of radionuclide *i* in vegetation type *v* during time step *j* (pCi/kg) (wet weight) [Equation 4.17], and

W_{vs} = weighting factor for vegetable type *v* in population segment *s* (fraction of total production), unitless.

The gross activity content in the regional food production for each food type is calculated by

$$Q_f(i,t_j) = \sum_s \sum_f P_{fs} C_f(i,s,t_j),$$

(5.13)

where

$Q_f(i,t_j)$ = total amount of radionuclide *i* in food type *f* (vegetables, meat, and milk) produced in the region during time step *j* (pCi/yr) (wet weight),

$C_f(i,s,t_j)$ = concentration of radionuclide *i* in food type *f* in population segment *s* during time step *j* (pCi/kg) (wet weight) [Equation 5.12 (vegetables), Equation 4.18 (meat), Equation 4.19 (milk)], and

P_{fs} = annual production rate of food type *f* in population segment *s* (kg/yr).

Because the population dose in each segment depends on ingestion of the food by different age groups that generally have different food consumption rates and DCs, the fraction of the food in each segment eaten by each age group needs to be calculated next, as given by

$$F_{fk} = \frac{F_{pk} U_{fk}}{\sum_k F_{pk} U_{fk}},$$

(5.14)

where

F_{fk} = fraction of food type *f* consumed by individuals in age group *k* (unitless),

F_{pk} = fraction of the population belonging to age group *k* (unitless), and

U_{fk} = average consumption rate of food type *f* for an individual in age group *k* (kg/yr for vegetables and meat, L/yr for milk).

The total population dose from all food produced in the region can be calculated by

$$PD_{ing,ko}(i,t_j) = 10^{-3} \sum_f \sum_i \sum_k F_{fa} Q_f(i,t_j) F_{fk} DC_{ing,iko},$$

(5.15)

where

$PD_{ing,ko}(i,t_j)$ = population ingestion dose rate to organ *o* from radionuclide *i* of an individual in age group *k* from time step t_j (person-rem/yr),

$DC_{ing,iko}$ = ingestion dose coefficient for radionuclide i in organ o of an individual in age group k (mrem/pCi ingested), and

F_{fa} = fraction of radionuclide activity remaining in food type f after food preparation (unitless).

5.3   Dose Coefficients

In keeping with the ICRP and other agencies, the term "dose coefficient (DC)," equivalent to the term "dose conversion factor" more commonly used in the past, is used in this report. The DCs in MILDOS4 are calculated by using the dosimetric model from ICRP Publication 30 (ICRP, 1979).

5.3.1   External Dose Coefficients

The code includes external DCs to calculate the external exposure to radionuclides in air and deposited on the ground surface. Tables B-1 and B-2 in Appendix B list the air submersion and ground surface DCs used in the code for U-238 and Th-232 decay series isotopes, respectively.

5.3.2   Internal Dose Coefficients

The internal DCs are calculated by using the methodology from ICRP Publications 26 and 30 (ICRP, 1977, 1979) and a NUREG/CR-4628 report prepared by ORNL for the NRC (Cristy et al., 1986).

5.3.2.1 Inhalation

5.3.2.1.1 Particulates

The relationship between the particle size and the DCs is irregular. The adult inhalation effective dose equivalent for a given particle size is calculated by linear interpolation from the data set provided for 12 particle sizes. Table B-3 in Appendix B lists the adult inhalation effective DCs for the U-238 decay series isotopes. In inhalation dosimetry, inhaled materials are assumed to belong to one of three classes, based on their removal from the respiratory tract. The three inhalation solubility classes in ICRP 30 methodology are designated as D (removal in days), W (removal in weeks), and Y (removal in years). In the ICRP classification, some elements do not have all three inhalation classes. In MILDOS4, the DC values for the unassigned classes are assumed to be the same as those of the adjacent classes.

The organ/tissue inhalation dose equivalent conversion factors for a given particle size H_{50} (in activity median aerodynamic diameter, or AMAD) for U-238 decay series isotopes are calculated from H_{50} (1 µm) by using the following equation:

$$\frac{H_{50}(AMAD)}{H_{50}(1\,\mu m)} = f_{N-P}\left(\frac{D_{N-P}(AMAD)}{D_{N-P}(1\,\mu m)}\right) + f_{T-B}\left(\frac{D_{T-B}(AMAD)}{D_{T-B}(1\,\mu m)}\right) + f_P\left(\frac{D_P(AMAD)}{D_P(1\,\mu m)}\right),\qquad(5.16)$$

where

f_{N-P} = fraction of the committed dose equivalent in the reference tissue resulting from deposition in the nasal-pharynx (N-P) respiratory region,

f_{T-B} = fraction of the committed dose equivalent in the reference tissue resulting from deposition in the trachea-bronchial (T-B) respiratory region,

f_P = fraction of the committed dose equivalent in the reference tissue resulting from deposition in the pulmonary (P) respiratory region,

D_{N-P} = deposition probability in the N-P respiratory region for a given AMAD,

D_{T-B} = deposition probability in the T-B respiratory region for a given AMAD, and

D_P = deposition probability in the P respiratory region for a given AMAD.

The deposition probabilities in different regions of the lung are calculated from the deposition and retention models for the internal dosimetry of the human respiratory tract developed by the ICRP task group on lung dynamics (ICRP, 1966).

Table B-4 in Appendix B lists U-238 decay series isotopes' tissue/organ DCs for a particle size of 1 μm, and Table B-5 provides values for the factors $f_{N-P}/f_{T-P}/f_P$ for the U-238 decay series isotopes. Table B-6 in Appendix B lists the adult inhalation effective DCs and organ/tissue dose equivalent conversion factors for the Th-232 decay series isotopes for 12 particle sizes.

Inhalation DCs for other age groups (infant, child, and teenager) are calculated by using the relative age-specific factors (normalized to adult) provided by Cristy et al. (1986). Tables B-7 and B-8 in Appendix B list the values for the U-238 and Th-232 decay series isotopes, respectively. Cristy et al. (1986) provided age-specific factors only for three particle sizes (AMADs of 0.3, 1, and 5 μm). For AMADs of less than 0.6 μm, between 0.6 and 3 μm, and greater than 3 μm, the corresponding factors for 0.3, 1, and 5 μm, respectively, are used.

5.3.2.1.2 Radon

The radon DCs are based on the air concentrations provided in Table 2 of Appendix B in 10 CFR Part 20 associated with an annual dose of 50 mrem.

For Rn-222, including its daughters, an air concentration of 1×10^{-10} μCi/ml (100 pCi/m³) corresponds to a dose of 50 mrem/yr, which is equivalent to 0.5 mrem/yr per pCi/m³. Likewise, for Rn-222 without its daughters, an air concentration of 1×10^{-8} μCi/ml (10,000 pCi/m³) is equivalent to 0.005 mrem/yr per pCi/m³. Thus, the DCs used in MILDOS4 for Rn-222 without its daughters and for the Rn-222 daughters are only 0.005 mrem/yr per pCi/m³ and 0.495 mrem/yr per pCi/m³ (0.5 - 0.005), respectively.

For Rn-220 and its progeny, the inhalation DC is given in units of mrem/yr per WL. The value of working level month (WLM) is given as 4.68×10^4 Bq·h/m³ (ICRP, 2010). Assuming there are 170 hours in a working month, dividing the value for the WLM by 170 gives a WL value of 275 Bq/m³ (7,430 pCi/m³) for Rn-220. From Table 2 in Appendix B in 10 CFR Part 20, an air concentration of 3×10^{-11} μCi/ml (30 pCi/m³) corresponds to a dose of 50 mrem/yr from Rn-220 and its daughters. Thus, exposure to a WL concentration for a year would be 7,430 pCi/m³ divided by 30 pCi/m³ multiplied by 50 mrem/yr to give 12,400 mrem/yr per WL.

5.3.2.2 Ingestion

The adult ingestion DCs are based on ICRP 30 methodology. Table B-9 lists ingestion DCs for U-238 decay series isotopes. The ingestion DCs for other age groups (infant, child, and teenager) are calculated by using the relative age-specific factors (normalized to adult) provided by Cristy et al. (1986). Table B-10 lists the values for the U-238 decay series isotopes. Tables B-11 and B-12 list ingestion DCs and relative age-specific factors for the Th-232 decay series isotopes.

6 USER INTERFACE AND PROGRAM INPUT

Information on using the MILDOS4 program is provided in this chapter. Detailed information on the different input options is explained in the context of the source term models (Chapter 2), the air dispersion model (Chapter 3), media concentration estimates (Chapter 4), and dose estimates (Chapter 5). Program installation and implementation details are provided in Appendix A.

6.1   General Program Guide

General operation of the MILDOS4 program is discussed in this section. MILDOS4 was developed to use a minimum screen resolution of 1280 × 768 pixels. Note that labels and text on the program windows may not display properly if the Windows® display text size is set to a nondefault value (i.e., "Medium" or "Larger" rather than "Smaller" [Windows 7]).

6.1.1   Program Layout

MILDOS4 consists of a main program window that implements a tab interface that groups program input and output into similar categories, as shown near the top of Figure 6-1. The seven tabs (categories) are: (1) "Case Information" (overview), (2) "Met Data" (meteorological input data), (3) "Population" (population input data), (4) "Soil/Food" (soil and ingestion input data), (5) "Output Options" (custom output table input), (6) "Map" (map representation of scenario), and (7) "Results" (calculation results; only present when results are available).

Figure 6-1 Main Program Window with the "Case Information" Tab Selected

6.1.2 Menus and Toolbars

Navigation within the program is provided by means of menus, toolbars, and hot-keys. Table 6-1 lists the main menu items and their associated hot keys. Typical user file management functions (Open, Save, and Save As) are provided, as is a way to exit the program (Exit). The File → New menu item creates a new user file that will be saved under a user-specified filename. If the file that is currently open has not been saved, the user will be given the option to save or not save the current file before creating the new file. Note that version 4 user files are not compatible with earlier versions of the program. Section 6.1.4 discusses the user file format. The File → Import menu item allows the user to "read in" a user file saved by previous versions of the program (MILDOS-AREA 3). Input data not previously available to the user will be set to the original values used in the code. Note that new input parameters added in version 4 (e.g., Rn-222 equilibrium fractions for individuals) will be set to the program default values, which should be approved by the user before use (as should any other default supplied by the program). The File → Compact File menu item is discussed in Section 6.1.4.

Table 6-1 Main Menu Items and Associated Hot Keys

Menu Item	Hot Key	Menu Item	Hot Key
File Menu (Alt + F)		View Menu (Alt + V)	
New	Alt + N	Case Information	Alt + I
Open	Alt + O	Map	Alt + M
Save	Alt + S	Met Data	Alt + W
Save As	Alt + A	Population	Alt + P
Import	Alt + T	Soil/Food	Alt + G
Compact File	—	Output Options	Alt + Y
Exit	Alt + E	Results	Alt + R
		Sensitivity Parameters	Alt + Z
		Windows Calculator	Alt + U
Calculations Menu (Alt + C)		Help Menu (Alt + H)	
Launch Calculations	Alt + L	About MILDOS	Alt + B
Delete Results	Alt + D	Shortcut Keys	Alt + K

The menu items under the View menu provide an alternate way to access the main tab pages. The View → Sensitivity Parameters menu item displays the sensitivity analysis summary window discussed in Section 6.10.

The main toolbar, located directly beneath the main menu (see Figure 6-2), provides one-click access to more commonly used functions such as opening and saving files, running calculations, and viewing sensitivity parameter input.
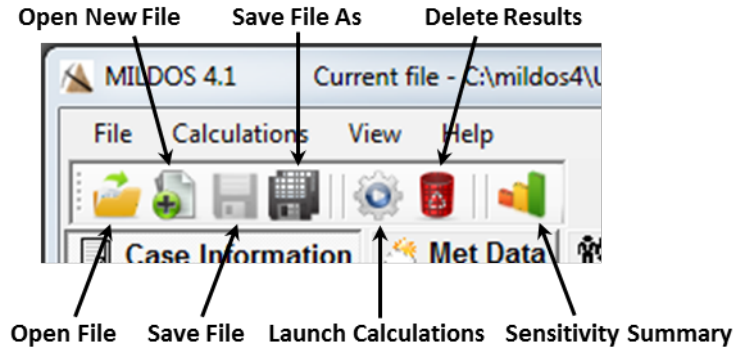
Figure 6-2 Main Toolbar Functions

6.1.3 Program Conventions

Data input involves selecting options from drop-down menus, checkboxes, and radiobuttons and providing entries in text input boxes/tables. Navigation between input items on a given form or window can be accomplished either by clicking on the input item with a mouse or using the Tab key to circulate through the items on the form.

User input is displayed only if it is relevant to the current set of options selected. For example, the "Population" tab page is not available if the "Calculate population exposure" checkbox on the right side of the main program window is not checked. Similarly, the "Results" tab page is not available if there are no results calculated for the current set of inputs.

MILDOS4 performs error-checking on numerical input. When the user enters numerical data into program input fields, the program ensures that the value entered is of the correct type (i.e., a valid number) and is within a valid range for that parameter. If an entry does not conform to either check, an error message will be given. A valid number must be given in order to proceed further. The user may view an input parameter's definition and lower and upper bounds by pressing the F2 function key when the input field for that parameter is selected.

When changes to the input are made by the user, they are not automatically saved to the user file. Any changes are maintained in computer memory until the user saves the revised input back to the user file or discards the changes when opening a different user file or exiting the program. A warning indicator (Modified – not yet saved) is shown next to the main toolbar after an input change is made, and it remains until the user file is saved. The user file also contains calculation results, as discussed in the next section. If a change is made to the input, any results from a prior calculation run will be automatically deleted after approval is given by the user following a prompt triggered by the change. No change in the input value will be accepted by the program if the user chooses not to allow the deletion of the current set of results.

Calculations involving the selected options will be performed when the user selects either the Calculations →Launch Calculations menu item or clicks on the appropriate main toolbar item. If there are changes to the user input, the user will be prompted to either cancel the run or save to the input file before running. The user must save to the input file before the calculation run is performed.

6.1.4 User File

The MILDOS4 user file is a database (DB) file that is used for storing both user input and the calculated results (output). Each case analyzed is stored in its own separate file and is not part of a central server located on the user's computer or on a remote computer. The SQLite file format and database engine are used. SQLite is a well-established open-source database. More information on SQLite can be found in Appendix A.

Employing a DB file for user input facilitates the input data handling and error-checking, and, because of the faster central processing unit (CPU) speeds and larger amounts of memory available on PCs running Windows, it allows results to be stored and retrieved on a more atomic scale. This implementation underlies the interactive results and custom table output capability of MILDOS4 as described in Sections 7.4 and 7.5.

While the move to a user (application) file in DB format provides added functionality to the program, versions of MILDOS-AREA prior to version 4.0 used a simple text file to save user input and a separate text file for program output. This format is not compatible with the current version. In addition, with the enhancements made to version 4.1, user files generated by earlier versions of MILDOS4 have a modified format and are automatically upgraded when input by version 4.1. User files generated by MILDOS 4.1 and later cannot be used by previous versions of the program. As discussed in Section 6.1.2, an import function is available that allows the user to read older version 3 text input files into the program for saving in the new format. Note that an HTML file that lists the user input and a summary of results, similar to the concept of the old version output file, is also available after a calculational run in version 4 as discussed in Chapter 7.

6.2   Case Definition

As shown in Figure 6-1, the "Case Information" tab page provides the user an overview of the case (i.e., scenario) to be analyzed in addition to some of the more detailed input. Information on sources and receptors is summarized, and the population and population ingestion options are available for selection. No specific limits are imposed on the number of sources and the number of individual receptors, but system or program memory will eventually limit execution of the specified case depending on the combination of sources, receptors, time steps, and the inclusion of population calculations. Now that MILDOS4 is compiled as a 64-bit application (versions 4.02 and later), the total program memory available is less likely to restrict limits on input (as opposed to the < 2GB limit on 32-bit Windows systems) unless the user's computer has limited memory available.

6.2.1 Source Information

The "Source Information" group, at the bottom of the page, enables the addition, modification, or deletion of individual sources of a particular source type, the particle distribution set to use for a given source, the location of the source, and the air dispersion coefficients to use when modeling air transport of the source emissions. This group contains input for the time steps (see Section 6.4) applicable to all receptors and source terms, and it also contains the input for the particle size distribution sets.

6.2.2 Individual Receptor Information

The "Individual Receptor Information" group, in the middle of the page, contains all of the individual receptor-specific input required for each receptor. Individuals may be added, modified, or deleted. They are defined by (1) their age group, (2) their location, (3) their indoor/outdoor occupancy, (4) the effectiveness of their indoor external and inhalation shielding, (5) the Rn-222 equilibrium fractions for their location, (6) whether or not they consume food containing radionuclides from the sources, and, if they do, (7) how much food they consume.

6.2.3 Options

In addition to providing source and individual receptor input, the "Case Information" tab page allows the user to give the scenario under consideration a descriptive title ("Case Title") and to enter any information relevant to the analysis ("Summary Information"). The user can specify whether or not to include the 80-km population in the dose analysis and whether or not ingestion should be considered for the population by checking the appropriate boxes in the "Population Information" group at the far right.

6.3   Sources

Input related to sources include the type of source involved, the radionuclides released and their amounts, the physical forms of the releases, and the heights of the releases. A minimum of one source is required.

6.3.1   Source Options

6.3.1.1 Dispersion Coefficients

Input for the dispersion coefficients used in the air transport model is source-specific and is found in a drop-down list associated with the source in the "Source Information" group. The Pasquill-Gifford dispersion coefficients are suitable for ground-level releases. The use of the Briggs rural coefficients should produce similar results. Elevated releases (on the order of 50 m or more) may be modeled better by using the Briggs urban coefficients. Section 3.7.1 provides the formulas used to estimate the dispersion coefficients.

6.3.1.2 Particle Distribution Sets

Particle size influences the air dispersion of particulate emissions and the subsequent behavior of particulates once inhaled. MILDOS4 is able to evaluate up to four different particle sizes associated with a single source term. For source terms involving particulates (i.e., releases other than just radon), a particle distribution set is assigned by selecting the appropriate set in an input drop-down list. A distribution set consists of four different particle sizes and their fractional contributions to the entire source release. (The fractional contributions from all four particle sizes in each distriubtion set must total 1.) In addition, each distribution set represents one particle density that may be adjusted by the user. For ground deposition, a deposition velocity is associated with each particle size. The role of particle density in deposition is much less than the role of size, and is taken into account if the settling velocity exceeds the deposition velocity for larger and heavier particulates (see Section 3.1.3). The characteristics for each distribution set are defined in the "Particle Distribution Sets" group in the lower right in Figure 6-1. Table 6-2 summarizes the default particle distribution sets in MILDOS4.

Table 6-2 Default Particle Distribution Sets in MILDOS4

Set	Density (g/cm³)	AMAD (μm)	Percentage of Material	Source Type
1	8.9	3	100	Yellowcake dryer packaging or equivalent
2	2.4	1.5	100	Crushers, grinders, rod mills, conveyors, fine ore blending, and other mill process sources
3	2.4	7.7	30	Tailings, ore-storage piles
	2.4	54	70	

Source: Table 1, NRC (1982); Table 4.5, Yuan et al. (1989)

6.3.2   Source Types

MILDOS4 recognizes eight distinct types of sources, as described in Sections 2.3.1 through 2.3.6 and in the following sections. The input form for a specific source type appears when a specific source in the "Source Information" group on the "Case Information" tab page is selected and the View/Modify button is clicked. At the top of all source type input forms, a place is provided that identifies the source. The name, location, and air dispersion coefficients for the source are repeated from the summary table in the "Source Information" group. Except for the source name, these input parameters may be modified here as well as in the source summary table.

6.3.2.1 Point Source

Point sources are described in Section 2.3.1. Figure 6-3 displays the input form for point sources. Radionuclide release rates for particulates from the longer-lived U-series and Th-series radionuclides and for radon are input here in the "Point Source Term." group. Solubility classes are also input for the major radionuclides considered by the inhalation model discussed in Section 5.3.2.1. For stack releases, the inside stack diameter is a required input, with the effluent exit velocity for momentum-driven plumes or the heat flux for buoyancy-induced plumes.

6.3.2.2 Area Source

Area sources are described in Sections 2.3.2 and 3.5. Figure 6-4 displays the input form for generic area sources. Like the point source input, the "Area Source Term" group provides input for the radionuclide solubility class and source term, but the data are given as concentration units rather than release rates. The "Release Rates" group provides input for radon release rates and particulate release rates. The actual release rates for the radionuclides associated with particulates are determined by multiplying the soil concentrations by the particulate release rate. The particulate release rate may be input directly, or, if the "Use Erosion Model for Particulates" checkbox is checked, the particulate release rate will be determined using the erosion model (see Section 2.3.2).

Figure 6-3 Point Source Input Form

Figure 6-4 Area Source Input Form

An area source shape is one of three sub-types: circular, rectangular, or polygonal. This selection is provided in the "Area Source Type/Dimensions" group near the top of Figure 6-4. The simple circular and rectangular sub-types are defined by either one or three straightforward geometric parameters, respectively. These sub-types are more appropriate when the sources being considered have similar shapes or are ill-defined. The polygonal type is intended for modeling irregular shapes that can be well-defined by using spatial coordinates. When the polygon is on the map (see Section 6.9), its location there is in reference to its origin (0,0) as shown in Figure 6-4. The defining coordinate points (nodes) of the polygon are assumed to follow a clockwise order from the origin and to return to the origin as the last node. This type of closed form is expected by the map interface. The nodes of the polygon may be repositioned either by directly editing the table on the area source input form or through the map interface, as described in Section 6.9.2.3.

6.3.2.3 New Well Field Source

New well field sources are described in Section 2.3.3. The input form for new well field sources is shown in Figure 6-5. Separate concentration inputs are provided for the radium precursors to Rn-220 and Rn-222 and the radon emanation fractions. The remainder of the input, common to both the uranium and thorium series, consists of the data needed to estimate the amount of material on the surface that contributes to radon emission.

Figure 6-5 New Well Field Source Input Form

6.3.2.4 Well Field Source

Well field sources and the associated calculations are described in Section 2.3.4. A "well field" source considers the radon releases due to venting (Section 2.3.4.3). Figure 6-6 displays the input form for this source type. As with the new well field sources case, separate inputs for the uranium and thorium series are given for radium concentrations in the ore. Other input data include the characteristics of the ore zone and the process water.

Figure 6-6 Well Field Source Input Form

6.3.2.5 Purge Source

Radon releases from purge sources at ISR facilities are described in Section 2.3.4.2. The input form for these sources is shown in Figure 6-7. The water chemistry associated with the purge source depends on the well field from which the water comes, either a production or restoration well field. Thus, the input for a purge source includes a reference to the source well field since the main process water (circulating water through the ore bed) is a factor in the amount of radon released. If the source is located within a processing facility or similar environment, stack release input are provided to account for potential plume rise.

Figure 6-7 Purge Source Input Form

6.3.2.6 Ion Exchange Source

Uranium is extracted from the process water of a production well field at an ion exchange source within an ISR facility; the potential release of radon is described in Section 2.3.4.4. Figure 6-8 displays the input form for this type of source. As is the case for a purge source, the input includes a reference to the source well field since the main process water (circulating water through the ore bed) is a factor in the amount of radon released. If the source is located within a processing facility or similar environment, stack release input are provided to account for potential plume rise.

6.3.2.7 Drying/Packaging Source

Drying/packaging sources are described in Section 2.3.5. Figure 6-9 displays the input form for this source type. Required input includes the facility production rate for yellowcake and the fraction released to the stack. Note that the input value for the "Fraction Released to Stack" is the actual fraction released, not the amount released as a percentage. For the activity released, the portions attributable to Th-230, Ra-226, and others (Pb-210) are also required input.

6.3.2.8 Land Application Area Source

Land application area sources are described in Section 2.3.6. The input form for land application area sources is shown in Figure 6-10. The radionuclide source term is limited to the longer-lived radionuclides in the uranium and thorium series. The shape options (circular, rectangular, or polygonal) are the same as those for the basic area source type (Section 6.3.2.2). The "Water/Soil Parameters" group, in conjunction with that labeled "Source Term Parameters," contain the input needed to determine the radionuclide concentrations in the soil due to irrigation or some other application of water with small amounts of radionuclides.

Figure 6-8 Ion Exchange Source Input Form

Figure 6-9 Drying/Packaging Source Input Form

Figure 6-10 Land Application Area Source Input Form

6.4   Time Parameters

MILDOS4 performs calculations for a series of sequential time steps that allow the user to vary the source emission rates and the surrounding population numbers as a function of time. This capability permits the user to generate estimates in a single run that cover the course of a facility's lifetime. For a single time-step, an adjustment factor is assigned for particulate emissions and radon emissions (as applicable), as shown in the bottom right of Figure 6-1 in the "Time Parameters" group.

The number and duration of time steps (increments) are the same for all defined sources. The adjustment factors for each defined source are displayed, and can be modified by the user, in the "Time Parameters" group when that particular source is selected in the source table. New time steps can be added or modified by the user, irrespective of which source is selected.

Typical time steps are for periods of one year or more. The release rates defined by the parameter values input for each source type correspond to an adjustment factor that is equal to one. Thus, for example, if two consecutive years of operation were to be defined by two one-year time steps, partial operation of a source the first year could be reflected by assigning adjustment factors commensurate with the reduced rate (e.g., values of 0.5 if they were to operate only half of the time during the first year) and then assigning adjustment factors of 1 for the second year to reflect full operation at that source. Note that the release rate equations presented in Section 2 do not explicitly include the adjustment factors that are used in the actual implementation in the code.

6.5 Air Dispersion and Meteorological Parameters

The air dispersion model discussed in Section 3, and the relevant input parameters are found under the tab labeled "Met Data" on the main program window, as shown in Figure 6-11.
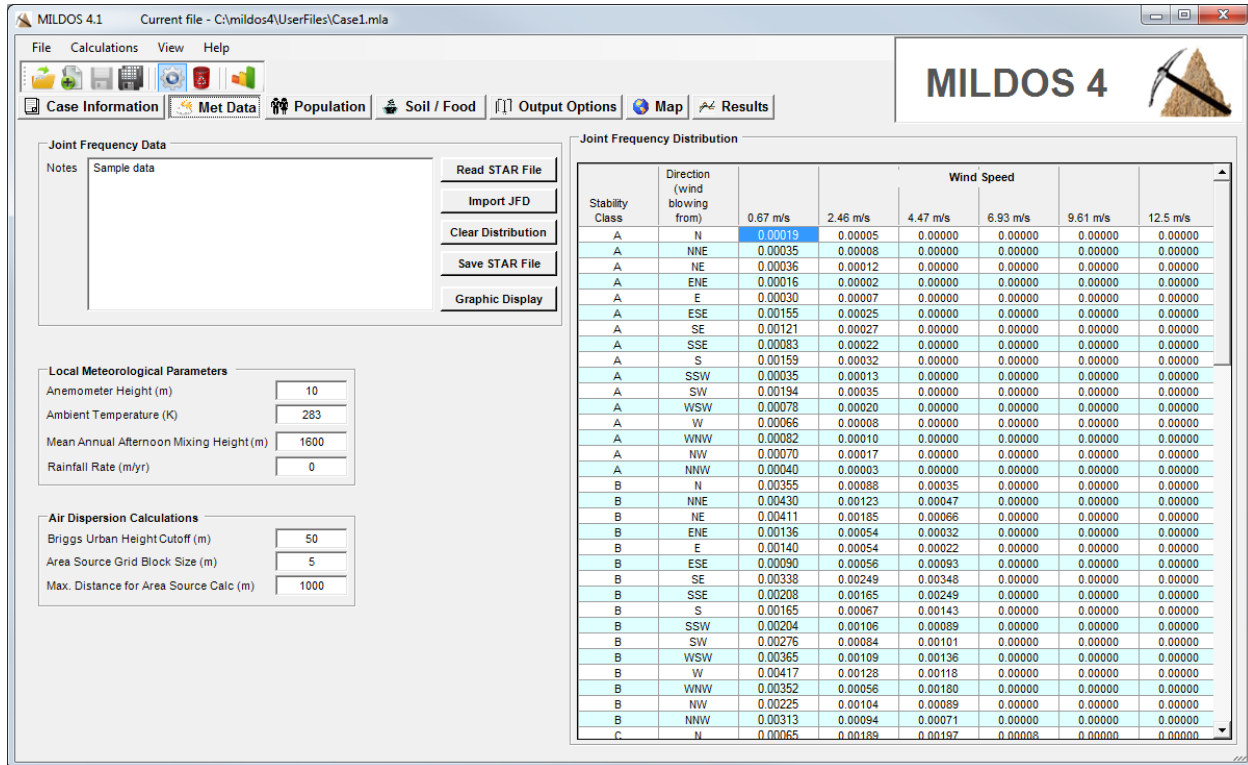
Figure 6-11 Main Program Window with the "Met Data" Tab Selected

6.5.1 General Meteorological Parameters

Inputs for local meteorological data such as average temperature, mixing heights, and rainfall rate are located in the "Local Meteorological Parameters" group. The average temperature is used in the plume rise calculations; the mixing heights are used in the estimation of plume reflection downwind; and the rainfall rate affects the deposition of particulates. The anemometer height is specific to the "Joint Frequency Distribution" listed in the right-hand side of the "Met Data" tab and is discussed in Section 6.5.2.

The "Air Dispersion Calculations" group below the "Local Meteorological Parameters" group contains input that is used for controlling the mechanics of the air dispersion calculation. If the dispersion coefficients selected for a given source (in the source table on the main "Case Information" tab) are set to "Effective Height," the "Briggs Urban Height Cutoff" input is used to determine the use of the Pasquill-Gifford or the Briggs urban dispersion coefficients, depending on the calculated effective release height at a given distance from that source. If the effective release height is less than the specified cutoff height, the Pasquill-Gifford coefficients will be used. Otherwise, the Briggs urban coefficients will be used. A discussion of the dispersion coefficients can be found in Section 3.7.1.

MILDOS4 calculates the downwind normalized air concentrations (χ/Q) of radionuclides emitted from an area source as a collective average obtained by performing a point-to-point evaluation from each grid point on an area source to the receptor location, as described in Section 3.5. The size of the grid spacing (i.e., the "Area Source Grid Block Size") determines the number of estimates and therefore the precision of the overall average. The smaller the block, the better the precision and the more calculations needed. The default value for the block size is 5 m, which generally provides precision to within two or three significant figures in most cases with source areas > 1,000 m^2, depending on source size and geometry, distance, and location relative to the receptor. The block size should be decreased in the case of a small area or could be increased in the case of much larger areas. The user should experiment with varying block sizes to obtain the appropriate value for the application.

Another input that can be used to help reduce run times when area sources are defined is the "Max. Distance for Area Source Calc." This parameter determines the distance to a receptor beyond which an area source is to be modeled as a point source. In such cases, run times will be significantly reduced with no loss in precision. Sample runs are needed to verify each circumstance to assure there is no loss in the fidelity of the calculations. Results will depend on the source size, distance to receptor, and relative location with respect to wind frequency data.

6.5.2 Joint Frequency Distribution Data

The joint frequency distribution data (JFD) describe the wind behavior at a given location; they provide information on the fraction of time the wind is blowing from a given direction, at a given wind speed, and under a given set of atmospheric conditions (stability class). MILDOS4 uses 16 directions, 6 wind speed categories, and 6 stability classes, resulting in a joint frequency of occurrence that constitutes 16 × 6 × 6 = 576 possible conditions; the total sum of all frequencies is equal to one. When MILDOS4 calculates the amount of material blown downwind of a source at a specific receptor location, it weights the downwind concentrations by the amount of time (frequency) the wind is blowing in that specific direction for each combination of stability class and wind speed.

The JFD format that MILDOS4 uses is referred to as the STAR format. The "Joint Frequency Distribution" group under the main "Met Data" tab (Figure 6-11) provides options for handling the STAR data. The user may read in the JFD data from an existing STAR formatted text file ("Read STAR File" button), import JFD from other data formats ("Import JFD" button), clear the current values in the JFD table ("Clear Distribution" button), save the values in the JFD table to a STAR formatted file for use in other applications ("Save STAR File" button), and obtain a visual display summary of the JFD data ("Graphic Display" button, which brings up the graphic presentation shown in Figure 6-12). The user may also edit the JFD table directly. More information on the STAR format and the import options available is provided in Appendix C.

6.6 Soil Parameters

The soil parameters in MILDOS4 are used in the resuspension model (Section 4.2.1) to estimate total radionuclide particulate air concentrations (Section 4.2.2.1). The parameter inputs are found in the "Soil" group on the main program "Soil/Food" tab, as shown in Figure 6-13.
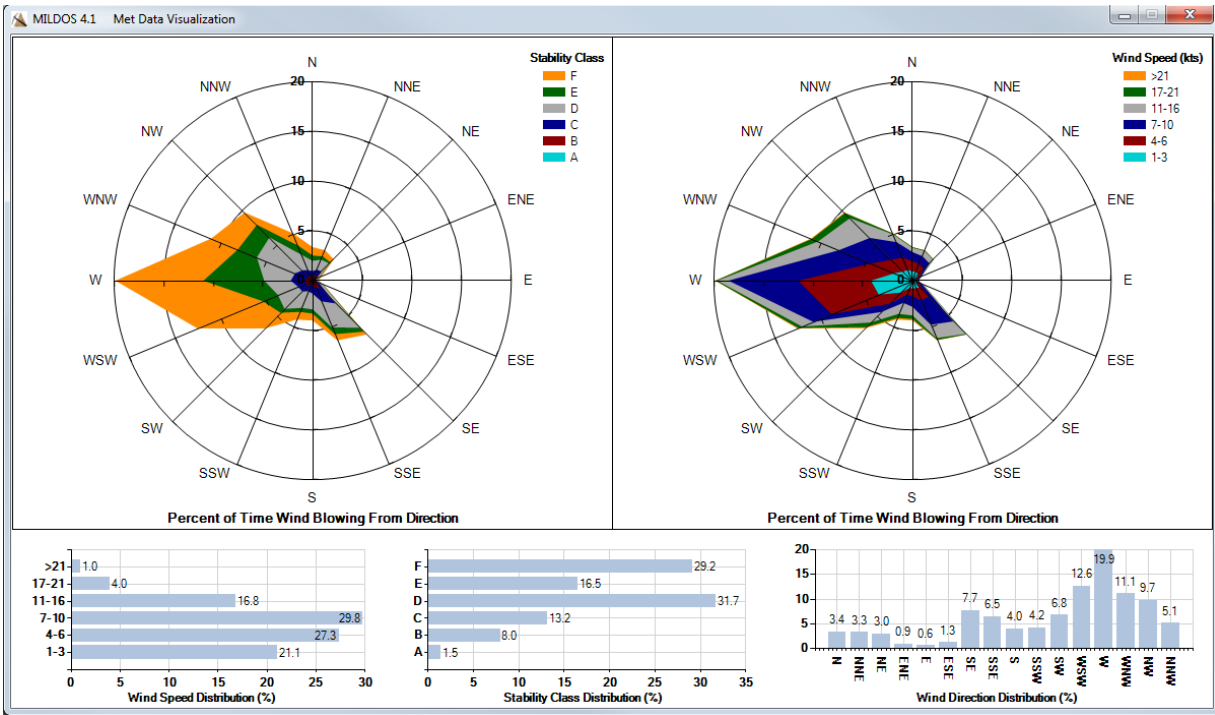
Figure 6-12 Graphic Presentation of the Meteorological Joint Frequency Distribution Data
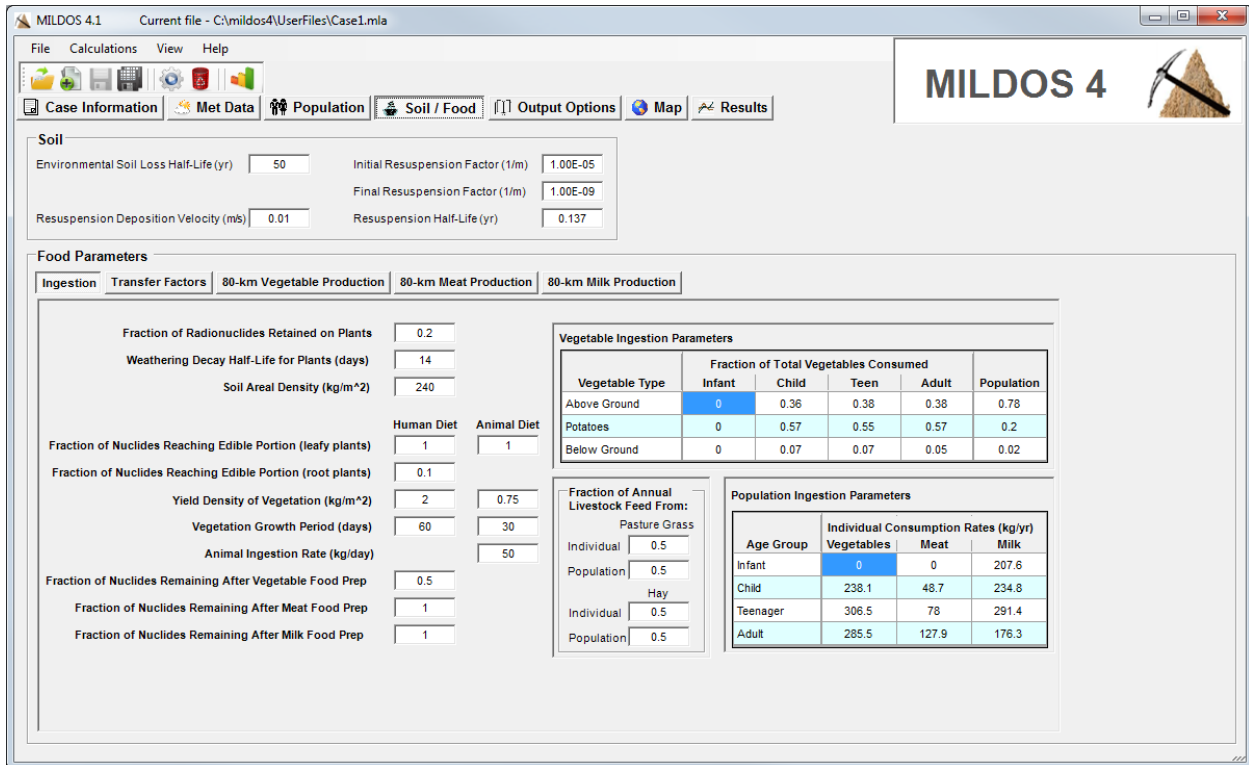
Figure 6-13 Main Program Window with the "Soil/Food" Tab Selected

6.7 Receptors

MILDOS4 provides dose estimates for both individual receptors and the local population out to a distance of 80 km from the location of the first source considered in the source table (seen in the "Source Information" group in Figure 6-1).

6.7.1 Individual Receptors

The "Individual Receptor Information" group, as seen in Figure 6-1, contains all of the individual receptor-specific input required. Receptor input can be modified directly in the receptor table. By using the buttons at the right in this group, the user can delete an individual by using the "Delete" button or add one either by making a copy of input for an existing receptor ("Copy" button) or by selecting one with default characteristics ("New" button). The relative order of receptors may be changed by using the "Move" up and down arrow buttons. A minimum of one receptor is required.

The receptor's age group (Infant, Child, Teenager, or Adult) is selected by means of a drop-down list. Their location is specified in *x, y* coordinates appropriate for the coordinate system being used in the map interface (see Section 6.9.1). The time spent by the receptor in that location, both indoors and outdoors, is accounted for by the respective occupancy fractions, the total of which cannot exceed one. However, the sum of the indoor and outdoor occupancy fractions may be less than one to account for time away at work or other activities. If the indoor occupancy fraction is greater than zero, the indoor shielding factors are applied to account for the reduced external and inhalation exposures afforded by the occupied structure (see Equations 5.3, 5.4, and 5.6). Thus, a shielding factor of zero represents total protection from external radiation or inhalation, and a factor of one represents no protection.

Indoor and outdoor equilibrium factors are input for the Rn-222 progeny at each receptor location. Two options are available for assignment of the outdoor equilibrium factor for the Rn-222 progeny. The user may directly input an equilibrium factor value or have it calculated by the program (Equation 5.5). If the outdoor checkbox for the selected receptor is checked, the program will use the input value provided in the adjacent text box; otherwise, the value will be calculated based on time, distance, wind speed, and the radioactive decay of radon and its progeny.

The remaining receptor input concerns the potential for ingestion of affected food. The user may specify the potential for ingestion of locally grown vegetables, meat, or milk, or some combination for each receptor by checking the checkbox for the appropriate food type(s). The ingestion rate specified for each food type is indicative of the amount of affected food consumed, not the total amount consumed, if some food is obtained from outside the local area.

6.7.2 80-km Population

Putting a check in the checkbox in the "Population Information" group on the main "Case Information" tab page (Figure 6-1) selects the collective population exposure calculations to be performed. When checked, the "Population" tab, as shown in Figure 6-14, will be available for inputting the number of people present in each population segment. The segments are defined by a circle; it is centered on the first source, has a radius of 80 km, and is divided into 16 directions, with each direction divided into 12 spatial intervals, with the distances as seen in Figure 6-14. Options are available to reset the number of people in each population segment to

zero ("Clear Distribution" button) or to import population data from an externally prepared comma separated value (CSV) file (also known as comma delimited format file).

Next to the population grid shown in Figure 6-14 is the population time step table. The number and duration of the time steps are defined as discussed in Section 6.4 and cannot be modified here under the "Population" tab. The population adjustment factor for each time step can be used to account for changes in population over time and can be less than or greater than one. This factor is used uniformly for all population segments for a given time step. Below the time step table is the input for specifying the fraction of the population that is within each of the four age groups.

Collective dose estimates are calculated for each segment by calculating doses to a receptor located at the center of the segment and multiplying by the number of persons in that segment, as discussed in Section 5.2. The inhalation and ingestion calculations are performed by age group, with the number of persons in a given segment weighted by the fraction of persons in that age group. While the position of the population grid is fixed, being centered around the first emission source as a point of reference, the air dispersion calculations are performed individually for each source/segment combination rather than assuming all emissions originate from the first source location for a given scenario, as was done in previous versions of the program (prior to version 4). Thus, a more accurate dose estimate is obtained when multiple sources, separated by a couple of hundred meters or more, are analyzed at the same time.
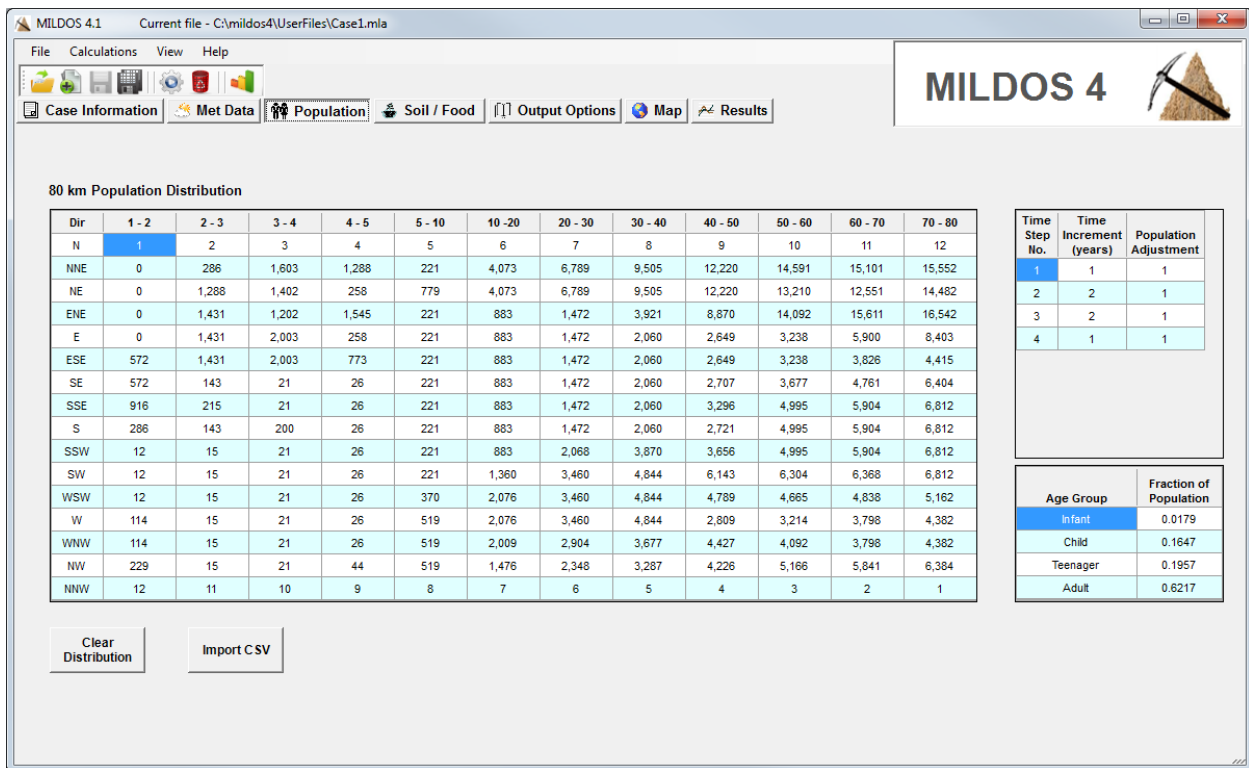
Figure 6-14 Main Program Window with the "Population" Tab Selected

6.8   Ingestion Pathway Parameters

User input for the food production data used in the ingestion pathway calculations, described in Sections 4.3 and 4.4, is located in the "Food Parameters" group on the main program "Soil/Food" tab, as shown in Figure 6-13. The "Ingestion" tab in the "Food Parameters" group contains the input needed to calculate vegetable and livestock concentrations. The selections of vegetable, meat, and milk ingestion, and their intakes for individual receptors are input in the receptors' table, as discussed in Section 6.7.1. The population ingestion pathway calculations are selected by checking the "Consider Ingestion" checkbox in the "Population Information" group in the upper right of the main program "Case Information" tab (Figure 6-1).

The food transfer factors reflect the quantity of radionuclides in soil that are taken-up by the five plant groups (above and below-ground vegetables, potatoes, pasture grass, and stored animal feed) or the quantity transferred from animal feed to meat and milk. These values can be modified by the user under the "Transfer Factors" tab in the "Food Parameters" group under the "Soil/Food" tab as shown in Figure 6-15.

In MILDOS4, the population ingestion dose is considered a societal dose, in that all of the food grown in the 80-km region is assumed to be consumed but not necessarily all of it by persons living within the 80-km region. The collective population ingestion dose is calculated by apportioning the total amount of food among the four different age groups according to their contribution to the total population and their individual food consumption rates. Input to specify the fraction of the population within each age group can be found under the "Population" tab (Figure 6-14). Input for the individual food consumption rates to be used with population calculations can be found in the "Population Ingestion Parameters" group under the "Ingestion" tab (Figure 6-13). For population vegetable ingestion, MILDOS4 also considers three subcategories: (1) edible aboveground vegetables, (2) potatoes, and (3) other edible belowground vegetables. Their respective fraction of each age group's diet is set in the "Vegetable Ingestion Parameters" group under the "Ingestion" tab.

Vegetable, meat, and milk annual production that corresponds to the area for each population segment may be input, or a value for uniform production per unit area per year may be input for each food type. Figure 6-16 shows the vegetable production food grid under the corresponding tab in the "Food Parameters" group under the main program's "Soil/Food" tab. Input may be entered directly into the food grid table, and the "Clear Distribution" and "Import CSV" buttons can be used to set all table entries to zero or to bring in data from a previously generated CSV file. The "80-km Meat Production" and "80-km Milk Production" tabs contain the corresponding input options for those food types.

6.9   Map Interface

The map interface in MILDOS4 is intended to enable the user to visualize site conditions better and more readily set up program input for the risk calculations. It is not intended to be an independent, full-fledged mapping program with extended analysis capabilities and self-contained map data. It is implemented by using an open-source GIS map control, which the user must supply with the desired map data if the user wishes to view local features in the context of the receptors and emission sources modeled. Figure 6-17 provides a view of the map interface.

Figure 6-15 showing MILDOS 4 window:

Soil

Environmental Soil Loss Half-Life (yr): 50
Initial Resuspension Factor (1/m): 1.00E-05
Final Resuspension Factor (1/m): 1.00E-09
Resuspension Deposition Velocity (m/s): 0.01
Resuspension Half-Life (yr): 0.137

Food Parameters

Ingestion | Transfer Factors | 80-km Vegetable Production | 80-km Meat Production | 80-km Milk Production

Radionuclide Food Transfer Factors

Type	Uranium	Thorium	Radium	Lead	Units
Soil to Above Ground Vegetables	0.0025	0.0042	0.014	0.004	(pCi/kg plant - wet weight)/(pCi/kg soil - dry weight)
Soil to Potatoes	0.0025	0.0042	0.003	0.004	(pCi/kg plant - wet weight)/(pCi/kg soil - dry weight)
Soil to Below Ground Vegetables	0.0025	0.0042	0.014	0.004	(pCi/kg plant - wet weight)/(pCi/kg soil - dry weight)
Soil to Pasture Grass	0.0025	0.0042	0.018	0.028	(pCi/kg plant - wet weight)/(pCi/kg soil - dry weight)
Soil to Stored Animal Feed	0.0025	0.0042	0.082	0.036	(pCi/kg plant - wet weight)/(pCi/kg soil - dry weight)
Animal Feed to Meat	0.00034	0.0002	0.00051	0.00071	(pCi/kg per pCi/day)
Animal Feed to Milk	0.00061	5E-06	0.00059	0.00012	(pCi/L per pCi/day)

Reset to Default Values

Figure 6-15 Main Program Window with the "Soil/Food" Tab Selected and the "Transfer Factors" Tab in the "Food Parameters" Group Selected

Figure 6-16 showing MILDOS 4 window:

Soil

Environmental Soil Loss Half-Life (yr): 50
Initial Resuspension Factor (1/m): 1.00E-05
Final Resuspension Factor (1/m): 1.00E-09
Resuspension Deposition Velocity (m/s): 0.01
Resuspension Half-Life (yr): 0.137

Food Parameters

Ingestion | Transfer Factors | 80-km Vegetable Production | 80-km Meat Production | 80-km Milk Production

Vegetable Production (kg/year)

Dir	1 - 2	2 - 3	3 - 4	4 - 5	5 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80
N	0	0	0	0	0	0	390000	1100000	1700000	2500000	42000	120000
NNE	0	0	0	0	0	690	450000	870000	1400000	2300000	350000	390000
NE	0	0	0	0	0	33000000	480000	790000	1200000	1200000	0	83000
ENE	0	0	0	0	0	44000	470000	790000	1000000	880000	0	100000
E	0	0	0	0	0	110000	45000	270000	440000	390000	0	91
ESE	0	0	0	0	0	120000	280000	1100	230	1300	120	700
SE	0	0	0	0	0	120000	530000	2800000	6600000	2200000	220	330
SSE	0	0	0	0	0	110000	580000	2800000	12000000	14000000	0	100000
S	0	0	0	0	0	90000	580000	970000	5100000	4800000	320000	110000
SSW	0	0	0	0	0	49000	580000	970000	1000000	740000	590000	640000
SW	0	0	0	0	0	3900	530000	890000	1000000	750000	170000	29
WSW	0	0	0	0	0	0	250000	490000	850000	1100000	0	100000
W	0	0	0	0	0	0	260000	340000	160000	700000	160	120
WNW	0	0	0	0	0	0	240000	400000	180000	56000	500	630
NW	0	0	0	0	0	0	4300000	310000	370000	310000	71	400
NNW	0	0	0	0	0	0	2600000	2000000	1100000	1000000	120	0

Uniform Production

Food yield (kg/km^2/yr): 55800

Apply to Food Gri

Clear Distribution

Import CSV

Figure 6-16 Main Program Window with the "Soil/Food" Tab Selected and the "80-km Vegetable Production" Tab in the "Food Parameters" Group Selected

Figure 6-17 Main Program Window with the "Map" Tab Selected

6.9.1 Coordinate System

MILDOS4 uses a right-handed Cartesian coordinate system in units of meters. The site geometry can be configured to be shown in a local mode, where the first emission source is considered to be at the center of the coordinate system at location (0,0) when a new user file is used. As an alternative, the user may import background map layers that have a universal transverse Mercator (UTM) projection for their local area and specify the locations of all emission sources and receptors. If population calculations are enabled, the population and food grids will be centered on the first emission source in either case. More details on map projections, the UTM coordinate system, and available data are discussed in Appendix E.

6.9.2 Map Functions

6.9.2.1 Rudimentary Functions

Working with the map interface involves using the tools on the map toolbar, which is shown in Figure 6-18.

Zoom-In tool	When selected, the Zoom-In tool will cause the map view to zoom in (decrease the amount of area shown in the map window) a certain percentage with a mouse click on the map. You can also click and drag the mouse using the Zoom-In tool to highlight a section of the map that will then be expanded.
Zoom-Out tool	When clicked on the map, the Zoom-Out tool causes the map view to zoom out (increase the amount of area shown in the map window) a certain percentage.
Position tool	When clicked and dragged, the map Position tool will cause the entire map view to shift in the direction of the mouse drag.
Pointer tool	The map Pointer tool is used to reposition sources and receptors on the map. Its operation is discussed in the next section.
Max Extents tool	Clicking the mouse on the Max(imum) Extents tool will cause the map to be sized so that the maximum (outer) extent of all map layers are visible within the map view.
Reverse tool	Clicking the mouse on the Reverse tool will cause the map view to reverse the last map action and revert back to its previous state.
Ruler tool	With the Ruler tool selected, the first click of the mouse on the map will set the start point for distance measurement. The second click will set the end point and result in a display of the distance between the two points in meters or kilometers depending on the distance. Subsequent clicks will provide the distance between the last two points and cumulative distance from the beginning. A double-click will end the measurement.
Area tool	With the Area tool selected, successive clicks of the mouse at different locations will result in the display of area within the defined polygon. A double-click will end the measurement. The units displayed will be in square meters, hectares (ha)(1 ha = 10,000 m^2) or square kilometers, depending on the size of the area selected.
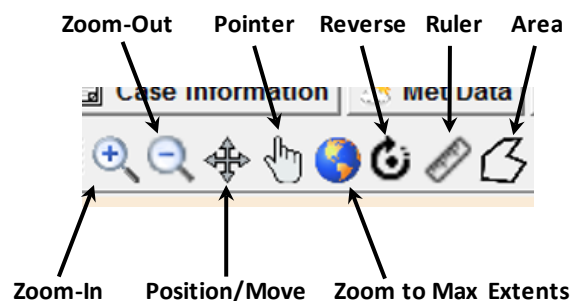
Figure 6-18 Map Toolbar

When the map control has the input focus and one of the first four or last two tools is selected (Zoom-In, Zoom-Out, Position, Pointer, Ruler, or Area), there is another way to cause the map view to zoom in or out: by rolling the mouse scroll wheel (or its equivalent).

6.9.2.2 Positioning Sources and Receptors

Sources and receptors can be repositioned at any time by directly editing the *x,y* input coordinates for that source or receptor provided in the tables on the main program's "Map" or "Case Information" tabs. The alternative method is to use the map interface.

To move a source or receptor by using the map interface, the corresponding checkbox ("Move Source" or "Move Selected Receptor to Mouse Click," respectively) must be selected AND the Pointer tool must be selected. Clicking the Pointer on the map will relocate the selected source or receptor to that position. When done, uncheck the corresponding checkbox or select a different map tool. Note that MILDOS4 will permit only one move checkbox (including the polygon edit checkboxes on the right-hand side of Figure 6-17) to be selected at any given time when the function of the Pointer tool is being defined.

6.9.2.3 Working with Polygon Area Sources

Polygon area sources can be moved ("Move Source" checkbox), their node coordinates can be changed ("Edit Polygon Source" checkbox), or they can be totally redefined ("Redefine Polygon Source" checkbox) by using the Pointer tool, depending on the function selected. When moving a polygon area source, the (0,0) coordinate of the polygon (see Figure 6-4) will be located at the new position selected.

To edit the size and shape of a polygon source in the map interface, the source should be selected in the source table, the "Edit Polygon Source" checkbox should be checked, and the Pointer tool should be selected. To move the node of a polygon, click the cursor (Pointer) in the near vicinity of the node. If close enough, the node will follow the cursor until there is another click. The second click will release the node at its new location. If the node does not follow the cursor after the first click, zoom in on the node and try again.

To completely redefine a polygon (number of nodes/shape and location), the source should be selected in the source table, the "Redefine Polygon Source" checkbox should be checked, and the Pointer tool should be selected. Move the cursor (Pointer) to the location for the first node of the new polygon and click. The first node will then be anchored at this location, and there will be a line following the cursor from it. A second mouse click will anchor the new second node at its location, and the third node will follow the cursor until the next mouse click. Continue this process until the appropriate number of sides is defined. At the last node, right-click the mouse, and the polygon will be released from the cursor. This procedure will complete the polygon redefinition. Afterwards, be sure to select a different map tool or to uncheck the "Redefine Polygon Source" checkbox so as to not inadvertently restart the polygon redefinition process upon the next mouse click.

Polygon vertices may also be modified directly using the polygon table associated with a particular area source (e.g., see Figure 6-4). The x,y coordinate pair for a vertex can be modified in the table, and vertices may be added or deleted using the "Add Vertex" and "Delete Vertex" buttons, respectively.

6.9.3   Managing Map Layers

Data are displayed in the map control in layers. Each layer corresponds to data displayed as either raster or vector data. Bitmap and TIFF files are examples of raster data, for which information is presented in a matrix of cells (images such as digital pictures or a scanned map).

Shapefiles, originally introduced by Esri, are examples of vector data for which the information about points, lines, or polygons is stored as a collection of coordinated points, enablein lines and polygons to be drawn as a series of connected points and are thus independent of the resolution of a display device.

The MILDOS4 map is used to provide an underlying view, if desired, and establishes the coordinate system. Receptors, point sources, area sources, and the scale bar are all represented by in-memory shapefile layers that are not directly accessible by the user and are automatically drawn on top of any layers loaded by the user. The "Edit Map" button in the "Map Settings" group (lower right of Figure 6-17), when clicked, will bring up the "Edit Map" form (Figure 6-19), which allows users to control whether local coordinates are used without additional map information or to load their own UTM coordinate map layers.
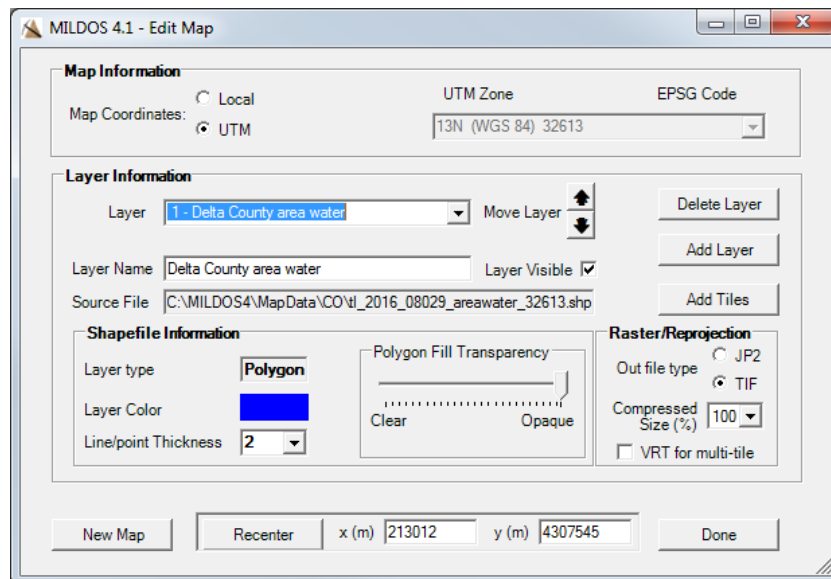
Figure 6-19 Edit Map Input Form

6.9.3.1 Map Coordinate Selection

In the "Map Information" group, the "Local" and "UTM" radiobuttons control whether or not local coordinates are used. If the setting is changed from "UTM" to "Local," all currently associated user layers will be deleted from the map, and the coordinates for all receptors and sources will be adjusted to correspond with the first emission source at (0,0). The same function can be performed by pressing the "New Map" button at the bottom of the form and can be used if the "Local" radiobutton is already selected. Using the "New Map" button will reset the coordinates of the first source to (0,0) if it had been moved or deleted and a different source is now the listed first source. Resetting the coordinates in this case is not necessary but does give the user a recognizable point of reference. If the radiobutton setting is changed from "Local" to "UTM," the user will be asked to select the desired UTM zone from the UTM selection drop-down list control before adding a map data layer (by pressing the "Add Layer" button) that should be in the specified coordinate system.

Because of the complexities associated with verifying the true coordinate system for map data from different sources, MILDOS4 does not perform any type of enforcement in this area other than to notify the user of the projection of the specified data to be loaded if that information can be determined. It is up to the user to make sure that the data are appropriate for the settings used. Once the UTM zone is specified, the map will use that as the underlying coordinate system. If a scenario had been previously setup using local coordinates, the "Recenter" button and associated x and y UTM coordinate inputs at the bottom of the "Edit Map" form allow the user to move the first source position to the proper location on the newly added map image. All receptors and other sources will maintain their position relative to the first source during this operation.

6.9.3.2 Raster Data

Generally, only one image raster map layer can be used, because such layers are opaque and would obscure any layers placed beneath them. However, if each raster map layer constitutes a tile in a series of tiles (i.e., image blocks arranged side by side to form a larger image), the tiles may be loaded at the same time and displayed concurrently. The "Add Tiles" button allows the selection of such a series of tiles. To display properly, these images should have the same map projection. It is assumed that the projection characteristics of the first tile are representative of the remaining tiles selected. Each tile will be rendered as a separate layer. This situation can be cumbersome when it comes to layer management if a large number of tiles is involved. All tiles loaded at the same time will be treated as a single layer if the "VRT for multi-tile" checkbox is checked in the "Raster / Reprojection" group.

The types of GIS formats that MILDOS4 supports are listed in Table 6-3, along with the file extension typically used for that format (and expected by MILDOS4). All types listed are raster data types with the exception of the shapefile (vector data). A second file that provides additional spatial data, which may include georeferenced coordinates or projection information (e.g., .tfw or .jpw "world" files in the case of TIFF and JPEG data), is often associated with the primary GIS data file. This second file should be in the same directory as the primary data file in order for MILDOS4 to properly load the map layer.

If needed, MILDOS4 has the capability to re-project the data in the layer into the UTM projection selected for the map. For raster data, the image is first re-projected to the map's UTM projection as a GeoTIFF file without compression. Because of the amount of data required to render an image, most raster data types are by their nature a compressed format or can incorporate varying degrees of compression. The second stage of re-projection in MILDOS4 is to take the re-projected image and save it as a compressed GeoTIFF or JPEG2000 file. This second step also checks to see if a fourth data band is present and asks the user if it should be removed. Color GIS data is displayed in three bands (R,G,B). The fourth band is often referred to as the alpha band that normally contains near-infrared data which will degrade the overall image if displayed with the normal color bands in MILDOS4.

Table 6-3 GIS File Types Supported by MILDOS4

File Type	File Extension
Bitmap	.bmp
Graphics Interchange Format (GIF)	.gif
Joint Photographic Experts Group (JPEG) and JPEG2000	.jpg, .jp2
Portable Network Graphics (PNG)	.png
Multiresolution Seamless Image Database (MrSID)	.sid
Shapefile	.shp
Tagged Image File Format (TIFF)	.tif
Geodata Data Abstraction Library (GDAL) Virtual TIFF	.vrt

The final output file type and amount of compression is specified by the user in the "Raster/Reprojection" group on the "Edit Map" form (Figure 6-19). While MILDOS4 can read many raster formats, it can only create new files in either TIFF or JPEG2000 format. The "Compressed Size (by percent)" selection determines the amount of compression to use. A value of 100 on a scale of 1 to 100 indicates that no additional compression is requested. Decreasing values selected will result in more compression and a smaller final file size. A value of 25 represents the largest amount of compression and smallest final file size, allowed by the code. The final compressed file size will also depend on the complexity of the imagery displayed. The compression formats used here will result in some data loss (higher compression, more loss), although the differences are not easily observed by eye.

6.9.3.3 Vector Data

Many data available in shapefile format use decimal degree coordinates. When MILDOS4 loads a specified shapefile and determines that it is not in the proper UTM format, it will save the re-projected data in a new file and then load the new file (if the user does not cancel the operation).

Rudimentary editing functions that control the display of shapefile data are available in the "Shapefile Information" group, as shown in Figure 6-19. Users may control the point sizes and line widths of point and line shapefiles, respectively, as well as set a color for all items in the shapefile. For polygon shapefiles, the transparency of the polygon fill can also be adjusted from transparent to opaque (so as to not cover, partially cover, or completely cover any underlying layers) by using the slide bar.

6.9.3.4 Layer Manipulation and Map Settings

Note that MILDOS4 does not store the actual map data in the user file, only the associated filename. If such files are subsequently moved or deleted on the user's computer, the program will not be able to load them into the map when the user file is loaded.

In the "Layer Information" group (Figure 6-19), the user may see what map layers are loaded by using the "Layer" drop-down list. The user may also modify the position of the display order of the loaded map layers, if there are two or more, by clicking the up and down arrows to move the currently selected layer. Remember that the map layers with the lower index will be displayed first and may be covered by layers with a higher index, depending on the type of layer (raster or vector) and the areal extents of the layer coverage. The "Layer Name" text input enables the

user to give the layer a more intuitive name that will be saved with the map information for later use. The user may also render a particular layer invisible or visible at any given time without deleting or adding the layer by unchecking or checking the "Layer Visible" checkbox.

The "Save Map" button in the "Map Settings" group (lower right in Figure 6-17) is used to save the current map settings (the current view and layers loaded). Once the map is saved, the user file must also be saved to preserve those settings for the next time that the user file is loaded.

6.10   Sensitivity Analysis

The sensitivity of the MILDOS4 model results to changes in the value of a specific input parameter can be analyzed by using the Sensitivity Analysis function. One-parameter-at-a-time sensitivity analysis is used to study the independent influence of each individual parameter on the estimated concentrations and doses. Each of the selected parameters is varied in turn, first by a factor that is higher than its deterministic (base) value, and then by one that is lower than it. Thus, two additional runs of the code are performed for each parameter selected for sensitivity analysis.

With the input selected for the parameter of interest, pressing the F9 function key will bring up the "Sensitivity Analysis" input form, as shown in Figure 6-20. The example in this figure is for the indoor external shielding factor for a specific receptor. As part of the sensitivity analysis, MILDOS4 will run its calculations by using the current value of the selected parameter listed as the "Base Value" on the form. The code will then run the calculations with the selected parameter set to higher and lower values, as determined by the radiobutton selection, to set the multiplication/division factor to use with the base value to obtain the higher and lower values, respectively. If the higher or lower values are above or below the permissible maximum or minimum values, then the higher or lower value will be set to the maximum or minimum permissible value for that parameter, respectively.

Not all parameters are eligible for sensitivity analysis. Parameters not eligible include items such as coordinate locations (i.e., x and y values) and JFD meteorological data. A message indicating the ineligibility of a parameter for sensitivity analysis will be displayed instead of the "Sensitivity Analysis" input form in such cases when the F9 button is pressed.

MILDOS4 will accept up to five parameters selected for sensitivity analysis in a given set of calculations. A base case calculation run with all selected sensitivity parameters having their base values is performed first, followed by higher- and lower-value runs for each selected sensitivity parameter. Clicking on the "Sensitivity Analysis" toolbar button or selecting the main menu "View → Sensitivity Parameters" item brings up the "Sensitivity Analysis Summary" form (Figure 6-21), which lists the selected parameters by their program variable names, their current values, the current multiplier/divisor for each, and their minimum and maximum allowed values. The form provides the options for modifying a parameter's sensitivity factor (clicking on the "Modify" button brings up the "Sensitivity Analysis" input form) or for removing it from the sensitivity analysis ("Delete" button).

No sensitivity analysis will be performed if the "No Analysis" button is pressed on the "Sensitivity Analysis" input form (Figure 6-20) when sensitivity options for any parameter are being viewed or if all parameters selected for sensitivity analysis are deleted from the "Sensitivity Analysis Summary" form (Figure 6-21).

Figure 6-20 Sensitivity Analysis Input Form

Figure 6-21 Sensitivity Analysis Summary Form

7 PROGRAM OUTPUT AND EVALUATION OF RESULTS

Summaries of the results calculated by MILDOS4 are available under the "Results" tab on the main program window (Figure 7-1). The "Standard Report" sub-tab contains a list of the input data and a summary of the results. The "ECL Check" sub-tab contains comparisons of the calculated radionuclide concentrations against the ECLs found in 10 CFR Part 20. The "40CFR190" sub-tab contains a summary of estimated doses, which excludes contributions from radon emissions, for comparison against the EPA's *Environmental Radiation Protection Standards for Nuclear Power Operations* (40 CFR Part 190). The "Custom Output" sub-tab contains user-specified result tables if the user selected the custom output option. The "ECL Check" and "40CFR190" output summaries are also included in the standard report output. All four output summaries (standard report, "10CFR20" comparison, "40CFR190" comparison, and custom output) are written to four separate files in HTML format (MILDOSreport.htm, ECLreport, 40CFR190Report.htm, and MILDOSuserTables.htm, respectively) in the program directory. These files are easily viewable in any Web browser and restored each time the user file is loaded when results are present. Since these results are in HTML format, the user can select and copy the results directly from the corresponding MILDOS4 sub-tab and paste into a spreadsheet or word processing program for further manipulation. The HTML files in the application directory are overwritten each time a program run is executed.

The "Interactive Results" sub-tab gives the user access to detailed results through an option-driven interface. Results are available through various combinations involving receptors, sources, time steps, radionuclides, solubility classes, particle sizes, age groups, pathways, and organs.
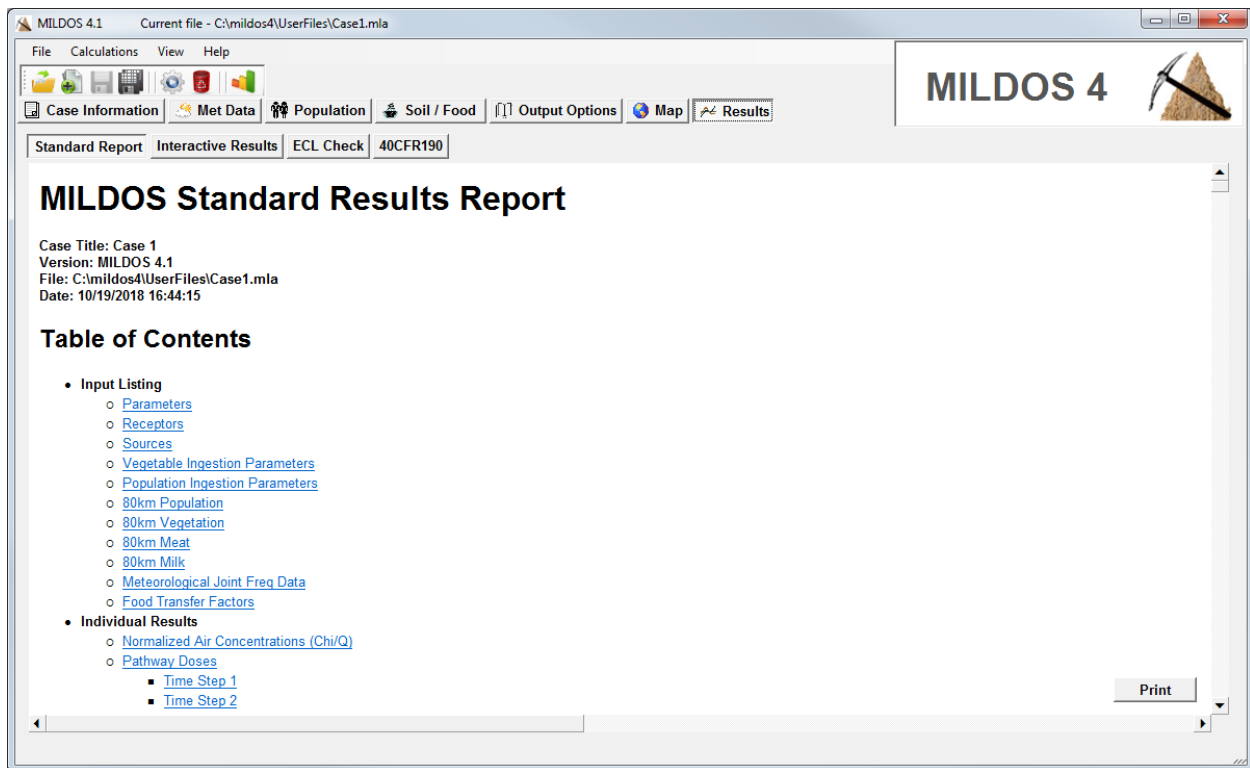
Figure 7-1 Main Program Window with the "Results" Tab Selected

7.1 Standard Output

The standard output contains a table of contents, as seen in Figure 7-1, which provides direct access to the appropriate table or series of tables with a click on the corresponding link. The output consists of sections for an input listing, calculated source term releases, individual results, population results (if selected), and results for comparisons with criteria in 10 CFR Part 20 and 40 CFR Part 190.

The input listing covers those parameters available to the user for modification. The calculated source term releases are listed following the user source term input. Individual and population results begin with a listing of normalized air concentrations (χ/Q) at the receptor locations and population grid points. Individual receptor-source distances and calculated radon equilibrium fractions are included in the χ/Q output. Pathway dose summaries are provided for each time step for each source and individual receptor followed by pathway dose summaries without contributions from radon releases (40 CFR Part 190 doses). The output listing continues with a comparison of radionuclide concentrations at the individual receptor locations against the allowable concentrations listed in 10 CFR Part 20. Population results include pathway dose summaries for each distance range and total effective doses by distance and direction.

7.2 Comparison with 10 CFR Part 20

The ECLs for the radionuclides are the values in column 1 (air) of Table 2 (effluent concentrations) in Appendix B of 10 CFR Part 20. The output tables given for each time step and individual receptor location provide the ratio of the total concentration of that radionuclide from a given source to its ECL. The ratio of the total radionuclide concentration from all sources at a given receptor location to the corresponding ECL is also provided. If the ECL for a given location and radionuclide exceeds a value of 1, the radionuclide concentration limit has been exceeded, and the value is highlighted in yellow in the output table.

7.3 Results for Comparison with 40 CFR Part 190

The EPA's regulation pertaining to the environmental standards for the uranium fuel cycle specifies that "the annual dose equivalent does not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public as the result of exposures to planned discharges of radioactive materials, radon and its daughters excepted, to the general environment from uranium fuel cycle operations and to radiation from these operations" (40 CFR 190.10(a)). The 40 CFR Part 190 output table in MILDOS4 provides the dose by pathway to the organs considered, including the effective whole body dose. These doses do not include contributions from radon emissions (including daughter products from future decay) considered in the source terms.

7.4 Interactive Results Output

For individual receptor and population results, the "Interactive Results" tab provides a means for breaking down contributions to dose by all possible combinations. Results are available for the three calculation steps (selected in the "Result Type" group under the "Interactive Results" tab in Figure 7-2: (1) normalized air concentrations (Section 3.5), (2) media concentrations (Sections 4.2 through 4.4), and (3) dose (Section 5.2). In the case of population results, each population segment, referenced by direction and distance range, is treated like an individual receptor in the output options and tables.
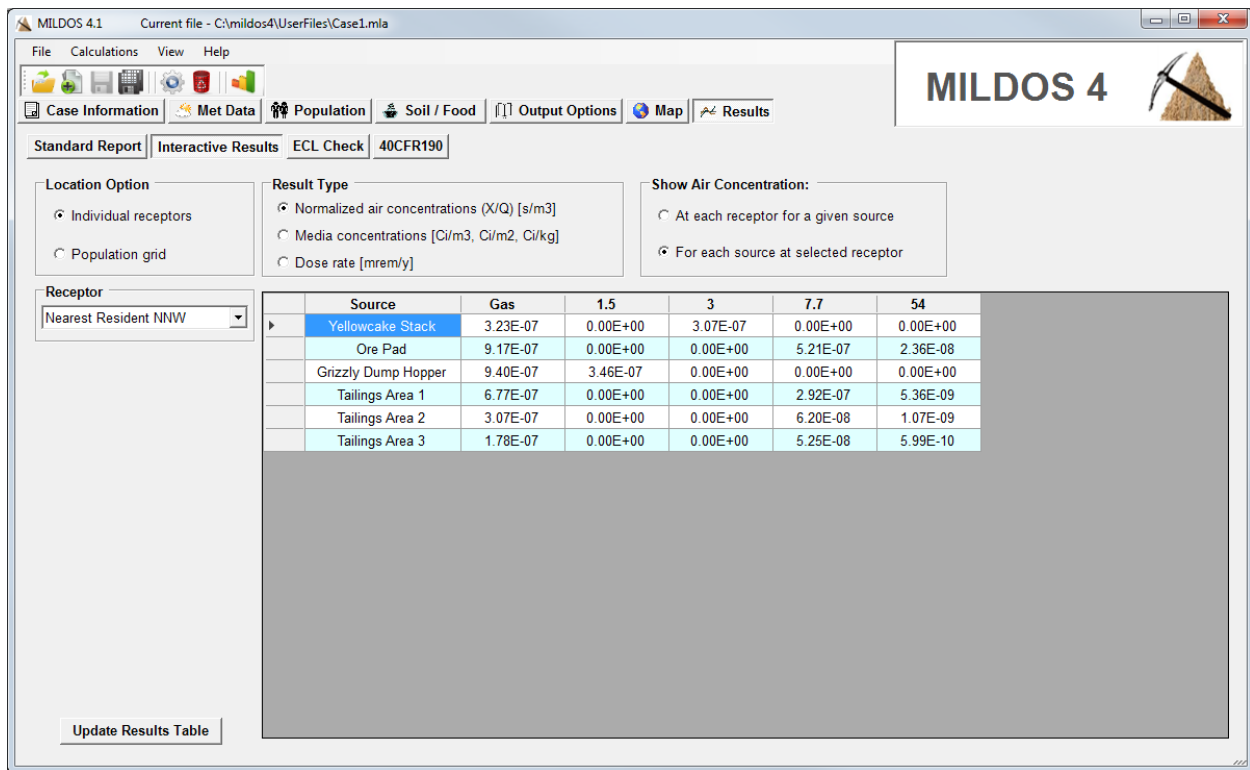
Figure 7-2 "Interactive Results" Output Tab Shown with Normalized Air Concentration Output Selected

7.4.1 Normalized Air Concentrations (χ/Q values)

Normalized air concentrations can be viewed at each receptor for a given source or for each source at the selected receptor, as shown in Figure 7-2. Values are estimated for gases (no deposition) for each source and for each particulate size, if considered with the source. The concentrations are independent of the time step.

7.4.2 Media Concentrations

The calculated media concentrations (air, ground, vegetable type, meat, and milk) for a particular radionuclide and associated particle size, at each receptor location, can be viewed for any given source and time step, as seen in Figure 7-3. The results for any combination can be viewed by selecting the appropriate choices from the drop-down lists to the left of the table.

7.4.3 Exposure Dose Rates

Several options are available for looking at the breakdown of dose rates received by modeled receptors. As seen in Figure 7-4, if the "Show Dose Rate To" selection is "Each receptor," the selected "Columns" item can be pathway, organ, or radionuclide. In Figure 7-4, the columns are set to represent the pathways analyzed, and the dose rates shown are to each receptor for the selected source, time step, particle size, radionuclide, and organ. If the columns selected represented either organ or radionuclide, the selections to the left would include radionuclide and pathway or organ and pathway.
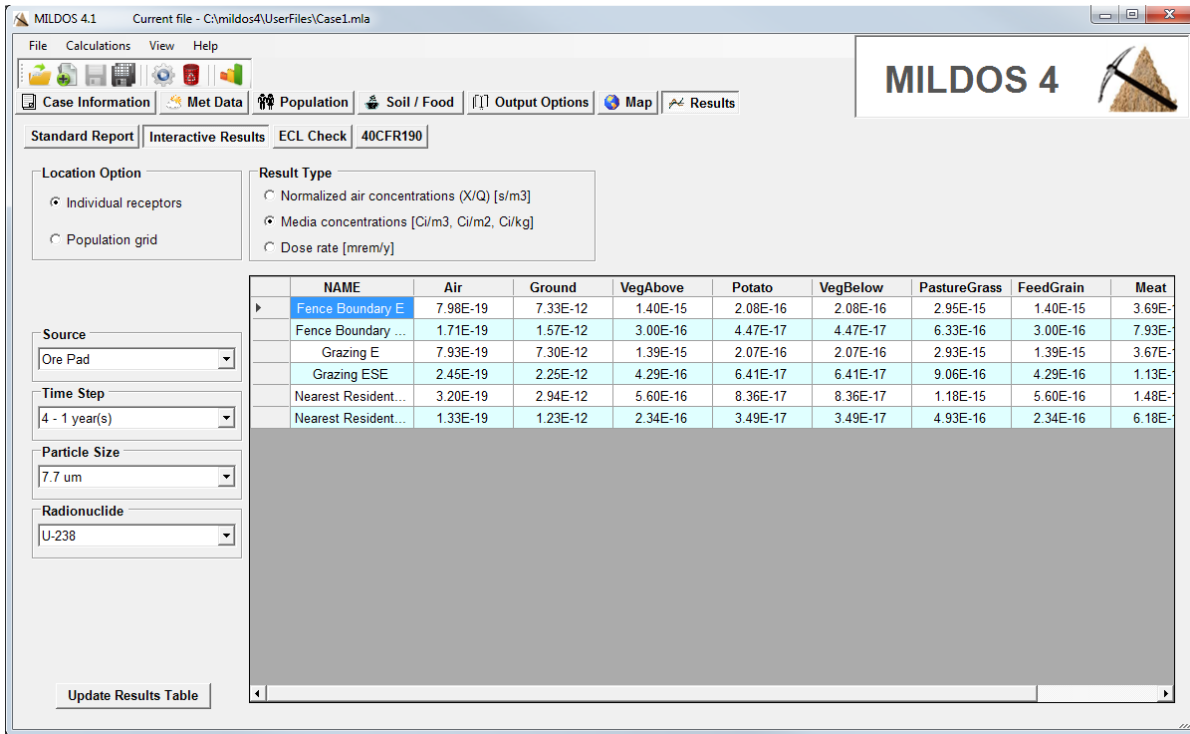
Figure 7-3 "Interactive Results" Output Tab Shown with Media Concentration Output Selected
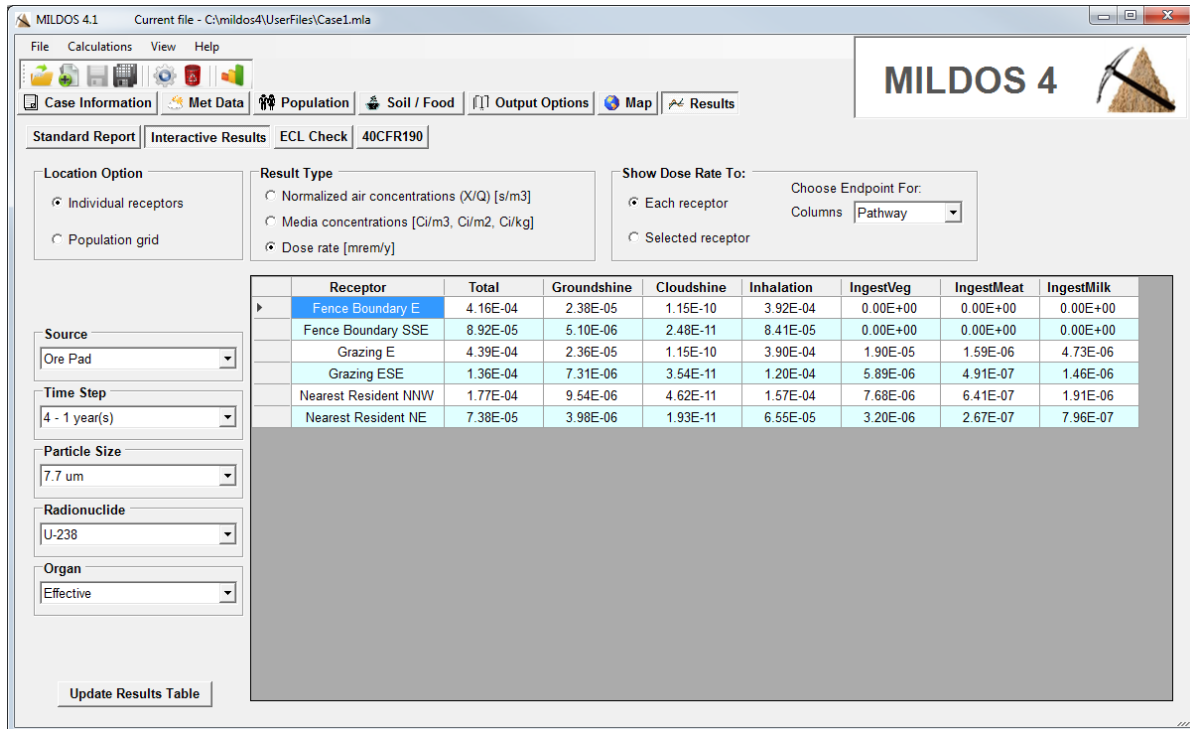
Figure 7-4 "Interactive Results" Output Tab Shown with Dose Output Selected

If the "Show Dose Rate To"' selection is "Selected receptor," the table columns and rows can be set to pathway, organ, or radionuclide (See Figure 7-5). The reported dose rates shown are for the selected column/row combination for the selected receptor, source, time step, particle size, and pathway, organ, or receptor (the option not selected as the table column or row).

7.5   Custom Output

MILDOS4 enables the user to specify the output of detailed tables of calculated results in addition to the standard report, the ECL check, and the 40 CFR 190 values discussed in Sections 7.1 through 7.3. The number and content of the additional output is controlled through input to the "Output Options" tab as shown in Figure 7-6.

Similar options are available for both individual and population results. The output specifications are stored in the user file as table schema determined by the user. A single table schema specifies whether the desired results are presented as a single table, a series of tables, or a set of tables for a specified result type and associated options.

Three different result types — (1) normalized air concentrations, (2) media concentrations, and (3) exposure dose rates — can be selected, as with the interactive results discussed in the previous section. Table 7-1 lists the parameter options available to define output for each result type.

Figure 7-5 "Interactive Results" Output Tab Shown with Dose Output Selected for a Selected Receptor

7-5

MILDOS 4.1   Current file - C:\mildos4\UserFiles\Case1.mla

File   Calculations   View   Help

Case Information   Met Data   Population   Soil / Food   Output Options   Map   Results

MILDOS 4

Table Output Options
- ○ Standard only
- ● Standard + Custom

Receptor Option
Custom Edit
Individual Receptors ☑   ●
Population ☐   ○

Population Options
- ○ Grid (Direction [rows] x Distance)
- ○ By grid segment
- ○ By distance   N
- ○ By direction   1-2 km

Output Table Generation
Generate

Options not saved

Save Output Options

Receptor
Fence Boundary E

Source
Yellowcake Stack

Time Step
1 - 1 year(s)

Particle Size
Gas

Radionuclide
Rn-222

Media
Air

Result Type
- ○ Normalized air concentrations (X/Q) [s/m3]
- ● Media concentrations [Ci/m3, Ci/m2, Ci/kg]
- ○ Dose rate [mrem/y]

Table Schema Setup
- ○ Single
- ● Series   For Each Time Step
- ○ Set   For Each   By

Table Format
Choose Option For:
Rows   Receptor
Columns Source

Table Schema No.	Setup	Type	For Each	By	Table Rows	Table Columns	Media Type	Receptor
1	SINGLE	ChiQ			Receptor	Source		
2	SERIES	ChiQ	Receptor		Source	Particle Size		
3	SERIES	ChiQ	Particle Size		Receptor	Source		
4	SERIES	ChiQ	Receptor		Particle Size	Source		
5	SINGLE	CONC			Receptor	Source	Air	
6	SINGLE	CONC			Receptor	Time Step	Air	
7	SERIES	DOSE	Time Step		Receptor	Source		
8	SERIES	CONC	Receptor		Media Type	Source		
9	SET	CONC	Media Type	Time Step	Receptor	Source		

Add Table Schema   Edit Schema   Move ↑↓   Copy Schema   Delete Schema   Save CSV   Import CSV

Figure 7-6 "Output Options" Tab

Table 7-1 Parameter Options Used in Output Table Definitions for Each Result Type

Normalized Air Concentrations	Media Concentrations	Dose Rates
Receptor	Receptor	Receptor
Source	Source	Source
Particle Size	Particle Size	Particle Size
	Time Step	Time Step
	Radionuclide	Radionuclide
	Media	Organ
		Pathway

For all result types, the parameter options defining the rows and columns of the output table(s) are selected in the "Table Format" group seen in Figure 7-6 (e.g., rows corresponding to receptors and columns corresponding to sources). For a table schema "single" table setup, the remaining options that define the desired results are selected using the drop-down list boxes on the left side of the input form. For a table schema "series" table setup, the "For Each" drop-down list next to the "Series" radio button is set to the desired option (e.g. Time Step). The remaining options that define the desired results are then selected using the drop-down list boxes on the left side of the input form. For example, the settings for air (media) concentration

7-6

(type) of U-238 (radinuclide), (particle size) 7.7 μm, at each receptor location (row) by source (column) for each time step produces a series of tables, one for each time step. Similarly, for a table schema "set" setup, options in the "For Each" and "By" drop-down lists are selected in addition to the rows and columns in the "Table Format" group, with the remaining options set in the drop-down boxes on the left side of the form. For example, settings for the concentration (type) of U-238 (radinuclide), (particle size) 7.7 μm, at each receptor location (row) by source (column) "for each" time step (series of tables) "by" (media) produces a set of tables by time step for air concentrations, ground conentrations, etc. Note that a table schema "Set" cannot be defined for normalized air concentrations, since there are only three options available.

Separate table schema lists are maintained for individual receptors and the general population. Either or both types can be chosen and edited as controlled by the options within the "Receptor Option" group. A previously defined list is not deleted from the user file (only rendered inaccessible and not used) if the user decides to turn off the custom output option completely or for either type. The list will reappear if the option is turned back on.

The population list is only available if population results are turned on. Options for the population results are the same as for individual receptors, except that individual receptors (locations) are replaced by the selection made in the "Population Options" group (by grid segment, distance, or direction). In the case of the "Grid" population option, the base table format is fixed with all results given in terms of direction (rows) and distance (columns).

Table schema can be added, modified, or deleted from the individual or population lists using the buttons across the bottom of the "Output Options" tab as shown in Figure 7-6. The lists can also be saved to and retrieved from CSV files for sharing of output designs. When designing tables for output, it is important to recognize that using (selecting) specific named receptors or sources in a table schema specification will result in that schema being deleted if that particular receptor or source is re-named or deleted elsewhere in the program. Similarly, if a list has been saved to a CSV file and later retrieved, the validity of any individual receptor or source name in each table schema will be checked against the existing input. If the receptor or source no longer exists, that schema will be automatically deleted from the imported list.

Since the output option input does not affect the results of the calculations, only how the results are presented, changes to the output options do not require that any existing results be deleted, unlike other user input. Thus, the user can redefine custom output after a calculation run has finished and view it using the provided 'Generate' button. This behavior is especially helpful if the calculations took a significant amount of time to complete and additional detail is needed. If new output is generated outside of a calculational run, the new custom output table(s) will replace any previous custom output tables in the user file.

7.6   Sensitivity Results Output

When parameters have been identified for sensitivity analysis, as discussed in Section 6.10, the "Sensitivity" tab provides a flexible means of viewing the analysis results, with options similar to those found under the "Interactive Results" tab. In the case of sensitivity analysis results, the selected result for the base case is presented next to the results of runs conducted with the low and high values for the selected sensitivity parameters, as shown in Figure 7-7. The selected parameters are summarized in the table at the top right of the "Sensitivity" tab. This table is for information purposes only and is not used in the selection of output to view.

7.7   Export Options

Right-clicking the mouse pointer anywhere in the results table under the "Interactive Results" tab or "Sensitivity" tab will copy the current table and values to a CSV file for use in other applications, such as a word processor or spreadsheet.

The user can directly copy results from the four output tab summaries (standard report, "10CFR20" comparison, "40CFR190" comparison, and custom output), since these results are in HTML format, and readily paste them into another application for further analysis.

Figure 7-7   "Sensitivity" Output Tab Shown with Air Concentration Selected for Each Receptor

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APPENDIX A PROGRAM INFORMATION AND INSTALLATION

This appendix provides information on the development, structure, components, and installation of MILDOS 4.

A.1   Program Development

This section covers the development environment, source code management, and programming language(s) used to develop the MILDOS4 code.

A.1.1 Development Environment and Source Code Management

Program development was done in the Microsoft Visual Studio 2015 integrated development environment (IDE). The IDE provides good integration of modules written in different programming languages and compiles programs for running under Microsoft Windows 7, 8, and 10 operating systems.

The MILDOS4 code is maintained under source code management. The Windows version of the "git" open source program (http://git-scm.com/) is used. Git is widely used in the software community as a version control system and is compatible with Visual Studio.

A.1.2 Programming Language

MILDOS 4.1 is written in Visual Basic .NET 4.5 (VB.NET). This language is the successor to the Visual Basic 6 legacy code used for the interface in version 3 of MILDOS-AREA. With the need to re-write the FORTRAN calculations, the calculations were also programmed in VB.NET, which simplifies program installation and execution. Consideration was also given to the use of the new database format and geographic information system (GIS) module, both of which were referenced in calls using VB.NET syntax.

Two exceptions to the use of VB.NET were the meteorological data input processor and a database routine. The meteorological data input processor relies heavily on verified legacy FORTRAN code for some data manipulation. The code was compiled into a dynamic link library (DLL) using the "Silverthrone" edition of Lahey/GNU Fortran. This compiler is fully integrated into the Visual Studio 2015 IDE and produced a DLL with subroutines callable from VB.NET.

As a result of the storage of intermediate results, large amounts of data must be handled and stored. A "C" DLL was written, again within the Visual Studio 2015 IDE, to handle large data transfers from computer memory to tables in the user file at the end of calculations. The routine incorporated into the DLL is a modified version of several routines found in the SQLite3 shell available with the SQLite libraries for Windows.

A.2   Program Structure and Components

MILDOS4 is based on a modular program structure and follows the recommended programming practice of keeping user interactions, data storage, and computational models separate from one another. In this case, the user database (DB) file (and program libraries such as the
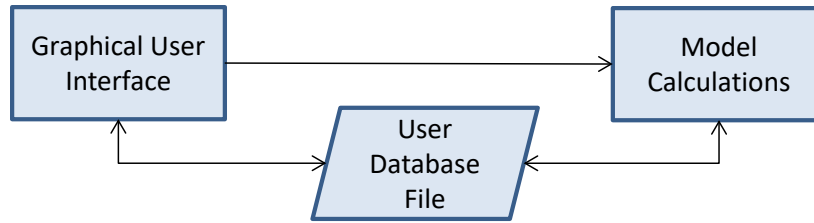
Figure A-1 Separation of User Interface, Data, and Calculations in MILDOS4

dose coefficients and nuclide data) is separate from the graphical user interface (GUI) and the performance of the calculations (Figure A-1). The user DB file contains the user input (as populated through the GUI), as well as intermediate and final model analysis results. The code calculations follow the structure shown in Figure A-1.

The GUI, written in VB.NET, controls the overall operation of the program. It controls how input is received from the user, and it stores or modifies that information in the current user DB file. The DB format used is discussed in Section A.2.2. The GUI incorporates a GIS module to help the user visualize the scenario being analyzed and to aid in program input. The GIS module is discussed further in Section A.2.3, and GIS input data are discussed in Appendix E. The GUI is also used to control the meteorological data processor, written in FORTRAN, for importing meteorological data not in STability ARray (STAR) data format, as described in Appendix C.

The model calculations, written in VB.NET, take the user data from the user DB file, perform the requested calculations, and store the results back in the user DB file. The GUI can then display the calculated results in a number of formats, as requested by the user.

A.2.1   Model Calculations

The calculation of human exposure follows a series of well-defined models and algorithms, as detailed in Chapters 2 through 5.

- Material release/source term – as described in Regulatory Guide 3.59 for conventional uranium ore facilities and in Appendix D of NUREG-1569 for *in situ* leach mining.

- Air dispersion – chronic area source Gaussian plume dispersion model.

- Downwind air concentrations – sum of air concentrations from material releases and resuspension at the receptor locations analyzed.

- Deposition – accounts for dry and wet deposition of material from the chronic material release plumes; particle size-dependent.

- Ground concentrations – based on deposition from the chronic material release plumes.

- Resuspension – resuspension of radionuclides is handled by using an exponential decay model associated with weathering of the deposited material.

- Plant uptake – vegetation concentrations for human and livestock consumption are based on standard soil-to-plant uptake factors.

- Vegetation concentrations – from air deposition and uptake from soil, includes a factor to account for weathering over time after deposition, also factors in length of growing season for uptake from soil.

- Livestock ingestion – accounts for animal vegetation consumption rates and incidental ingestion of contaminated soil; also accounts for fraction of vegetation which is contaminated.

- Meat/milk concentrations – based on animal consumption of contaminated vegetation and soil.

- External exposure – based on radiation from material deposited on the ground and existing air concentrations at the receptor locations; accounts for occupancy times at receptor locations.

- Inhalation exposure – based on estimated air concentrations (particle size-dependent), occupancy times at receptor locations, and breathing rates.

- Ingestion exposure – accounts for ingestion of contaminated vegetation, meat products, and milk.

A.2.2 Database Format

SQLite is the database format used in MILDOS4. It is an open source standard that has evolved over the past decade, is freely distributable, is in use worldwide, and has an active development community with some corporate support. SQLite is easily installable with VB.NET libraries available for Windows computers. With support for both 32-bit and 64-bit systems on a variety of computer platforms, this DB format is expected to remain viable over the life of the MILDOS4 code. The primary Web address for SQLite is http://www.sqlite.org/.

It is not recommended that users modify the user files outside of the MILDOS4 program. However, files can be viewed by using an appropriate editor.

A.2.3 GIS Module

An open-source GIS module (MapWinGIS) has the functionality needed to replace the existing graphics display (with added GIS capabilities). The MapWinGIS module is incorporated into MILDOS4 and is available through the MapWindow GIS Open Source Project (http://www.mapwindow.org/). It provides an embedded map control for use in 32-bit and 64-bit Windows applications, and it is programmable in VB.NET, freely distributable, and easily installed on user computers. It is this module that provides the capability to import geo-referenced maps (e.g., Esri shapefiles, world files in JPEG/TIFF/BMP format), if desired, as the background for creating custom scenarios. Because of the complexities associated with geo-referencing, MILDOS4 supports only universal transverse Mercator (UTM) projections, measuring distance in meters. Appendix E provides more information on map data and the map display.

A.3   Program Components, Installation, and Performance

A.3.1 Installation

MILDOS4 installation is accomplished through executing the install program (MILDOS_AREA_4_install.exe). This program requires administrative privileges for the installation of two modules (Microsoft .NET Framework 4.5.1 and MapWinGIS) that support the operation of MILDOS4. Windows 7 has the .NET Framework 4.0 already installed but needs to have it updated to version 4.5.1. Windows 8 and 10 already include version 4.5.1, and the installer will skip that installation step for those systems. Use of the MapWinGIS (v. 4.9.5.0) map control requires the installation of the Microsoft Visual C++ 2013 redistributable package and registration of the map control in the Windows registry. Note that as of version 4.02, MILDOS4 is compiled and installed as a 64-bit application.

The MILDOS4 installer includes and will run the .NET 4.5.1 and MapWinGIS installers. After this, the MILDOS4 installer will place the required application files in the \MILDOS4 directory. Note that the MapWinGIS installer will create a directory at C:\dev\MapWinGIS and populate it with supporting files. It is recommended that users keep their MILDOS4 user files in a directory such as \MILDOS4\UserFiles and keep any map data that they use in \MILDOS4\MapData. User files can be saved in any directory of the user's choosing, but any map data used are referenced at their current location and are not entirely loaded into the user file. Thus, if the map data files are moved after referenced in a user file, the map will not load properly the next time that the user file is loaded.

A.3.2 Performance

The use of area sources, sensitivity parameters, and population assessments can all significantly increase run time. The status of calculations is displayed on a calculation status window during analysis of calculations. Area source calculations will depend on the size of the source and its proximity to receptor locations, including those on the population grid. Considerations of execution times involving area sources are discussed further in Sections 3.5 and 6.5.1. Each additional sensitivity parameter selected will add two complete runs (or "Loops" as listed on the Calc Status form) to the calculations in order to assess the changes due to lower and higher values of the parameter. Selection of the population analysis essentially adds 192 receptor locations (16 directions and 12 distance ranges) to the analysis.

APPENDIX B DOSE COEFFICIENTS AND ADJUSTMENT FACTORS

This appendix lists the dose coefficients used in MILDOS4. Section 5.3 in Section 5 discusses their origin. In keeping with the International Commission on Radiological Protection (ICRP) and other agencies, the term "dose coefficient," equivalent to the term "dose conversion factor" more commonly used in the past, is used in this report.

B.1 External Dose Coefficients

Table B-1 External Dose Coefficients for the U-238 Decay Series Isotopes

	Skin Dose Coefficient		Effective Dose Coefficient	
Isotope	Air Submersion (mrem/yr per pCi/m^3)	Ground Surface (mrem/yr per pCi/m^2)	Air Submersion (mrem/yr per pCi/m^3)	Ground Surface (mrem/yr per pCi/m^2)
U-238	3.40E-06	8.66E-07	3.98E-07	6.43E-08
Th-234	8.76E-05	2.01E-06	3.95E-05	9.71E-07
Pa-234m	6.40E-03	1.10E-03	8.40E-05	1.79E-06
Pa-234	1.45E-02	4.54E-04	1.09E-02	2.15E-04
U-234	4.96E-06	1.06E-06	8.91E-07	8.73E-08
Th-230	5.27E-06	8.37E-07	2.03E-06	8.76E-08
Ra-226	5.59E-05	9.48E-07	3.68E-05	7.52E-07
Rn-222	2.66E-06	6.07E-08	2.23E-06	4.61E-08
Po-218	8.83E-08	1.37E-09	5.23E-08	1.04E-09
Pb-214	3.23E-03	1.06E-04	1.38E-03	2.85E-05
At-218	2.48E-05	2.71E-06	1.39E-05	4.88E-07
Bi-214	1.49E-02	9.90E-04	8.93E-03	1.65E-04
Po-214	5.50E-07	1.27E-08	4.76E-07	9.49E-09
Pb-210	1.49E-05	2.31E-06	6.59E-06	2.90E-07
Bi-210	2.69E-03	3.99E-04	3.84E-06	1.23E-07
Po-210	5.62E-08	1.30E-09	4.86E-08	9.68E-10

Source: EPA (1993)

Table B-2 External Dose Coefficients for the Th-232 Decay Series Isotopes

| Isotope | Skin Dose Coefficient | | Effective Dose Coefficient | |
	Air Submersion (mrem/yr per pCi/m³)	Ground Surface (mrem/yr per pCi/m²)	Air Submersion (mrem/yr per pCi/m³)	Ground Surface (mrem/yr per pCi/m²)
Th-232	4.02E-06	8.01E-07	1.02E-06	6.43E-08
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ac-228	9.20E-03	5.55E-04	5.58E-03	1.08E-04
Th-228	1.75E-05	1.14E-06	1.07E-05	2.74E-07
Ra-224	7.41E-05	1.35E-06	5.50E-05	1.12E-06
Rn-220	2.57E-06	6.08E-08	2.16E-06	4.45E-08
Po-216	1.12E-07	2.57E-09	9.68E-08	1.93E-09
Pb-212	1.58E-03	2.20E-05	8.02E-04	1.67E-05
Bi-212	4.73E-03	6.25E-04	1.08E-03	2.09E-05
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tl-208	2.73E-02	1.14E-03	2.07E-02	3.48E-04

Source: EPA (1993)

B.2   Internal Dose Coefficients

B.2.1   Inhalation Dose Coefficients

Table B-3 Adult Inhalation Effective Dose Coefficients (mrem/pCi) for the U-238 Decay Series Isotopes (D = day, W = week, Y = year)

AMAD (µm)	U-238			U-234			Th-230			Ra-226		
	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	4.18E-03	1.63E-02	2.84E-01	4.57E-03	1.84E-02	3.18E-01	NA[a]	5.88E-01	6.11E-01	1.94E-02	NA	NA
0.15	3.48E-03	1.44E-02	2.53E-01	3.88E-03	1.62E-02	2.83E-01	NA	4.65E-01	5.43E-01	1.71E-02	NA	NA
0.2	3.04E-03	1.31E-02	2.31E-01	3.39E-03	1.47E-02	2.58E-01	NA	3.93E-01	4.94E-01	1.54E-02	NA	NA
0.3	2.79E-03	1.14E-02	1.99E-01	3.11E-03	1.28E-02	2.23E-01	NA	3.65E-01	4.28E-01	1.35E-02	NA	NA
0.5	2.57E-03	9.31E-03	1.61E-01	2.86E-03	1.05E-02	1.81E-01	NA	3.40E-01	3.50E-01	1.11E-02	NA	NA
1	2.45E-03	7.01E-03	1.18E-01	2.73E-03	7.89E-03	1.33E-01	NA	3.26E-01	2.62E-01	8.57E-03	NA	NA
2	2.51E-03	4.86E-03	7.73E-02	2.80E-03	5.47E-03	8.66E-02	NA	3.30E-01	1.80E-01	6.25E-03	NA	NA
3	2.61E-03	3.95E-03	5.94E-02	2.90E-03	4.44E-03	6.65E-02	NA	3.39E-01	1.44E-01	5.29E-03	NA	NA
5	2.74E-03	3.03E-03	4.13E-02	3.05E-03	3.40E-03	4.62E-02	NA	3.56E-01	1.09E-01	4.34E-03	NA	NA
10	2.87E-03	2.13E-03	2.36E-02	3.20E-03	2.39E-03	2.65E-02	NA	3.64E-01	7.50E-02	3.41E-03	NA	NA
20	2.68E-03	1.23E-03	8.58E-03	2.98E-03	1.37E-03	9.61E-03	NA	3.02E-01	4.35E-02	2.38E-03	NA	NA
50	2.57E-03	7.12E-04	7.10E-05	2.87E-03	7.92E-04	7.82E-05	NA	2.66E-01	2.57E-02	1.80E-03	NA	NA

AMAD (µm)	Pb-210			Bi-210			Po-210		
	D	W	Y	D	W	Y	D	W	Y
0.1	1.49E-02	NA	NA	4.21E-05	5.41E-04	NA	1.58E-02	1.86E-02	NA
0.15	1.24E-02	NA	NA	3.60E-05	4.70E-04	NA	1.31E-02	1.61E-02	NA
0.2	1.08E-02	NA	NA	3.20E-05	4.23E-04	NA	1.14E-02	1.44E-02	NA
0.3	1.00E-02	NA	NA	2.87E-05	3.72E-04	NA	1.05E-02	1.27E-02	NA
0.5	9.35E-03	NA	NA	2.51E-05	3.13E-04	NA	9.76E-03	1.08E-02	NA
1	9.24E-03	NA	NA	2.20E-05	2.51E-04	NA	9.50E-03	8.84E-03	NA
2	9.86E-03	NA	NA	2.01E-05	1.98E-04	NA	9.97E-03	7.23E-03	NA
3	1.04E-02	NA	NA	1.98E-05	1.02E-02	NA	1.05E-02	6.63E-03	NA
5	1.12E-02	NA	NA	1.96E-05	1.58E-04	NA	1.11E-02	6.08E-03	NA
10	1.19E-02	NA	NA	1.95E-05	1.39E-04	NA	1.18E-02	5.54E-03	NA
20	1.13E-02	NA	NA	1.74E-05	1.09E-04	NA	1.11E-02	4.42E-03	NA
50	1.10E-02	NA	NA	1.63E-05	9.24E-05	NA	1.07E-02	3.79E-03	NA

[a]   Some elements do not have all three inhalation classes. In MILDOS4, the dose coefficients for the unassigned classes are assumed to be the same as those of the adjacent classes.

Source: Table 2.4 in Yuan et al. (1989)

Table B-4 Tissue Dose Coefficients (mrem/pCi) of AMAD = 1 µm for the U-238 Decay Series Isotopes

Isotope/Class	Bone	Lung	Liver	Kidney
U-238				
D	3.62E-02	1.04E-03	8.21E-05	1.48E-02
W	1.09E-02	5.25E-02	2.49E-05	4.48E-03
Y	3.74E-03	9.84E-01	1.16E-05	1.58E-03
U-234				
D	4.03E-02	1.18E-03	9.25E-05	1.67E-02
W	1.22E-02	5.92E-02	2.78E-05	5.03E-03
Y	4.18E-03	1.10E+00	9.88E-06	1.77E-03
Th-230				
D	NA	NA	NA	NA
W	7.99E+00	5.96E-02	1.32E-02	1.51E-03
Y	3.22E+00	1.11E+00	5.59E-03	6.36E-04
Ra-226				
D	NA	NA	NA	NA
W	2.81E-02	5.96E-02	3.77E-04	3.77E-04
Y	NA	NA	NA	NA

Isotope/Class	Bone	Lung	Liver	Kidney
Pb-210				
D	7.40E-02	1.04E-03	5.55E-02	2.63E-02
W	NA[a]	NA	NA	NA
Y	NA	NA	NA	NA
Bi-210				
D	5.66E-07	6.51E-05	1.55E-06	2.10E-04
W	8.29E-06	1.60E-03	2.26E-05	7.88E-04
Y	NA	NA	NA	NA
Po-210				
D	2.09E-03	8.21E-04	8.10E-03	4.40E-02
W	7.40E-04	4.81E-02	2.31E-03	1.40E-02
Y	NA	NA	NA	NA

[a] Some elements do not have all three inhalation classes. In MILDOS4, the dose coefficient values for the unassigned classes are assumed to be the same as those of the adjacent classes.

Source: Table 2.2 in Yuan et al. (1989)

Table B-5 Values of the Factors $f_{N-P}/f_{T-P}/f_P$ for the U-238 Decay Series Isotopes

Isotope/ Tissue	Inhalation Class			Isotope/ Tissue	Inhalation Class		
	D	W	Y		D	W	Y
U-238				**Pb-210**			
Bone	33/16/51	30/29/41	7/2/91	Bone	36/15/49	NA[a]	NA
Lung	3/2/95	0/0/100	0/0/100	Lung	36/15/49	NA	NA
Liver	33/16/51	30/29/41	5/1/94	Liver	36/15/49	NA	NA
Kidney	33/16/51	30/29/41	7/2/91	Kidney	35/15/50	NA	NA
U-234				**Bi-210**			
Bone	33/16/51	30/29/41	7/2/91	Bone	31/15/54	63/11/26	NA
Lung	3/2/95	0/0/100	0/0/100	Lung	6/3/91	0/0/100	NA
Liver	33/16/51	30/29/41	5/1/94	Liver	31/15/54	63/11/26	NA
Kidney	33/16/51	30/29/41	7/2/91	Kidney	31/15/54	42/36/22	NA
Th-230				**Po-210**			
Bone	NA	25/33/42	6/2/92	Bone	34/16/50	37/29/34	NA
Lung	NA	1/1/98	0/0/100	Lung	5/5/90	0/0/100	NA
Liver	NA	25/33/42	6/2/92	Liver	34/16/50	37/29/34	NA
Kidney	NA	25/33/42	6/2/92	Kidney	34/16/50	37/29/34	NA
Ra-226							
Bone	38/22/40	NA	NA				
Lung	0/0/100	NA	NA				
Liver	38/22/40	NA	NA				
Kidney	38/22/40	NA	NA				

[a] Some elements do not have all three inhalation classes. In MILDOS4, the dose coefficient values for the unassigned classes are assumed to be the same as those of the adjacent classes.

Source: Table 2.3 in Yuan et al. (1989)

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes

Th-232

AMAD (μm)	Effective D	W	Y	Bone D	W	Y	Kidney D	W	Y	Liver D	W	Y	Lung D	W	Y
0.1	NA[a]	2.98E+00	2.73E+00	NA	7.47E+01	4.29E+01	NA	5.14E-03	5.37E-03	NA	4.18E-02	4.48E-02	NA	1.30E-01	8.55E+00
0.15	NA	2.36E+00	2.43E+00	NA	5.92E+01	3.81E+01	NA	4.07E-03	4.77E-03	NA	3.32E-02	3.96E-02	NA	1.15E-01	7.62E+00
0.2	NA	1.99E+00	2.21E+00	NA	4.96E+01	3.45E+01	NA	3.43E-03	4.33E-03	NA	2.79E-02	3.61E-02	NA	1.04E-01	6.96E+00
0.3	NA	1.85E+00	1.92E+00	NA	4.64E+01	3.00E+01	NA	3.19E-03	3.77E-03	NA	2.60E-02	3.13E-02	NA	9.06E-02	6.01E+00
0.5	NA	1.72E+00	1.57E+00	NA	4.33E+01	2.47E+01	NA	2.98E-03	3.07E-03	NA	2.42E-02	2.55E-02	NA	7.36E-02	4.88E+00
1	NA	1.64E+00	1.15E+00	NA	4.10E+01	1.84E+01	NA	2.83E-03	2.24E-03	NA	2.30E-02	1.86E-02	NA	5.32E-02	3.47E+00
2	NA	1.68E+00	8.18E-01	NA	4.22E+01	1.35E+01	NA	2.90E-03	1.57E-03	NA	2.37E-02	1.31E-02	NA	3.64E-02	2.32E+00
3	NA	1.73E+00	6.63E-01	NA	4.33E+01	1.13E+01	NA	2.98E-03	1.26E-03	NA	2.43E-02	1.04E-02	NA	2.85E-02	1.77E+00
5	NA	1.79E+00	5.08E-01	NA	4.50E+01	9.09E+00	NA	3.10E-03	9.48E-04	NA	2.53E-02	7.87E-03	NA	1.91E-02	1.22E+00
10	NA	1.86E+00	3.61E-01	NA	4.70E+01	6.99E+00	NA	3.23E-03	6.48E-04	NA	2.63E-02	5.37E-03	NA	1.29E-02	6.92E-01
20	NA	1.55E+00	2.32E-01	NA	3.89E+01	4.99E+00	NA	2.68E-03	3.92E-04	NA	2.18E-02	3.26E-03	NA	6.18E-03	2.75E-01
50	NA	1.57E+00	2.11E-01	NA	3.96E+01	4.70E+00	NA	2.72E-03	3.53E-04	NA	2.22E-02	2.93E-03	NA	5.25E-03	2.09E-01

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

	Ra-228														
	Effective			Bone			Kidney			Liver			Lung		
AMAD (µm)	D	W	Y	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	NA	1.03E-02	NA	NA	3.81E-02	NA	NA	1.10E-03	NA	NA	1.11E-03	NA	NA	6.51E-02	NA
0.15	NA	8.95E-03	NA	NA	3.08E-02	NA	NA	8.92E-04	NA	NA	9.03E-04	NA	NA	5.77E-02	NA
0.2	NA	8.03E-03	NA	NA	2.63E-02	NA	NA	7.66E-04	NA	NA	7.77E-04	NA	NA	5.25E-02	NA
0.3	NA	7.09E-03	NA	NA	2.48E-02	NA	NA	7.17E-04	NA	NA	7.26E-04	NA	NA	4.56E-02	NA
0.5	NA	5.99E-03	NA	NA	2.38E-02	NA	NA	6.81E-04	NA	NA	6.88E-04	NA	NA	3.70E-02	NA
1	NA	4.76E-03	NA	NA	2.40E-02	NA	NA	6.77E-04	NA	NA	6.80E-04	NA	NA	2.67E-02	NA
2	NA	3.89E-03	NA	NA	2.69E-02	NA	NA	7.44E-04	NA	NA	7.44E-04	NA	NA	1.82E-02	NA
3	NA	3.54E-03	NA	NA	2.88E-02	NA	NA	7.89E-04	NA	NA	7.90E-04	NA	NA	1.41E-02	NA
5	NA	3.20E-03	NA	NA	3.12E-02	NA	NA	8.49E-04	NA	NA	8.49E-04	NA	NA	1.01E-02	NA
10	NA	2.89E-03	NA	NA	3.37E-02	NA	NA	9.10E-04	NA	NA	9.10E-04	NA	NA	6.25E-03	NA
20	NA	2.36E-03	NA	NA	3.16E-02	NA	NA	8.48E-04	NA	NA	8.50E-04	NA	NA	3.02E-03	NA
50	NA	2.31E-03	NA	NA	3.18E-02	NA	NA	8.51E-04	NA	NA	8.55E-04	NA	NA	2.53E-03	NA

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

Ac-228

AMAD (µm)	Effective D	Effective W	Effective Y	Bone D	Bone W	Bone Y	Kidney D	Kidney W	Kidney Y	Liver D	Liver W	Liver Y	Lung D	Lung W	Lung Y
0.1	5.33E-04	1.73E-04	3.03E-04	9.14E-03	2.32E-03	4.59E-04	2.08E-07	9.99E-08	8.58E-08	2.41E-03	6.14E-04	1.21E-04	5.77E-06	3.16E-04	2.30E-03
0.15	4.44E-04	1.40E-04	2.70E-04	7.59E-03	1.82E-03	4.00E-04	1.72E-07	8.03E-08	7.10E-08	2.00E-03	4.81E-04	1.06E-04	5.11E-06	3.55E-04	2.05E-03
0.2	3.85E-04	1.20E-04	2.46E-04	6.62E-03	1.53E-03	3.61E-04	1.49E-07	6.85E-08	6.14E-08	1.75E-03	4.03E-04	9.58E-05	4.63E-06	2.57E-04	1.87E-03
0.3	3.55E-04	1.10E-04	2.13E-04	6.10E-03	1.43E-03	3.19E-04	1.40E-07	6.45E-08	5.70E-08	1.60E-03	3.78E-04	8.46E-05	4.01E-06	2.22E-04	1.61E-03
0.5	3.26E-04	9.99E-05	1.73E-04	5.62E-03	1.34E-03	2.71E-04	1.34E-07	6.18E-08	5.29E-08	1.48E-03	3.55E-04	7.18E-05	3.27E-06	1.80E-04	1.31E-03
1	3.08E-04	9.09E-05	1.25E-04	5.29E-03	1.29E-03	2.19E-04	1.36E-07	6.18E-08	5.10E-08	1.39E-03	3.41E-04	5.81E-05	2.37E-06	1.28E-04	9.36E-04
2	3.20E-04	8.88E-05	8.62E-05	5.51E-03	1.34E-03	1.86E-04	1.55E-07	6.81E-08	5.44E-08	1.45E-03	3.56E-04	4.92E-05	1.63E-06	8.55E-05	6.25E-04
3	3.33E-04	8.92E-05	6.79E-05	5.71E-03	1.38E-03	1.73E-04	1.67E-07	7.26E-08	5.69E-08	1.50E-03	3.68E-04	4.59E-05	1.28E-06	6.55E-05	4.77E-04
5	3.50E-04	9.06E-05	4.95E-05	6.01E-03	1.45E-03	1.62E-04	1.82E-07	7.82E-08	6.05E-08	1.58E-03	3.84E-04	4.29E-05	9.31E-07	4.51E-05	3.29E-04
10	3.69E-04	9.21E-05	3.18E-05	6.33E-03	1.52E-03	1.52E-04	1.99E-07	8.40E-08	6.44E-08	1.67E-03	4.03E-04	4.03E-05	5.92E-07	2.56E-05	1.86E-04
20	3.44E-04	7.56E-05	1.74E-05	5.89E-03	1.26E-03	1.35E-04	1.94E-07	7.77E-08	6.02E-08	1.55E-03	3.35E-04	3.57E-05	2.82E-07	1.01E-05	7.42E-05
50	3.44E-04	7.62E-05	1.51E-05	5.88E-03	1.29E-03	1.32E-04	1.94E-07	7.81E-08	6.03E-08	1.55E-03	3.40E-04	3.50E-05	2.43E-07	7.70E-06	5.62E-05

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

Th-228

AMAD (µm)	Effective			Bone			Kidney			Liver			Lung		
	D	W	Y	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	NA	4.77E-01	8.29E-01	NA	9.10E+00	1.78E+00	NA	8.95E-03	1.81E-03	NA	7.77E-02	1.54E-02	NA	8.62E-01	6.29E+00
0.15	NA	3.85E-01	7.36E-01	NA	7.14E+00	1.56E+00	NA	7.03E-03	1.59E-03	NA	6.11E-02	1.34E-02	NA	7.66E-01	5.59E+00
0.2	NA	3.30E-01	6.70E-01	NA	5.99E+00	1.41E+00	NA	5.92E-03	1.44E-03	NA	5.11E-02	1.21E-02	NA	6.99E-01	5.11E+00
0.3	NA	3.03E-01	5.82E-01	NA	5.61E+00	1.24E+00	NA	5.53E-03	1.26E-03	NA	4.79E-02	1.07E-02	NA	6.04E-01	4.42E+00
0.5	NA	2.71E-01	4.74E-01	NA	5.25E+00	1.05E+00	NA	5.18E-03	1.07E-03	NA	4.51E-02	9.07E-03	NA	4.88E-01	3.58E+00
1	NA	2.50E-01	3.42E-01	NA	5.07E+00	8.47E-01	NA	4.99E-03	8.51E-04	NA	4.33E-02	7.28E-03	NA	3.50E-01	2.55E+00
2	NA	2.44E-01	2.34E-01	NA	5.25E+00	7.10E-01	NA	5.18E-03	7.07E-04	NA	4.51E-02	6.11E-03	NA	2.35E-01	1.71E+00
3	NA	2.45E-01	1.84E-01	NA	5.45E+00	6.57E-01	NA	5.37E-03	6.47E-04	NA	4.66E-02	5.65E-03	NA	1.80E-01	1.30E+00
5	NA	2.49E-01	1.33E-01	NA	5.70E+00	6.08E-01	NA	5.62E-03	5.93E-04	NA	4.87E-02	5.23E-03	NA	1.25E-01	8.99E-01
10	NA	2.53E-01	8.44E-02	NA	5.96E+00	5.62E-01	NA	5.88E-03	5.44E-04	NA	5.11E-02	4.85E-03	NA	7.25E-02	5.11E-01
20	NA	2.07E-01	4.47E-02	NA	4.97E+00	4.95E-01	NA	4.90E-03	4.71E-04	NA	4.25E-02	4.26E-03	NA	2.88E-02	2.02E-01
50	NA	2.10E-01	3.85E-02	NA	5.03E+00	4.85E-01	NA	4.96E-03	4.59E-04	NA	4.33E-02	4.18E-03	NA	2.24E-02	1.54E-01

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

Ra-224

AMAD (µm)	Effective			Bone			Kidney			Liver			Lung		
	D	W	Y	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	NA	7.44E-03	NA	NA	5.22E-03	NA	NA	6.85E-05	NA	NA	6.85E-05	NA	NA	5.96E-02	NA
0.15	NA	6.59E-03	NA	NA	3.74E-03	NA	NA	5.00E-05	NA	NA	5.00E-05	NA	NA	5.29E-02	NA
0.2	NA	5.96E-03	NA	NA	2.94E-03	NA	NA	3.92E-05	NA	NA	3.92E-05	NA	NA	4.85E-02	NA
0.3	NA	5.19E-03	NA	NA	3.08E-03	NA	NA	4.10E-05	NA	NA	4.10E-05	NA	NA	4.18E-02	NA
0.5	NA	4.26E-03	NA	NA	3.47E-03	NA	NA	4.59E-05	NA	NA	4.59E-05	NA	NA	3.39E-02	NA
1	NA	3.16E-03	NA	NA	4.33E-03	NA	NA	5.69E-05	NA	NA	5.69E-05	NA	NA	2.42E-02	NA
2	NA	2.27E-03	NA	NA	5.70E-03	NA	NA	7.47E-05	NA	NA	7.47E-05	NA	NA	1.62E-02	NA
3	NA	1.87E-03	NA	NA	6.50E-03	NA	NA	8.52E-05	NA	NA	8.52E-05	NA	NA	1.25E-02	NA
5	NA	1.46E-03	NA	NA	7.42E-03	NA	NA	9.73E-05	NA	NA	9.73E-05	NA	NA	8.69E-03	NA
10	NA	1.08E-03	NA	NA	8.36E-03	NA	NA	1.10E-04	NA	NA	1.10E-04	NA	NA	5.03E-03	NA
20	NA	6.97E-04	NA	NA	7.98E-03	NA	NA	1.04E-04	NA	NA	1.04E-04	NA	NA	1.99E-03	NA
50	NA	6.48E-04	NA	NA	8.07E-03	NA	NA	1.06E-04	NA	NA	1.06E-04	NA	NA	1.55E-03	NA

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

Pb-212

AMAD (µm)	Effective			Bone			Kidney			Liver			Lung		
	D	W	Y	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	3.22E-04	NA	NA	1.85E-03	NA	NA	1.22E-04	NA	NA	2.48E-04	NA	NA	1.78E-03	NA	NA
0.15	2.75E-04	NA	NA	1.46E-03	NA	NA	9.58E-05	NA	NA	1.96E-04	NA	NA	1.58E-03	NA	NA
0.2	2.45E-04	NA	NA	1.22E-03	NA	NA	8.07E-05	NA	NA	1.65E-04	NA	NA	1.44E-03	NA	NA
0.3	2.20E-04	NA	NA	1.19E-03	NA	NA	7.87E-05	NA	NA	1.60E-04	NA	NA	1.24E-03	NA	NA
0.5	1.94E-04	NA	NA	1.22E-03	NA	NA	7.99E-05	NA	NA	1.64E-04	NA	NA	1.01E-03	NA	NA
1	1.69E-04	NA	NA	1.37E-03	NA	NA	8.88E-05	NA	NA	1.81E-04	NA	NA	7.28E-04	NA	NA
2	1.59E-04	NA	NA	1.68E-03	NA	NA	1.08E-04	NA	NA	2.21E-04	NA	NA	4.96E-04	NA	NA
3	1.58E-04	NA	NA	1.87E-03	NA	NA	1.19E-04	NA	NA	2.44E-04	NA	NA	3.86E-04	NA	NA
5	1.58E-04	NA	NA	2.10E-03	NA	NA	1.34E-04	NA	NA	2.73E-04	NA	NA	2.76E-04	NA	NA
10	1.59E-04	NA	NA	2.33E-03	NA	NA	1.48E-04	NA	NA	3.30E-04	NA	NA	1.71E-04	NA	NA
20	1.45E-04	NA	NA	2.27E-03	NA	NA	1.44E-04	NA	NA	2.94E-04	NA	NA	8.24E-05	NA	NA
50	1.44E-04	NA	NA	2.28E-03	NA	NA	1.45E-04	NA	NA	2.96E-04	NA	NA	6.92E-05	NA	NA

Table B-6 Adult Inhalation Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes (Cont'd.)

Bi-212

AMAD (μm)	Effective			Bone			Kidney			Liver			Lung		
	D	W	Y	D	W	Y	D	W	Y	D	W	Y	D	W	Y
0.1	4.37E-05	4.40E-05	NA	6.44E-07	2.42E-07	NA	1.05E-04	3.81E-05	NA	6.51E-07	2.56E-07	NA	3.06E-04	3.47E-04	NA
0.15	3.67E-05	3.77E-05	NA	4.51E-07	1.62E-07	NA	7.36E-05	2.52E-05	NA	4.63E-07	1.73E-07	NA	2.68E-04	2.99E-04	NA
0.2	3.27E-05	3.33E-05	NA	3.47E-07	1.18E-07	NA	5.66E-05	1.81E-05	NA	3.57E-07	1.27E-07	NA	2.42E-04	2.68E-04	NA
0.3	2.93E-05	2.94E-05	NA	3.80E-07	1.26E-07	NA	6.19E-05	1.96E-05	NA	3.89E-07	1.34E-07	NA	2.10E-04	2.34E-04	NA
0.5	2.55E-05	2.47E-05	NA	4.55E-07	1.43E-07	NA	7.40E-05	2.26E-05	NA	4.63E-07	1.51E-07	NA	1.72E-04	1.94E-04	NA
1	2.16E-05	1.91E-05	NA	6.06E-07	1.75E-07	NA	9.88E-05	2.82E-05	NA	6.14E-07	1.82E-07	NA	1.25E-04	1.43E-04	NA
2	1.94E-05	1.47E-05	NA	8.36E-07	2.24E-07	NA	1.36E-04	3.63E-05	NA	8.47E-07	2.29E-07	NA	8.66E-05	1.02E-04	NA
3	1.87E-05	1.27E-05	NA	9.70E-07	2.51E-07	NA	1.58E-04	4.09E-05	NA	9.79E-07	2.56E-07	NA	6.83E-05	8.33E-05	NA
5	1.81E-05	1.07E-05	NA	1.12E-06	2.82E-07	NA	1.82E-04	4.61E-05	NA	1.13E-06	2.87E-07	NA	4.98E-05	6.37E-05	NA
10	1.76E-05	8.81E-06	NA	1.28E-06	3.15E-07	NA	2.08E-04	5.14E-05	NA	1.29E-06	3.19E-07	NA	3.20E-05	4.48E-05	NA
20	5.03E-06	5.03E-06	NA	2.70E-07	2.70E-07	NA	2.02E-04	4.44E-05	NA	1.25E-06	2.74E-07	NA	1.25E-05	1.73E-05	NA
50	1.49E-05	2.94E-05	NA	1.26E-06	1.26E-07	NA	2.05E-04	1.96E-05	NA	1.27E-06	1.35E-07	NA	1.08E-05	2.34E-04	NA

a Some elements do not have all three inhalation classes. In MILDOS4, the dose coefficient values for the unassigned classes are assumed to be the same as those of the adjacent classes
Source: Eckerman and Leggett (1996)

Table B-7 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the U-238 Decay Series Isotopes

Isotope/Age Group	Size/Class								
	0.3 µm			1.0 µm			5.0 µm		
	D	W	Y	D	W	Y	D	W	Y
U-238									
Effective									
Infant	21	12	4.8	22	14	4.8	23	17	4.8
Child	2.9	3.3	2.3	2.9	3.3	2.3	2.9	3.3	2.3
Teenager	1.8	1.5	1.2	1.8	1.6	1.2	1.8	1.7	1.2
Bone									
Infant	4.3	5.1	1.9	4.4	5.4	2.1	4.5	6	3.2
Child	0.96	1	1.4	0.96	1	1.4	0.97	1	1.3
Teenager	2.7	3	1.7	2.8	3.1	1.8	2.8	3.2	2.2
Lung									
Infant	13	12	4.7	13.0	12	4.7	13	12	4.8
Child	3.4	3.4	2.3	3.4	3.4	2.3	3.4	3.4	2.3
Teenager	1.5	1.5	1.2	1.5	1.5	1.2	1.4	1.5	1.2
Liver									
Infant	11	13	4.4	12	14	5	12	16	7.7
Child	3.1	3.2	2.2	3.1	3.3	2.3	3.2	3.4	2.6
Teenager	1.4	1.5	1.1	1.4	1.6	1.2	1.4	1.6	1.3
Kidney									
Infant	11	13	4.1	11	14	4.8	12	15	7.8
Child	2.8	2.9	2.1	2.8	2.9	2.1	2.8	3	2.4
Teenager	1.4	1.5	1.1	1.4	1.5	1.2	1.4	1.6	1.3
U-234									
Effective									
Infant	22	12	4.8	22	14	4.8	23	17	4.8
Child	2.9	3.4	2.3	2.9	3.4	2.3	2.9	3.3	2.3
Teenager	1.8	1.5	1.2	1.8	1.6	1.2	1.8	1.7	1.2
Bone									
Infant	4.3	5.1	1.9	4.4	5.5	2.1	4.5	6	3.2
Child	0.96	1	1.4	0.96	1	1.4	0.97	1	1.2
Teenager	2.7	3	1.7	2.8	3.1	1.8	2.8	3.2	2.2
Lung									
Infant	13.0	12	4.8	13	12	4.8	13	12	4.8
Child	3.4	3.4	2.3	3.5	3.4	2.3	3.5	3.4	2.3
Teenager	1.5	1.5	1.2	1.5	1.5	1.2	1.4	1.5	1.2
Liver									
Infant	11	13	4.6	12	14	5.3	12	16	8.3
Child	3.1	3.3	2.3	3.2	3.3	2.4	3.2	3.4	2.7
Teenager	1.4	1.5	1.1	1.4	1.6	1.2	1.4	1.6	1.3
Kidney									
Infant	11	13	4.1	11	14	4.8	12	16	7.9
Child	2.8	2.9	2.1	2.8	2.9	2.1	2.8	3	2.4
Teenager	1.4	1.5	1.1	1.4	1.6	1.2	1.4	1.6	1.3

Table B-7 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the U-238 Decay Series Isotopes (Cont'd.)

| | Size/Class | | | | | | | | |
| | 0.3 µm | | | 1.0 µm | | | 5.0 µm | | |
Isotope/Age Group	D	W	Y	D	W	Y	D	W	Y
Th-230									
Effective									
Infant	2.9	1.8	2.9	2.9	1.8	2.9	2.8	1.7	2.8
Child	1.6	1.1	1.6	1.6	1.1	1.6	1.5	1.1	1.5
Teenager	1.1	0.91	1.1	1.1	0.91	1.1	1	o.89	1
Bone									
Infant	1.1	1.2	1.1	1.1	1.2	1.1	1.3	1.2	1.3
Child	0.97	0.98	0.97	0.97	0.98	0.97	0.98	0.98	0.98
Teenager	1	1	1	1	1	1	1	1	1
Lung									
Infant	4.8	11	4.8	4.8	11	4.8	4.8	9.9	4.8
Child	2.3	3.3	2.3	2.3	3.3	2.3	2.3	3	2.3
Teenager	1.2	1.5	1.2	1.2	1.5	1.2	1.2	1.4	1.2
Liver									
Infant	3.1	5.2	3.1	3.4	5.3	3.4	4.8	5.4	4.8
Child	1.9	2.6	1.9	1.9	2.6	1.9	2.1	2.6	2.1
Teenager	1	1.1	1	1.1	1.1	1.1	1.1	1.1	1.1
Kidney									
Infant	2.8	4.5	2.8	3.1	4.6	3.1	4.3	4.7	4.3
Child	1.8	2.4	1.8	1.8	2.4	1.8	2	2.4	2
Teenager	1	1.1	1	1.1	1.1	1.1	1.1	i.1	1.1
Ra-226									
Effective									
Infant	12	12	12	12	12	12	11	11	11
Child	3.1	3.1	3.1	3	3	3	2.4	2.4	2.4
Teenager	1.6	1.6	1.6	1.7	1.7	1.7	2.1	2.1	2.1
Bone									
Infant	2.6	2.6	2.6	2.7	2.7	2.7	3	3	3
Child	0.85	0.85	0.85	0.85	0.85	0.85	0.87	0.87	0.87
Teenager	3.1	3.1	3.1	3.2	3.2	3.2	3.4	3.4	3.4
Lung									
Infant	12	12	12	12	12	12	12	12	12
Child	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Teenager	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Liver									
Infant	13	13	13	15	15	15	17	17	17
Child	3	3	3	3.1	3.1	3.1	3.3	3.3	3.3
Teenager	1.7	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9
Kidney									
Infant	5.1	5.1	5.1	5.7	5.7	5.7	6.7	6.7	6.7
Child	1.4	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.6
Teenager	1.7	1.7	1.7	2	2	2	2.3	2.3	2.3

Table B-7 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the U-238 Decay Series Isotopes (Cont'd.)

				Size/Class					
	0.3 µm			1.0 µm			5.0 µm		
Isotope/Age Group	D	W	Y	D	W	Y	D	W	Y

Pb-210

Effective									
Infant	2.4	2.4	2.4	2.5	2.5	2.5	2.7	2.7	2.7
Child	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Teenager	1.2	1.2	1.2	1.3	. 1.3	1.3	1.3	1.3	1.3
Bone									
Infant	0.91	0.91	0.91	0.97	0.97	0.97	1.1	1.1	1.1
Child	0.69	0.69	0.69	0.71	o. 71	o. 71	o. 72	o.72	0.72
Teenager	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8
Lung									
Infant	6	6	6	6.4	6.4	6.4	7	7	7
Child	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Liver									
Infant	6.3	6.3	6.3	6.7	6.7	6.7	7.3	7.3	7.3
Child	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Kidney									
Infant	5.1	5.1	5.1	5.4	5.4	5.4	5.7	5.7	5.7
Child	2.4	2.4	2.4	2.5	2.5	2.5	2.6	2.6	2.6
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3

Bi-210

Effective									
Infant	2.4	2.4	2.4	2.5	2.5	2.5	2.7	2.7	2.7
Child	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Teenager	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3
Bone									
Infant	0.91	0.91	0.91	0.97	0.97	0.97	1.1	1.1	1.1
Child	0.69	0.69	0.69	0.71	0.71	o. 71	o. 72	0.72	0.12
Teenager	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8
Lung									
Infant	6	6	6	6.4	6.4	6.4	7	7	*1*
Child	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Liver									
Infant	6.3	6.3	6.3	6.7	6.7	6.7	7.3	7.3	7.3
Child	2.8	2.8	2.8	2.8	2.8	2.8	2.9	2.9	2.9
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Kidney									
Infant	5.1	5.1	5.1	5.4	5.4	5.4	5.9	5.9	5.9
Child	2.4	2.4	2.4	2.5	2.5	2.5	2.6	2.6	2.6
Teenager	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3

Table B-7 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the U-238 Decay Series Isotopes (Cont'd.)

| | Size/Class | | | | | | | | |
| | 0.3 µm | | | 1.0 µm | | | 5.0 µm | | |
Isotope/Age Group	D	W	Y	D	W	Y	D	W	Y
Po-210									
Effective									
Infant	13	14	14	13	15	15	15	18	18
Child	3.3	3.5	3.5	3.3	3.5	3.5	3.4	3.7	3.7
Teenager	1.4	1.6	1.6	1.4	1.6	1.6	1.5	1.7	1.7
Bone									
Infant	24	33	33	25	36	36	26	40	40
Child	3.4	3.8	3.8	3.5	3.9	3.9	3.5	4	4
Teenager	2.1	2.4	2.4	2.1	2.5	2.5	2.2	2.7	2.7
Lung									
Infant	11	12	12	11	12	12	9.9	12	12
Child	3.4	3.4	3.4	3.3	3.4	3.4	3.3	3.4	3.4
Teenager	1.3	1.5	1.5	1.3	1.5	1.5	1.2	1.5	1.5
Liver									
Infant	9.1	12	12	9.5	14	14	10	15	15
Child	3	3.2	3.2	3	3.3	3.3	3	3.4	3.4
Teenager	1.3	1.5	1.5	1.3	1.5	1.5	1.3	1.6	1.6
Kidney									
Infant	7.9	11	11	8.2	12	12	8.7	13	13
Child	2.6	2.8	2.8	2.6	2.9	2.9	2.7	3	3
Teenager	1.2	1.5	1.5	1.3	1.5	1.5	1.3	1.6	1.6

Source: Tables IV-5 and IV-6 in Cristy et al. (1986)

Table B-8 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the Th-232 Decay Series Isotopes

Isotope/Age Group	0.3 µm			1.0 µm			5.0 µm		
	D	W	Y	D	W	Y	D	W	Y
Th-232									
Effective									
Infant	2.0	2.0	2.3	1.9	1.9	2.3	1.9	1.9	2.3
Child	1.3	1.3	1.5	1.2	1.2	1.5	1.2	1.2	1.4
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Bone									
Infant	0.9	0.9	1.0	0.9	0.9	1.0	0.9	0.9	1.1
Child	0.9	0.9	1.0	0.9	0.9	1.0	0.9	0.9	0.9
Teenager	1.2	1.2	1.0	1.2	1.2	1.0	1.2	1.2	1.1
Lung									
Infant	11.0	11.0	2.6	10.0	10.0	2.6	8.2	8.2	2.6
Child	3.2	3.2	1.6	3.1	3.1	1.6	2.7	2.7	1.6
Teenager	1.5	1.5	1.1	1.4	1.4	1.1	1.3	1.3	1.1
Liver									
Infant	4.2	4.2	2.6	4.3	4.3	2.8	4.4	4.4	3.8
Child	2.3	2.3	1.7	2.4	2.4	1.7	2.4	2.4	1.9
Teenager	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Kidney									
Infant	3.7	3.7	2.3	3.7	3.7	2.5	3.8	3.8	3.3
Child	2.2	2.2	1.6	2.2	2.2	1.6	2.2	2.2	1.8
Teenager	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Ra-228									
Effective									
Infant	5.4	5.4	5.4	5.2	5.2	5.2	4.5	4.5	4.5
Child	2.1	2.1	2.1	2.0	2.0	2.0	1.8	1.8	1.8
Teenager	1.3	1.3	1.3	1.3	1.3	1.3	1.5	1.5	1.5
Bone									
Infant	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Child	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Teenager	2.4	2.4	2.4	2.6	2.6	2.6	2.6	2.6	2.6
Lung									
Infant	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Child	3.3	3.3	3.3	3.3	3.3	3.3	3.2	3.2	3.2
Teenager	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Liver									
Infant	3.6	3.6	3.6	4.0	4.0	4.0	5.0	5.0	5.0
Child	1.8	1.8	1.8	1.9	1.9	1.9	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2
Kidney									
Infant	2.7	2.7	2.7	2.9	2.9	2.9	3.7	3.7	3.7
Child	1.5	1.5	1.5	1.6	1.6	1.6	1.8	1.8	1.8
Teenager	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2

Table B-8 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the Th-232 Decay Series Isotopes (Cont'd.)

Isotope/Age Group	0.3 µm			1.0 µm			5.0 µm		
	D	W	Y	D	W	Y	D	W	Y
Ac-228									
Effective									
Infant	5.4	5.4	5.4	5.2	5.2	5.2	4.5	4.5	4.5
Child	2.1	2.1	2.1	2.0	2.0	2.0	1.8	1.8	1.8
Teenager	1.3	1.3	1.3	1.3	1.3	1.3	1.5	1.5	1.5
Bone									
Infant	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Child	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Teenager	2.4	2.4	2.4	2.6	2.6	2.6	2.6	2.6	2.6
Lung									
Infant	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Child	3.3	3.3	3.3	3.3	3.3	3.3	3.2	3.2	3.2
Teenager	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Liver									
Infant	3.6	3.6	3.6	4.0	4.0	4.0	5.0	5.0	5.0
Child	1.8	1.8	1.8	1.9	1.9	1.9	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2
Kidney									
Infant	2.7	2.7	2.7	2.9	2.9	2.9	3.7	3.7	3.7
Child	1.5	1.5	1.5	1.6	1.6	1.6	1.8	1.8	1.8
Teenager	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2
Th-228									
Effective									
Infant	7.7	9.6	7.7	7.8	9.0	7.8	8.3	9.0	8.3
Child	3.0	3.0	3.0	3.0	2.9	3.0	3.0	2.8	3.0
Teenager	1.4	1.2	1.4	1.4	1.2	1.4	1.4	1.2	1.4
Bone									
Infant	5.5	7.2	5.5	6.5	7.4	6.5	9.3	7.6	9.3
Child	2.6	3.0	2.6	2.6	3.0	2.6	2.9	3.0	2.9
Teenager	1.2	1.4	1.2	1.3	1.4	1.3	1.4	1.4	1.4
Lung									
Infant	7.8	12.0	7.8	7.8	12.0	7.8	7.8	11.0	7.8
Child	3.1	3.3	3.1	3.1	3.3	3.1	3.1	3.2	3.1
Teenager	1.4	1.5	1.4	1.4	1.5	1.4	1.4	1.4	1.4
Liver									
Infant	4.0	4.9	4.0	4.7	5.0	4.7	6.5	5.2	6.5
Child	2.0	2.2	2.0	2.0	2.2	2.0	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kidney									
Infant	3.2	3.8	3.2	3.7	3.9	3.7	5.1	4.0	5.1
Child	1.7	1.9	1.7	1.7	1.9	1.7	1.8	1.9	1.8
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table B-8 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the Th-232 Decay Series Isotopes (Cont'd.)

Isotope/Age Group	Size/Class								
	0.3 µm			1.0 µm			5.0 µm		
	D	W	Y	D	W	Y	D	W	Y
Ra-224									
Effective									
Infant	7.7	9.6	7.7	7.8	9.0	7.8	8.3	9.0	8.3
Child	3.0	3.0	3.0	3.0	2.9	3.0	3.0	2.8	3.0
Teenager	1.4	1.2	1.4	1.4	1.2	1.4	1.4	1.2	1.4
Bone									
Infant	5.5	7.2	5.5	6.5	7.4	6.5	9.3	7.6	9.3
Child	2.6	3.0	2.6	2.6	3.0	2.6	2.9	3.0	2.9
Teenager	1.2	1.4	1.2	1.3	1.4	1.3	1.4	1.4	1.4
Lung									
Infant	7.8	12.0	7.8	7.8	12.0	7.8	7.8	11.0	7.8
Child	3.1	3.3	3.1	3.1	3.3	3.1	3.1	3.2	3.1
Teenager	1.4	1.5	1.4	1.4	1.5	1.4	1.4	1.4	1.4
Liver									
Infant	4.0	4.9	4.0	4.7	5.0	4.7	6.5	5.2	6.5
Child	2.0	2.2	2.0	2.0	2.2	2.0	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kidney									
Infant	3.2	3.8	3.2	3.7	3.9	3.7	5.1	4.0	5.1
Child	1.7	1.9	1.7	1.7	1.9	1.7	1.8	1.9	1.8
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Pb-212									
Effective									
Infant	7.7	9.6	7.7	7.8	9.0	7.8	8.3	9.0	8.3
Child	3.0	3.0	3.0	3.0	2.9	3.0	3.0	2.8	3.0
Teenager	1.4	1.2	1.4	1.4	1.2	1.4	1.4	1.2	1.4
Bone									
Infant	5.5	7.2	5.5	6.5	7.4	6.5	9.3	7.6	9.3
Child	2.6	3.0	2.6	2.6	3.0	2.6	2.9	3.0	2.9
Teenager	1.2	1.4	1.2	1.3	1.4	1.3	1.4	1.4	1.4
Lung									
Infant	7.8	12.0	7.8	7.8	12.0	7.8	7.8	11.0	7.8
Child	3.1	3.3	3.1	3.1	3.3	3.1	3.1	3.2	3.1
Teenager	1.4	1.5	1.4	1.4	1.5	1.4	1.4	1.4	1.4
Liver									
Infant	4.0	4.9	4.0	4.7	5.0	4.7	6.5	5.2	6.5
Child	2.0	2.2	2.0	2.0	2.2	2.0	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kidney									
Infant	3.2	3.8	3.2	3.7	3.9	3.7	5.1	4.0	5.1
Child	1.7	1.9	1.7	1.7	1.9	1.7	1.8	1.9	1.8
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table B-8 Relative Age-Specific Dose Factors (Normalized to an Adult) from Inhalation for the Th-232 Decay Series Isotopes (Cont'd.)

Isotope/Age Group	Size/Class								
	0.3 µm			1.0 µm			5.0 µm		
	D	W	Y	D	W	Y	D	W	Y

<div align="center">Bi-212</div>

	D	W	Y	D	W	Y	D	W	Y
Effective									
Infant	7.7	9.6	7.7	7.8	9.0	7.8	8.3	9.0	8.3
Child	3.0	3.0	3.0	3.0	2.9	3.0	3.0	2.8	3.0
Teenager	1.4	1.2	1.4	1.4	1.2	1.4	1.4	1.2	1.4
Bone									
Infant	5.5	7.2	5.5	6.5	7.4	6.5	9.3	7.6	9.3
Child	2.6	3.0	2.6	2.6	3.0	2.6	2.9	3.0	2.9
Teenager	1.2	1.4	1.2	1.3	1.4	1.3	1.4	1.4	1.4
Lung									
Infant	7.8	12.0	7.8	7.8	12.0	7.8	7.8	11.0	7.8
Child	3.1	3.3	3.1	3.1	3.3	3.1	3.1	3.2	3.1
Teenager	1.4	1.5	1.4	1.4	1.5	1.4	1.4	1.4	1.4
Liver									
Infant	4.0	4.9	4.0	4.7	5.0	4.7	6.5	5.2	6.5
Child	2.0	2.2	2.0	2.0	2.2	2.0	2.2	2.2	2.2
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kidney									
Infant	3.2	3.8	3.2	3.7	3.9	3.7	5.1	4.0	5.1
Child	1.7	1.9	1.7	1.7	1.9	1.7	1.8	1.9	1.8
Teenager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Source: Tables IV-5 and IV-6 in Cristy et al. (1986)

B.2.2 Ingestion Dose Coefficients

Table B-9 Ingestion Dose Coefficients (mrem/pCi) for the U-238 Decay Series Isotopes

Age Group	Tissue	U-238	U-234	Th-234	Th-230	Ra-226	Pb-210	Bi-210	Po-210
Infant	Effective	1.61E-02	1.79E-02	8.57E-04	2.51E-02	2.11E-02	3.11E-02	3.88E-05	7.95E-02
Infant	Bone	4.49E-02	5.43E-02	9.24E-07	4.39E-02	1.09E-01	1.86E-01	6.00E-07	3.29E-02
Infant	Liver	2.72E-04	3.15E-04	4.93E-07	3.74E-03	8.48E-03	3.62E-01	7.52E-06	4.48E-02
Infant	Kidney	4.93E-02	5.71E-02	4.38E-07	3.53E-04	3.32E-03	1.35E-01	2.86E-04	2.23E-01
Infant	Lung	2.89E-04	3.34E-04	8.87E-08	3.02E-04	3.73E-03	6.94E-03	1.09E-06	7.61E-03
Child	Effective	9.95E-04	1.14E-03	5.30E-05	1.53E-03	2.38E-03	8.67E-03	1.08E-05	9.12E-03
Child	Bone	4.86E-03	5.43E-03	1.00E-07	3.32E-03	2.50E-02	7.86E-02	2.53E-07	2.07E-03
Child	Liver	3.74E-05	4.20E-05	6.78E-08	1.45E-04	1.32E-03	8.81E-03	1.83E-06	6.88E-03
Child	Kidney	6.01E-03	6.75E-03	5.34E-08	1.54E-05	6.44E-04	3.54E-03	7.48E-05	3.44E-02
Child	Lung	4.08E-05	4.58E-05	1.25E-08	1.18E-05	9.15E-04	1.76E-03	2.77E-07	1.40E-03
Teenager	Effective	7.90E-04	8.80E-04	4.22E-05	1.20E-03	4.22E-03	1.12E-02	1.40E-05	4.85E-03
Teenager	Bone	1.83E-02	2.05E-02	3.77E-07	3.32E-03	1.09E-01	2.35E-01	7.57E-07	1.65E-03
Teenager	Liver	2.13E-05	2.39E-05	3.85E-08	5.94E-05	8.14E-04	4.75E-02	9.87E-07	3.68E-03
Teenager	Kidney	3.85E-03	4.33E-03	3.43E-08	6.80E-06	1.02E-03	2.18E-02	4.62E-05	2.04E-02
Teenager	Lung	2.04E-05	2.29E-05	6.26E-09	5.79E-06	1.02E-03	9.71E-04	1.53E-07	5.79E-04
Adult	Effective	2.55E-04	2.84E-04	1.36E-05	5.46E-04	1.32E-03	5.10E-03	6.36E-06	1.94E-03
Adult	Bone	3.74E-03	4.18E-03	7.70E-08	1.33E-03	2.53E-02	8.10E-02	2.61E-07	4.22E-04
Adult	Liver	8.51E-06	9.55E-06	1.54E-08	2.20E-05	3.39E-04	2.26E-02	4.70E-07	1.60E-03
Adult	Kidney	1.54E-03	1.73E-03	1.37E-08	2.52E-06	3.39E-04	1.04E-02	2.20E-05	9.29E-03
Adult	Lung	8.51E-06	9.55E-06	2.61E-09	2.52E-06	3.39E-04	4.63E-04	7.29E-08	3.05E-04

Source: Values for adults are from EPA (1988). Values for other age groups calculated by multiplying adult values by age-specific factors from Cristy et al. (1986).

Table B-10 Relative Age-Specific Dose Factors (Normalized to an Adult) from Ingestion for the U-238 Decay Series Isotopes

Isotope and Age Group	Dose Factor				
	Effective	Bone	Liver	Kidney	Lung
U-238					
Infant	63	12	32	32	34
Child	3.9	1.3	4.4	3.9	4.8
Teenager	3.1	4.9	2.5	2.5	2.4
U-234					
Infant	63	13	33	33	35
Child	4	1.3	4.4	3.9	4.8
Teenager	3.1	4.9	2.5	2.5	2.4
Th-234					
Infant	63	12	32	32	34
Child	3.9	1.3	4.4	3.9	4.8
Teenager	3.1	4.9	2.5	2.5	2.4
Th-230					
Infant	46	33	170	140	120
Child	2.8	2.5	6.6	6.1	4.7
Teenager	2.2	2.5	2.7	2.7	2.3
Ra-226					
Infant	16	4.3	25	9.8	11
Child	1.8	0.99	3.9	1.9	2.7
Teenager	3.2	4.3	2.4	3	3
Pb-210					
Infant	6.1	2.3	16	13	15
Child	1.7	0.97	3.9	3.4	3.8
Teenager	2.2	2.9	2.1	2.1	2.1
Bi-210					
Infant	6.1	2.3	16	13	15
Child	1.7	0.97	3.9	3.4	3.8
Teenager	2.2	2.9	2.1	2.1	2.1
Po-210					
Infant	41	78	28	24	25
Child	4.7	4.9	4.3	3.7	4.6
Teenager	2.5	3.9	2.3	2.2	1.9

Source: Table IV-4 in Cristy et al. (1986)

Table B-11 Ingestion Dose Coefficients (mrem/pCi) for the Th-232 Decay Series Isotopes

Age Group	Tissue	Th-232	Ra-228	Ac-228	Th-228	Ra-224	Pb-212	Bi-212
Infant	Effective	1.37E-01	2.74E-02	4.10E-05	9.11E-02	8.42E-02	1.05E-02	2.44E-04
Infant	Bone	1.64E+00	1.20E-01	6.22E-05	2.02E+00	1.35E+00	1.41E-01	7.77E-06
Infant	Liver	4.90E-03	1.10E-02	5.76E-05	9.66E-03	9.91E-03	1.06E-02	6.54E-06
Infant	Kidney	5.08E-04	8.72E-03	2.15E-06	8.62E-04	7.62E-03	4.03E-03	4.10E-04
Infant	Lung	1.04E-07	1.88E-06	8.81E-11	1.87E-07	1.66E-06	1.32E-07	7.99E-10
Child	Effective	8.46E-03	5.90E-03	8.86E-06	2.53E-03	2.34E-03	2.91E-04	6.78E-06
Child	Bone	1.50E-01	4.09E-02	2.11E-05	6.49E-02	4.35E-02	4.54E-03	2.50E-07
Child	Liver	2.22E-04	2.85E-03	1.48E-05	3.94E-04	4.04E-04	4.33E-04	2.67E-07
Child	Kidney	2.54E-05	2.50E-03	6.15E-07	3.79E-05	3.35E-04	1.77E-04	1.80E-05
Child	Lung	5.63E-09	6.12E-07	2.86E-11	9.93E-09	8.82E-08	7.01E-09	4.24E-11
Teenager	Effective	6.55E-03	3.46E-03	5.18E-06	1.03E-03	9.52E-04	1.18E-04	2.76E-06
Teenager	Bone	2.12E-01	8.60E-02	4.44E-05	3.16E-02	2.12E-02	2.21E-03	1.22E-07
Teenager	Liver	1.06E-04	1.28E-03	6.67E-06	1.86E-04	1.91E-04	2.04E-04	1.26E-07
Teenager	Kidney	1.29E-05	1.22E-03	3.00E-07	2.07E-05	1.83E-04	9.67E-05	9.84E-06
Teenager	Lung	3.25E-09	2.98E-07	1.39E-11	4.39E-09	3.90E-08	3.10E-09	1.87E-11
Adult	Effective	2.73E-03	1.44E-03	2.16E-06	3.96E-04	3.66E-04	4.55E-05	1.06E-06
Adult	Bone	6.84E-02	2.15E-02	1.11E-05	8.77E-03	5.88E-03	6.14E-04	3.38E-08
Adult	Liver	3.77E-05	5.81E-04	3.03E-06	7.43E-05	7.62E-05	8.17E-05	5.03E-08
Adult	Kidney	4.62E-06	5.81E-04	1.43E-07	8.62E-06	7.62E-05	4.03E-05	4.10E-06
Adult	Lung	1.25E-09	1.57E-07	7.34E-12	2.31E-09	2.05E-08	1.63E-09	9.86E-12

Source: Values for adults are from EPA (1988). Values for other age groups calculated by multiplying adult values by age-specific factors from Cristy et al. (1986).

**Table B-12 Relative Age-Specific Dose Factors (Normalized to an Adult)
from Ingestion for the Th-232 Decay Series Isotopes**

Isotope and Age Group	Dose Factor				
	Effective	Bone	Liver	Kidney	Lung
Th-232					
Infant	50	24	130	110	83
Child	3.1	2.2	5.9	5.5	4.5
Teenager	2.4	3.1	2.8	2.8	2.6
Ra-228					
Infant	19	5.6	19	15	12
Child	4.1	1.9	4.9	4.3	3.9
Teenager	2.4	4.0	2.2	2.1	1.9
Ac-228					
Infant	19	5.6	19	15	12
Child	4.1	1.9	4.9	4.3	3.9
Teenager	2.4	4.0	2.2	2.1	1.9
Th-228					
Infant	230	230	130	100	81
Child	6.4	7.4	5.3	4.4	4.3
Teenager	2.6	3.6	2.5	2.4	1.9
Ra-224					
Infant	230	230	130	100	81
Child	6.4	7.4	5.3	4.4	4.3
Teenager	2.6	3.6	2.5	2.4	1.9
Pb-212					
Infant	230	230	130	100	81
Child	6.4	7.4	5.3	4.4	4.3
Teenager	2.6	3.6	2.5	2.4	1.9
Bi-212					
Infant	230	230	130	100	81
Child	6.4	7.4	5.3	4.4	4.3
Teenager	2.6	3.6	2.5	2.4	1.9

Source: Table IV-4 in Cristy et al. (1986)

B.3   References

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APPENDIX C   METEOROLOGICAL DATA PREPROCESSOR

This appendix presents information on the STability ARray (STAR) format expected by MILDOS4 for meteorological data input and its data preprocessor available to generate STAR input data files.

C.1   Introduction

Most meteorological data available in STAR format for use in a program such as MILDOS4 were developed decades ago. However, average storm tracks (defined as the path followed by a center of low atmospheric pressure) have shifted northward over the last several decades, as evidenced by a decrease in the frequency of storms in mid-latitude areas of the Northern Hemisphere, while high-latitude activity has increased. Meteorological patterns in many areas of the United States have been altered due to the northward migration of storm tracks associated with climatic changes. Thus, meteorological patterns for a site of interest several decades ago could be somewhat different from those of today.

In addition, discrepancies exist between old and recent meteorological data with regard to a number of factors (e.g., wind measurement height, wind sampling duration, instrumentation, land use around the monitoring station). For example, today's instruments are more advanced, and new measurement protocols are in place. Now the height of the meteorological tower has been standardized at 10 m (33 ft); compare this to heights ranging from a few meters to a few tens of meters for old meteorological towers. Due to differences in wind measurement heights, direct comparisons between two sites with different wind measurement heights could be problematic, with the result that the modeling of impacts would be inconsistent among sites.

A meteorological data preprocessor was developed to construct a three-way joint frequency distribution of wind speed, wind direction, and Pasquill stability class (STAR summary table) for direct input into MILDOS4. The preprocessor accepts not only data files in older formats but also meteorological data collected recently. The STAR data are directly incorporated into the user file and written to the STARout.STR file in the application directory at the time of generation. The input preprocessor's input form (as shown in Figure C-1) is accessed by pressing the "Import JFD" button under the main program "Met Data" tab (see Figure 6-10).

C.2   STability ARray (STAR) Format

The STAR format summarizes meteorological conditions as a joint frequency distribution. The frequency distribution considers atmospheric Pasquill stability class, wind direction, and wind speed. It involves six stability classes, 16 wind direction sectors (with the first 22.5-degree sector centered on winds from the north – increasing clockwise), and six wind speed classes. The wind speed classes are 1–3, 4–6, 7–10, 11–16, 17–21 and >21 knots. The Pasquill stability categories are grouped into classes as shown in Table C-1.

The STAR file is a plain text (or ASCII) file that can be viewed with any common text editor or viewing program (e.g., MS-WORD). The STAR file shows the frequencies of occurrence for wind that is blowing from a particular wind direction, at a particular stability, and at a particular wind speed. In old STAR files, the numerical format of the frequencies was "x.xxxxx" (e.g., "0.00012") with no space between entries, but this STAR preprocessor includes one space between entries (e.g., " .00012") for improved readability. The summation over all

stability, wind direction, and wind speed categories should equal one. Table C-2 summarizes the format for each line in the STAR file.

Figure C-1 Input Form for Meteorological Preprocessor

Table C-1 Pasquill Stability Categories[a]

Pasquill Stability Category		Stability Classification
1	A	Extremely unstable
2	B	Moderately unstable
3	C	Slightly unstable
4	D	Neutral
5	E	Slightly stable
6	F	Moderately stable

[a] The U.S. Nuclear Regulatory Commission (NRC) delta-T method defines "G" (extremely stable) stability class (NRC, 2007). However, Pasquill originally did not classify nights with winds blowing at less than 2 m/s, referred to as G stability, because for this condition, the surface-level plume is unlikely to have any definable travel (Turner and Schulze, 2007). For U.S. Environmental Protection Agency (EPA) regulatory modeling applications, Pasquill stability categories F and G are combined and considered F stability.

Table C-2 STAR File Format

Column	Value
1	Blank
2-4	Wind direction (N, NNE, NE, ENE, E, etc.)
5	Blank
6	Stability category (A, B, C, D, E, or F)
7	Blank
8–14	Wind speeds of 1–3 knots[a]
15–21	Wind speeds of 4–6 knots
22–28	Wind speeds of 7–10 knots
29–35	Wind speeds of 11–16 knots
36–42	Wind speeds of 17–21 knots
43–49	Wind speeds of >21 knots

[a] For each stability class, calms are distributed among the directions within the first wind speed class (1–3 knots) in proportion to the sum of the frequencies of winds on the first two classes for each direction (EPA, 1997).

C.3   Method to Generate Pasquill Stability Class and Meteorological Input Data

There are many meterological stations around the world where routine meterological data observations have been made (e.g., airports or military installations). Typically, these data have passed through quality assurance/quality control (QA/QC) procedures, are comprehensive, and are characterized by long-term historic data. However, many project sites of interest (e.g., research laboratories, experimental facilities, waste management facilities) and major emission source facilities (e.g., coal-fired power plants) might be far away from airports and located in complex terrains or near large water bodies, for which nearby airport data are not

representative of meteorological patterns around the sites. In these cases, a site collects onsite data representative of the meteorological patterns around it. In consideration of these situations, the preprocessor was expanded to accommodate all site-specific data to determine the stability classes.

Atmospheric stability classes are not measured and are thus estimated based on other routinely collected meteorological parameters. There are four primary methods to determine Pasquill stability class, which are briefly outlined in Table C-3 (EPA, 2000): Turner; solar radiation/delta-T (SRDT); σ_E; and σ_A. Two other methods (NRC and AERMET surface file [SFC]) are added and are briefly described below. Please refer to the references in each section for details.

The preprocessor accepts the following meteorological data to construct STAR files:

- Integrated surface hourly (ISH) data;

- Preprocessed AERMET surface file (SFC);

- Vertical temperature difference (delta-T or ΔT) data from NRC-administered facilities (NRC);

- Solar radiation (day) and delta-T (night) data (SRDT);

- Standard deviation of wind elevation angle (σ_E); and

- Standard deviation of wind azimuth angle (σ_A).

The ISH and SFC data are in a standard format. However, the last four (NRC, SRDT, σ_E, and σ_A) data formats may vary from site to site (i.e., be in a nonstandard format). To use the data in nonstandard formats in the STAR preprocessor, the user should rearrange the orginal data into the format required by the preprocessor, which is discussed in Section C.3.7.

The SRDT method uses different meteorological parameters for day and night. Some sites use different combinations of parameters for day and night (e.g., solar radiation data during daytime hours and σ_E or σ_A data during nighttime hours) to determine Pasquill stability class. The STAR preprocessor is designed to accept a variety of site-specific data and any combination of meteorological parameters for day and night.

Five years of representative meteorological data should be used when concentrations are estimated by using an air quality model. The use of consecutive years from the most recent, readily available five-year period are preferred (40 CFR Part 51, Appendix W). In addition, the data recovery rate for use in regulatory dispersion modeling applications should be more than 90 percent complete (EPA, 2000) not only for each individual year but also for all years combined. This STAR preprocessor displays data recovery rates for both each individual year and all years combined at the completion of STAR file generation and saves this information in the STARout.SUM file. This file is saved in the application directory and also displayed at the successful completion of data importation and conversion (Figure C-2). If the data recovery rates do not meet the 90 percent requirement, those data should be replaced with those for other years for which data recovery rates are over 90 percent. The data recovery rate may be lower than but close to 90 percent for some data. These data can be accepted at the user's discretion in cases for which no other options are available.

Table C-3 Methods to Determine Pasquill Stability Class and Their Input Data

Method	Description	Input Data[a]	Notes
Turner's method	Solar insolation (daytime only), cloud cover, ceiling height (daytime only), and wind speed	Integrated surface hourly (ISH) data	Applicable to most data collected at airports and military installations; data are reported in UTC (universal time coordinated), so time conversion to local time is needed
SFC method	Conversion of Monin-Obukhov length to Pasquill stability class	AERMET surface file (*.SFC) input to AERMOD	
NRC (Delta-T) method	Vertical temperature difference	Site-specific delta-T data	Data collected at facilities administered by NRC (e.g., nuclear power plants)
SRDT method	Solar radiation during daytime and vertical temperture gradient during nighttime, and wind speed	Site-specific solar radiation/delta-T data	
σ_E method	Standard deviation of wind elevation angle (σ_E); and wind speed	Site-specific σ_E data, surface roughness length, wind measurement height	Also known as σ_ϕ, sigma-E, and sigma-phi method
σ_A method	Standard deviation of wind azimuth angle (σ_A); and wind speed	Site-specific σ_A data, surface roughness length, wind measurement height	Also known as σ_θ, sigma-A, and sigma-theta method

[a] All methods except the NRC and the SFC methods assume wind speed data are at or near the 10-m (33-ft) level. The σ_E and σ_A methods are developed based on a default surface roughness length of 0.15 m and a default wind measurement height of 10 m (33 ft), but they accept the roughness length and/or wind measurement height at values other than the default.

Note these facts:

- The preprocessor is designed to accept all types of data collected both in the United States and in other countries.

- The preprocessor expects meteorological data to be in metric units (e.g., m/s, °C).

- The preprocessor expects wind speeds at the 10-m (33-ft) level, except for the SFC and NRC methods, which do not use wind speed explicitly. The σ_E and σ_A methods accept surface roughness lengths other than a default value of 0.15 m and/or wind measurement heights other than a default value of 10 m.

```
MILDOS    STAR File Generation Summary

      USER INPUT FILE: MILDOS GUI
           DATA FORMAT: ISH
      ALGORITHM FOR PG:
                STN ID: 725300_usaf  94846_wban
  LATITUDE/LONGITUDE:    41.980  -87.930
  TIME DIFF FROM UTC:  6
  STATION NAME/STATE:
  SURF ROUGHNESS (M):  0.1500
   ANEMOMETER HT (M):   10.0
     STAR OUTPUT FILE: STARout.STR
  DEL INTERMED FILES: N
       RECORD OF YEARS:  5
  YEAR/MET DATA FILE: 2011  C:\mildos4\MetData\725300-94846-2011
                    : 2012  C:\mildos4\MetData\725300-94846-2012
                    : 2013  C:\mildos4\MetData\725300-94846-2013
                    : 2014  C:\mildos4\MetData\725300-94846-2014
                    : 2015  C:\mildos4\MetData\725300-94846-2015
  EXTRACTED MET DATA: STARout.OT1
   FILTERED MET DATA: STARout.OT2
  PROCESSED MET DATA: STARout.OT3
  STAR-FORMAT OUTPUT: STARout.STR
       SUMMARY OUTPUT: STARout.SUM
      DETAILED OUTPUT: STARout.DET


                         TOTAL   11    12    13    14    15
                         -----   --    --    --    --    --
  NO OF HRS POSSIBLE:   43824 8760 8784 8760 8760 8760
  NO OF HRS READ    :   43818 8760 8784 8760 8760 8754
  NO OF HRS MISSING :     914  113  104  218  227  252
  NO OF HRS  CALM/A :     184   35   35   29   52   33
  NO OF HRS  CALM/B :     227   42   35   58   45   47
  NO OF HRS  CALM/C :     174   42   26   44   28   34
  NO OF HRS  CALM/D :     347   90   76   53   61   67
  NO OF HRS  CALM/E :       0    0    0    0    0    0
  NO OF HRS  CALM/F :    1809  429  411  347  301  321
  NO OF HRS CALM/TOT:    2741  638  583  531  487  502
  NO OF HRS NON-CALM:   40163 8009 8097 8011 8046 8000
  NO OF HRS USED    :   42904 8647 8680 8542 8533 8502

  Data Recovery % of Hours Used (Non-calm + Calm)
  -----------------------------------------------
    TO HRS POSSIBLE :      98   99   99   98   97   97
    TO HRS READ     :      98   99   99   98   97   97

The STAR file has been successfully generated.  Press 'OK' to continue.    OK
```

Figure C-2 Summary of Meteorological Joint Frequency Distribution Data Conversion to STAR Format

- The preprocessor accepts individual hourly data entries by year or several years' data combined in a single file.

C.3.1 Integrated Surface Hourly (ISH) Data

Integrated surface hourly data, also known as ISH, ISD, ISHD, TD-3505, DS3505, or DSI-3505 data, are available from the National Centers for Environmental Information (NCEI; formerly the National Climatic Data Center [NCDC]) ftp site for meteorological stations around the world (NCEI, 2018). There are about 1,000 stations in the United States that collect ISH data. To calculate the Pasquill stability class, Turner's method using cloud data is used most often because the required data are routinely collected at most airports and military installations (EPA, 1997, 1999). The method estimates the effects of net radiation on stability from solar altitude (a function of time of day and time of year), total cloud cover, and ceiling height (Section 6.4.1 in EPA, 2000). Then the Pasquill stability class is determined based on the net radiation index and wind speed at the 10-m (33-ft) level.

The following are the steps required to process ISH data:

1. Find the station that is most representative of the site of interest from either the "ish-history.csv" file or "ish-history.txt" file at the NCEI ftp site (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/). In the same directory, a listing of the ISH data inventory by station-year-month can be found in either the "isd-inventory.csv" or "isd-inventory.txt" file.

2. Click the hyperlink for the year at the same ftp site and download the zipped ISH data file one year at a time to any subfolder on your computer. If possible, it is recommended that you use the most-recent consecutive five years of data. Typically, a data recovery requirement of 90 percent (EPA, 2000) is met for zipped files of more than 500 kilobytes (kB) but not met for those with less than 300 kB. Zipped files ranging from 300 to 500 kB may or may not meet the data recovery requirement.

3. Unzip the downloaded files by using Windows Explorer® or software such as WinZip®, and import the data using the STAR preprocessor.

4. If one or more years do not meet the data recovery requirement (data recovery rates are shown in the STARout.SUM file in the application directory after the preprocessor is executed), download earlier years and go to Step 3.

5. If all the data for the station do not meet the data recovery requirement, go back to Step 1 and find the next representative site.

C.3.2 AERMET Surface File (SFC)

AERMET is a meteorological preprocessor used to organize available meteorological data into a format suitable for use by AERMOD, an EPA regulatory model and one of the most widely used air dispersion models. It can process many different file formats, one of which is the ISH data format. The AERMET surface file with boundary-layer parameters uses the continuous Monin-Obukhov length (L)[1] rather than the discrete Pasquill stability class as an atmospheric stability parameter. This L is converted to a Pasquill stability class by using an algorithm from the scientific literature (Golder, 1972). The Golder algorithm (represented by a plot) establishes a relationship between the Pasquill stability class, the roughness length z_0,[2] and L. To simplify the calculation procedures, the Golder plot was approximated by the correlation from Seinfeld and Pandis (1998).

Preprocessed AERMET surface files (ending with SFC, such as SLC_12.SFC) are available on the Web sites of several state air quality agencies and private consulting firms to facilitate air quality impact assessments for criteria or toxic air pollutants. These data sets include most meteorological stations in a state (e.g., major airports, military installations, major emission-

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[1] Monin-Obukhov length (L) is a parameter for the ratio of the mechanical turbulent energy to that produced by buoyancy, which demarcates the height below which mechanically generated turbulence dominates in the mixing process.

[2] The roughness length is a length scale that characterizes the surface roughness characteristics of the terrain. The larger the roughness length, the greater the mechanical turbulence (and thus the atmospheric dispersion).

source facilities such as coal-fired power plants). For example, there are AERMET files at the Arizona Department of Environmental Quality AERMET Meteorological Sites (https://www.azdeq.gov/environ/air/permits/meteorologicaldata.html).

For data with high calm frequencies, the STAR summaries generated from ISH and SFC data (generated from the same ISH data) are somewhat different, because AERMET sets the Monin-Obukhov length to "missing" for calm hours. For data with a calm frequency of <10 percent, the STAR summaries are similar. For data with higher calm frequencies, it is recommended to process the original ISH data, if possible.

C.3.3   Delta-T Data (NRC)

The NRC prefers the vertical temperature difference (delta-T or ΔT) method for determining the Pasquill stability class at nuclear power plants for licensing purposes (Table 1 in NRC, 2007). This delta-T method is referred to as the "NRC method" hereinafter to avoid confusion with delta-T in the SRDT method, as discussed in Section C.3.4. Typically, the vertical temperature difference is measured on the same open-lattice tower or mast on which wind speed and wind direction between the 10-m (33-ft) level and 60-m (197-ft) or higher levels are measured. It is defined as the upper-level temperature measurement minus the lower-level temperature measurement (in units of °C/100 m). The Pasquill stability class is determined from the table given as a function of ΔT. This method does not use wind speed explicitly, which is different from what other methods do.

Site-specific data need to be rearranged into the format expected by the STAR preprocessor (see Section C.3.7).

C.3.4   Solar Radiation/Delta-T Data (SRDT)

The solar radiation/delta-T (SRDT) method retains the basic structure and rationale of Turner's method while obviating the need for observations of cloud cover and ceiling height (Section 6.4.2 in EPA, 2000). The method uses the surface-layer wind speed (measured at or near 10 m) in combination with measurements of total solar radiation in W/m^2 during the day and a low-level (2–10 m) vertical temperature difference (ΔT) in °C/m at night. The original method was developed based on 2–10 m ΔT; however, using 10–50 m ΔT produced virtually the same distribution of stability categories (EPA, 1993). As a result, any ΔT data can be used, regardless of measurement height interval. Along with a 10-m wind speed, the Pasquill stability class is determined based on solar radiation during the day and ΔT at night.

The difference between NRC's ΔT method and this ΔT method is that the former determines the Pasquill stability class by ΔT only (given as a function of ΔT), while the latter determines the Pasquill stability class by both ΔT (classified as either positive or negative) and a 10-m wind speed.

Site-specific data need to be rearranged into the format expected by the STAR preprocessor (see Section C.3.7).

C.3.5   Standard Deviation of Wind Elevation Angle (σ_E) Data

The σ_E method is a turbulence-based method that uses the standard deviation of the elevation angle of the wind (σ_E) in combination with the 10-m wind speed (Section 6.4.3 in EPA, 2000).

The algorithm was formulated for data collected at a surface roughness length of 0.15 m and a wind measurement height of 10 m. This method consists of two steps to calculate the Pasquill stability class. The initial estimate of the Pasquill stability class is made based on σ_E data. In the next step, the final estimate of the Pasquill stability class is determined based on the initial estimate of the Pasquill stability class and 10-m wind speed, according to whether it is daytime or nighttime.

The method can handle cases other than those in which the surface roughness length (z_o) is 0.15 m and/or measuement height is 10 m by adjusting category boundaries. It is likely to be a useful adjustment for cases in which z_o is greater than 0.15 m but a problematical one for cases in which z_o is less than 0.15 m.

Site-specific data need to be rearranged into the format expected by the STAR preprocessor (see Section C.3.7).

C.3.6 Standard Deviation of Wind Azimuth Angle (σ_A) Data

The σ_A method is a turbulence-based method that uses the standard deviation of the azimuth angle of the wind (σ_A) in combination with the 10-m wind speed (Section 6.4.4 in EPA, 2000). The algorithm was formulated for data collected at a surface roughness length of 0.15 m and a wind measurement height of 10 m. Like the σ_E method, this method consists of two steps to calculate the Pasquill stability class. The initial estimate of the Pasquill stability class is made based on σ_A data. In the next step, the final estimate of the Pasquill stability class is determined based on the initial estimate of the Pasquill stability class and the 10-m wind speed, according to whether it is daytime and nighttime.

The method can handle cases other than those in which the surface roughness length (z_o) is 0.15 m and/or measurement height is 10 m by adjusting category boundaries. It is likely to be a useful adjustment for cases in which z_o is greater than 0.15 m but a problematical one for cases in which z_o is less than 0.15 m.

Site-specific data need to be rearranged into the format expected by the STAR preprocessor (see Section C.3.7).

C.3.7 Site-Specific Data and User Input Runstream

This program can process three types of input data: ISH, SFC, and site-specific (SSP) data. ISH and SFC data collected at airports or military installations have standardized formats, which can be directly input to the preprocessor. SSP data collected at non-airport sites (such as research laboratories, experimental facilities, waste management facilities, and major emission source facilities like coal-fired power plants) are not in a standardized format; that is, they vary from site to site. Accordingly, SSP data, with a nonstandard format, should be written by using the input format expected by the preprocessor (see Table C-4). A sample list of abbreviated hourly input SSP data for solar radiation (daytime) and σ_A (nighttime) is shown in Table C-5. Missing data fields should be filled with a missing indicator (e.g., 999 or –999) or left blank, as indicated in the third and fourth lines in Table C-5.

Table C-4 Site-Specific Input Data Format

Column	Parameter	Example
1–5	Year	2008
6–10	Month[a]	1
11–15	Day[a]	1
16–20	Hour	8
21–30	Wind direction (0°–360°)	285.2
31–40	Wind speed (m/s)	4.4
41–50	Temperature (°C), optional	–6.8
51–60	Data for Pasquill stability class (daytime)[b]	6.2
61–70	Data for Pasquill stability class (nighttime)[b]	13.4

[a] If Julian date is used rather than month and day, make "Month" field (columns 6–10) blank spaces and place Julian date in "Day" field (columns 11–15).

[b] If one set of data needed to determine the Pasquill stability class is used for both daytime and nighttime, no data in column 61–70 are needed.

Table C-5 Sample Site-Specific Input Data, with Solar Radiation for Daytime and σ_A for Nighttime

Year	Month	Day	Hour	Wind Direction (0°–360°)	Wind Speed (m/s)	Temperature (°C), optional	Data for Pasquill Stability Class (daytime)	Data for Pasquill Stability Class (nighttime)
2008	1	1	1	295.7	6.1	-3.9	0	13.0
2008	1	1	2	292.0	5.8	-4.8	0	13.0
2008	1	1	3	999.	999.	999.	999.	999.
2008	1	1	4					
2008	1	1	5	288.4	4.5	-5.6	0	12.5
2008	1	1	6	286.4	4.9	-6.1	0	13.3
2008	1	1	7	290.1	5.1	-6.7	0	12.6
2008	1	1	8	285.2	4.4	-6.8	6.2	13.4[a]
2008	1	1	9	282.2	4.5	-6.9	37.5	12.2
2008	1	1	10	273.7	5.4	-6.7	129.0	12.9

[a] Data in yellow-highlighted row are used as an example in Table C-4.

In addition to hourly meteorological data, the user should specify the input options to run the STAR preprocessor, as seen in Table C-6. These input options appear on the input preprocessor's input form (as shown in Figure C-1), which is accessed by pressing the "Import JFD" button under the main program "Met Data" tab (see Figure 6-10).

Table C-6 User-Input Parameters

	Data Format[a]						
			Site-Specific Data				
Input Parameter	**ISH**	**SFC**	**NRC**	**SR**	**ΔT**	**σE**	**σA**
Data for determining Pasquill stability class	–	–	R	R	R	R	R
USAF/WABN ID (for ISH/SFC)	R	R[b]	–	–	–	–	–
Latitude/longitude	R	R	–	R	R	R	R
Time zone difference from UTC[d] (e.g., NY = 5, LA = 8)	R	R	–	R	R	R	R
Surface roughness (m, default at 0.15 m)	–	–	–	–	–	R[e]	R[e]
Wind measurement height (m; default at 10 m)	–	–	–	–	–	R[f]	R[f]
Number of hourly input files (maximum 10)	R	R	R	R	R	R	R
Year and data file name (one line per year)[g]	R	R	R	R	R	R	R

[a] R = Required; – = Not Applicable.
[b] Only the WBAN ID is needed.
[c] The latitude and longitude are specified in decimal degrees. For latitude, "+" denotes north and "–" denotes south. For longitude, "+" denotes east and "–" denotes west. For example, (41.979–87.905) should be input for O'Hare International Airport, Illinois.
[d] Greater than or equal to 0.
[e] Uses a default value of 0.15 m, if not provided by the user.
[f] Uses a default value of 10 m, if not provided by the user.
[g] Enter the first year only if data for several years are combined into one file.

C.4   References

40 CFR Part 51, Appendix W, *Code of Federal Regulations,* Appendix W to Part 51, "Guideline on Air Quality Models," in Title 40, "Protection of Environment."

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APPENDIX D   RESUSPENSION MODEL

This appendix presents the derivation of the equations used in MILDOS4 to estimate the initial radionuclide ground concentrations resulting from the downwind air deposition of the source terms considered by the program and the subsequent resuspended air concentrations at receptor locations.

D.1   Radionuclide Ground Concentrations

The ground concentration of radionuclide i is given by its deposition rate at a given location multiplied by the amount of time considered. The deposition rate of the radionuclide is the product of the sector-averaged air concentration of the radionuclide, $\overline{C_{sec}}(i,x)$ [see Equations 3.26 and 3.28 in Section 3], and the deposition velocity, V_{d_p}, for the associated particulate size. In addition, this product is multiplied by an exponential decay term to account for radioactive decay and environmental losses. Thus, the ground concentration of radionuclide i after a period of time t_1 at a constant deposition rate can be represented by

$$C_g(i,x,t) = \int_0^{t_1} \overline{C_{sec}}(i,x,t_{s_j}) V_{d_p} \exp\left[-(\lambda_i + \lambda_e)t\right] dt \; , \tag{D.1}$$

where

$\quad C_g(i,x,t)$ = ground concentration of radionuclide i after time t (Ci/m^2),

$\quad\quad V_{d_p}$ = deposition velocity for particle size p (m/s),

$\quad \overline{C_{sec}}(i,x,t_{s_j})$ = sector-averaged air concentration of radionuclide i at a distance x (in meters) from the source during time step j (Ci/m^3) [Equation 3.26 or 3.28 or a combination of the two],

$\quad\quad \lambda_i$ = radioactive decay constant for radionuclide i (1/s), and

$\quad\quad \lambda_e$ = decay constant to account for environmental loss from the soil (1/s).

The environmental soil loss decay constant, λ_e, accounts for weathering processes, such as downward soil migration, chemical binding to soil, and wind and water erosion. This constant applies to all radionuclides considered to be deposited on the ground. Equation D.1 applies in the case where no previous deposition of radionuclide i on the surface has occurred.

The evaluation of the integral in Equation D.1 leads to

$$C_g(i,x,t) = \overline{C_{sec}}(i,x,t_{s_j}) V_{d_p} \left. \frac{-\exp\left[-(\lambda_i + \lambda_e)t\right]}{\lambda_i + \lambda_e} \right|_0^{t_1} =$$

$$\overline{C_{sec}}(i,x,t_{s_j}) V_{d_p} \left(\frac{-\exp\left[-(\lambda_i + \lambda_e)t_1\right]}{\lambda_i + \lambda_e} - \frac{-1}{\lambda_i + \lambda_e} \right), \tag{D.2}$$

which gives

$$C_g(i,x,t) = V_{d_p} \overline{C_{\sec}(i,x,t_{s_j})} \frac{1 - \exp\left[-(\lambda_i + \lambda_e)t_1\right]}{\lambda_i + \lambda_e}.$$ (D.3)

D.2   Resuspension

Resuspended air concentrations in MILDOS4 are calculated with a time-dependent resuspension factor (NRC, 1980) given as:

$$R(t) = \begin{cases} \dfrac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t), \text{ for } t \le t_R \\[2ex] \dfrac{V_{d_r}}{V_{d_p}} R_F, \text{ for } t > t_R \end{cases}$$ (D.4)

where

$R(t)$ = ratio of resuspended air concentration to ground concentration for a ground concentration at time t after deposition (1/m),

V_{dr} = deposition velocity for the reference particle size that corresponds to the values of R_I and R_F (m/s),

V_{dp} = deposition velocity for particle size p (m/s),

R_I = initial value of the resuspension factor for fresh deposits (1/m),

λ_r = resuspension factor decay constant (1/yr) [(ln 2)/resuspension half-life],

R_F = final value of the resuspension factor after time (1/m), and

t_R = time required for the resuspension factor to decrease from its initial to final value (yr), $t = t_R$ when

$$\frac{V_{d_r}}{V_{d_p}} R_F = \frac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t_R)$$ (D.5)

Equation D.5 can be rearranged to solve for t_R to give

$$t_R = -\frac{1}{\lambda_r}\ln\frac{R_F}{R_I}.$$

(D.6)

The inverse relationship with respect to the deposition velocity in Equation D.4 accounts for the decrease in the amount resuspended as the particle size increases.

MILDOS4 estimates the resuspended air concentration at times corresponding to the end of each time step as specified by the user. Figure D-1 presents a graphic representation of the time breakdown considered in the program.
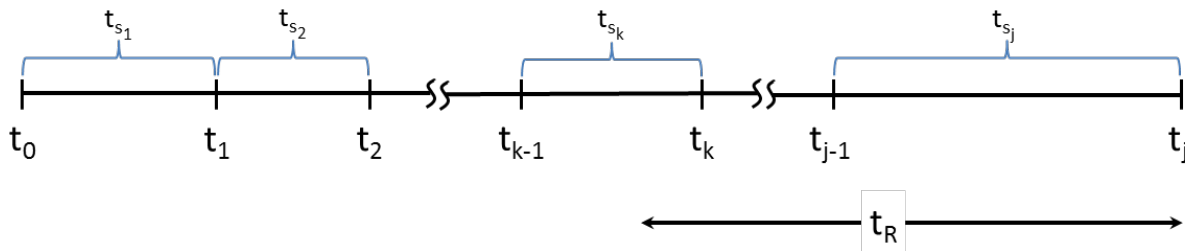
Figure D-1 Representative Timeline Used in MILDOS4

For a given time step j in MILDOS4, the resuspended air concentration of radionuclide i is the product of the resuspension factor with the radionuclide's ground concentration, as follows:

$$C_{air_R}(i,x,t_j) = R(t)C_g(i,x,t_j).$$

(D.7)

The following sections (D.2.1 through D.2.3) provide the derivation of the resuspended air concentration at the end of each time step interval t_{sm} that corresponds to a cumulative time t_j, where:

$$t_j = \sum_{m=1}^{j} t_{s_m}$$

(D.8)

and where

- $t_m < t_j - t_R$ (R_F applies),

- $t_m > t_j - t_R$ and $t_{m-1} < t_j - t_R$ (t_{sm} interval split between application of R_I and R_F), or

- $t_m > t_j - t_R$ and $t_{m-1} > t_j - t_R$ (R_I applies), and

- j is the total number of time steps.

A general equation is then derived in Section D.2.4 to give the calculation used in MILDOS4 to estimate the resuspended air concentration for each time step.

D.2.1 Time Steps in the Final Resuspension Factor Region

For times where t_m is $< t_j - t_R$, resuspension is assumed to occur at a constant rate specified by the final resuspension factor R_F. The resuspended air concentration, Equation D.7, can then be written in terms of Equation D.4 for the resuspension factor and Equation D.3 for the ground concentration multiplied by a decay term to account for radioactive decay and weathering following the cessation of deposition during time step m, as follows:

$$C_{air_R}(i,x,t_{s_m}) = \frac{V_{d_r}}{V_{d_p}} R_F \overline{C_{sec}}(i,x,t_{s_m}) V_{d_p} \frac{1-\exp\left[-(\lambda_i + \lambda_e)t_{s_m}\right]}{\lambda_i + \lambda_e} \exp\left[-(\lambda_i + \lambda_e)(t_j - t_m)\right], \quad \text{(D.9)}$$

which can be rearranged to give

$$C_{air_R}(i,x,t_{s_m}) = \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_F \frac{\exp\left[-(\lambda_i + \lambda_e)(t_j - t_m)\right] - \exp\left[-(\lambda_i + \lambda_e)(t_j - t_m + t_{s_m})\right]}{\lambda_i + \lambda_e}.$$

$$\text{(D.10)}$$

D.2.2 Time Steps in the Initial Resuspension Factor Region

For times where t_m is $> t_j - t_R$ and t_{m-1} is $> t_j - t_R$, resuspension is assumed to occur according to the time-dependent exponential decay function given in the first part of Equation D.4. For a given time step, the resuspended air concentration, Equation D.7, takes the form of Equation D.4, the initial resuspension factor, multiplied by the ground concentration, Equation D.1, to give

$$C_{air_R}(i,x,t_{s_m}) = \int_0^{t_{s_m}} \frac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t) \overline{C_{sec}}(i,x,t_{s_m}) V_{d_p} \exp\left[-(\lambda_i + \lambda_e)t\right] dt. \quad \text{(D.11)}$$

When the integral is evaluated, the resuspended air concentration at the end of the time step, as a result of the contamination deposited during the time step, takes the form of

$$C_{air_R}(i,x,t_{s_m}) = \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_I \frac{-\exp\left[-(\lambda_i + \lambda_e + \lambda_r)t\right]}{\lambda_i + \lambda_e + \lambda_r}\Bigg|_0^{t_{s_m}} =$$

$$\overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_I \frac{1-\exp\left[-(\lambda_i + \lambda_e + \lambda_r)t_{s_m}\right]}{\lambda_i + \lambda_e + \lambda_r} \quad \text{(D.12)}$$

To account for further decay between t_m and t_j, the contribution to the total resuspended air concentration from deposition during time step m is given by Equation D.12 multiplied by the decay function:

$$C_{air_R}(i,x,t_{s_m}) = \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_I \frac{1-\exp\left[-(\lambda_i + \lambda_e + \lambda_r)t_{s_m}\right]}{\lambda_i + \lambda_e + \lambda_r} \exp\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_m)\right],$$

$$\text{(D.13)}$$

which becomes

$$C_{air_R}(i,x,t_{s_m}) =$$

$$\overline{C_{\sec}}(i,x,t_{s_m})V_{d_r}R_I \frac{\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)\left(t_j-t_m\right)\right]-\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)\left(t_j-t_m+t_{s_m}\right)\right]}{\lambda_i+\lambda_e+\lambda_r}\cdot$$

<div align="center">(D.14)</div>

D.2.3 Transition Time Step between the Initial and Final Resuspension Factor Regions

For the time period within the time step that falls within the final resuspension factor region, Equation D.9 can be used with the appropriate times, and Equation D.13 can likewise be used in a similar manner to give the total resuspended air concentration contribution for the time step, as follows:

$$C_{air_R}(i,x,t_{s_m}) = \frac{V_{d_r}}{V_{d_p}}R_F\overline{C_{\sec}}(i,x,t_{s_m})V_{d_p}\frac{1-\exp\left[-\left(\lambda_i+\lambda_e\right)\left(t_j-t_R-t_{m-1}\right)\right]}{\lambda_i+\lambda_e}\exp\left[-\left(\lambda_i+\lambda_e\right)t_R\right]+$$

$$\overline{C_{\sec}}(i,x,t_{s_m})V_{d_r}R_I\frac{1-\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)\left(t_m+t_R-t_j\right)\right]}{\lambda_i+\lambda_e+\lambda_r}\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)\left(t_j-t_m\right)\right].$$

<div align="center">(D.15)</div>

The simplified equation is then as follows:

$$C_{air_R}(i,x,t_{s_m}) = \overline{C_{\sec}}(i,x,t_{s_m})V_{d_r}\left[\begin{array}{c} R_F\left(\dfrac{\exp\left[-\left(\lambda_i+\lambda_e\right)t_R\right]-\exp\left[-\left(\lambda_i+\lambda_e\right)\left(t_j-t_{m-1}\right)\right]}{\lambda_i+\lambda_e}\right)+ \\[2ex] R_I\left(\dfrac{\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)\left(t_j-t_m\right)\right]-\exp\left[-\left(\lambda_i+\lambda_e+\lambda_r\right)t_R\right]}{\lambda_i+\lambda_e+\lambda_r}\right) \end{array}\right].\quad \text{(D.16)}$$

D.2.4 Total Resuspended Air Concentration

The total resuspended air concentration for radionuclide *i* and a given particulate size and time step *j* includes contributions from radionuclide deposition in previous time steps. These contributions are calculated on a time-step basis according to the resuspension region (initial, transition, or final; Equations D.10, D.17, or D.14, respectively) in which the time step occurs.

Thus, the total resuspended air concentration for radionuclide i at time step j is the sum of contributions from the current and preceding time steps in each region, as follows:

$$
\begin{aligned}
C_{air_R}(i,x,t_j) = {} & \\
& \sum_{m=1}^{k-1} \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_F \, \frac{\exp\!\left[-(\lambda_i + \lambda_e)(t_j - t_m)\right] - \exp\!\left[-(\lambda_i + \lambda_e)(t_j - t_m + t_{s_m})\right]}{\lambda_i + \lambda_e} + \\
& \sum_{m=k+1}^{j} \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} R_I \, \frac{\exp\!\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_m)\right] - \exp\!\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_m + t_{s_m})\right]}{\lambda_i + \lambda_e + \lambda_r} + \\
& \overline{C_{sec}}(i,x,t_{s_m}) V_{d_r} \left[\begin{array}{l} R_F \left(\dfrac{\exp\!\left[-(\lambda_i + \lambda_e) t_R\right] - \exp\!\left[-(\lambda_i + \lambda_e)(t_j - t_{k-1})\right]}{\lambda_i + \lambda_e} \right) + \\[2em] R_I \left(\dfrac{\exp\!\left[-(\lambda_i + \lambda_e + \lambda_r)(t_j - t_k)\right] - \exp\!\left[-(\lambda_i + \lambda_e + \lambda_r) t_R\right]}{\lambda_i + \lambda_e + \lambda_r} \right) \end{array} \right].
\end{aligned}
$$

(D.17)

D.3 Reference

NRC (U.S. Nuclear Regulatory Commission), 1980, *Final Generic Environmental Impact Statement on Uranium Milling*, *Vols. I–III*, NUREG-0706, Office of Nuclear Material Safety and Safeguards, September.

APPENDIX E   ADDITIONAL MAP INFORMATION

This appendix discusses concepts used in mapping and their application to the geographic information system (GIS) module in MILDOS4.

E.1   MapWinGIS

MILDOS4 uses the MapWinGIS module, which is available through the MapWindow GIS Open Source Project (http://www.mapwindow.org/). It provides an embedded map control for use in 32-bit and 64-bit Windows applications, is programmable in Visual Basic .Net (VB.NET), is freely distributable, and is easily installed on user computers. The module provides the capability to import geo-referenced maps (e.g., Esri shapefiles, world files in JPEG/TIFF/BMP format), if desired, as the background for creating custom scenarios. Table E-1 lists the file types supported in the implementation of the GIS module by MILDOS4.

Table E-1 GIS File Types Supported by MILDOS4

File Type	File Extension
Bitmap	.bmp
Graphics Interchange Format (GIF)	.gif
Joint Photographic Experts Group (JPEG) and JPEG2000	.jpg, .jp2
Portable Network Graphics (PNG)	.png
Multiresolution Seamless Image Database (MrSID)	.sid
Shapefile	.shp
Tagged Image File Format (TIFF)	.tif
Geodata Data Abstraction Library (GDAL) Virtual TIFF	.vrt

E.2   Map Projections

A map projection provides a means of representing the curved surface of the Earth on a flat map. Any projection is likely to distort at least some aspect of the real world when one is trying to determine distance and direction from a given point. There are hundreds of possible projections to use. The advantages and disadvantages of a given projection depend, in part, on the scale and location of the area of interest.

The scale of interest for most MILDOS4 applications is only a few kilometers. Thus, a map projection that is reasonable for that scale is the widely used universal transverse Mercator (UTM) projection. The UTM projection is actually a collection of 60 projection zones for the Northern Hemisphere and 60 projections for the Southern Hemisphere. Zone widths are 6° of longitude, with numbering beginning at 180°W longitude. The Continental United States falls within northern zones 10 through 19 (10N through 19N), as shown in Figure E-1. Distances are measured in meters. It is a Cartesian coordinate (x,y) system with the east–west (x) coordinate referred to as the easting and the north–south (y) coordinate referred to as the northing.
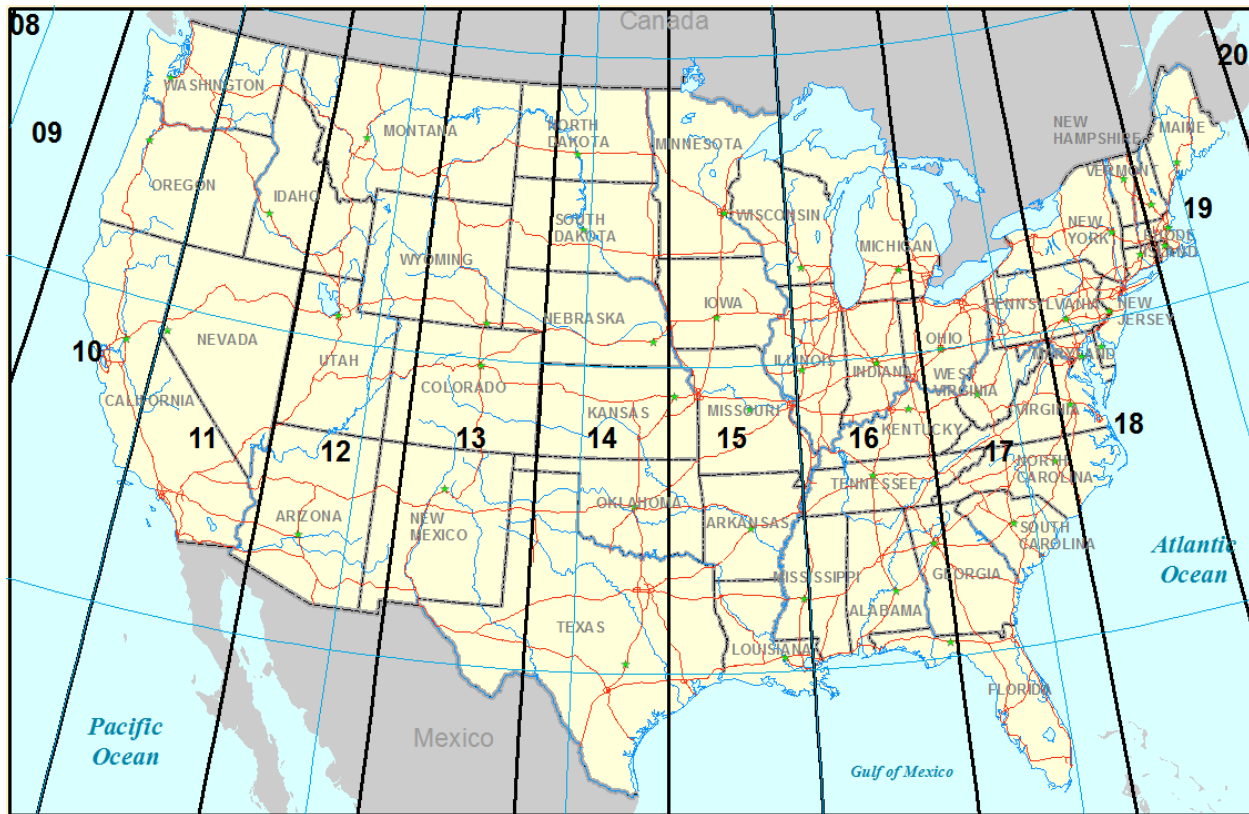
Figure E-1 Northern UTM Projection Zones Covering the Continental United States

The site geometry can be configured to be shown in a local mode, where the first emission source is considered to be at the center of the coordinate system at location (0,0) when a new user file is used. As an alternative, the user may import background map layers that have a UTM projection for their local area and specify the locations of all emission sources and receptors. If population calculations are enabled, the population and food grids will be centered on the first emission source in either case.

E.3   MILDOS4 Map Interface

Data are displayed in the map control in layers. Data in each layer correspond to similar data displayed as either raster or vector data. Bitmap and TIFF files are examples of raster data for which information is presented in a matrix of cells (images such as digital pictures or a scanned map). Shapefiles, originally introduced by Esri, are examples of vector data for which the information can be stored as points, lines, or polygons as a collection of coordinated points, where lines and polygons are drawn as a series of connected points and thus are independent of the resolution of a display device.

E.3.1   Individual Receptors and Emission Sources

To represent sources and receptors on the map, MILDOS4 generates in-memory shapefiles for use in the map control. Receptors are represented by a single point shapefile. Sources are represented by a point shapefile for point sources and a polygon shapefile for area sources.

These map layers are not accessible to the user other than to show the number and position of individual receptors and emission sources. The receptors and sources are labeled on the map display with their user-supplied names. Specific labels may not appear at certain magnifications if there is an overlap with another label.

E.3.2 Background Layers

Geo-referenced data may be loaded into the map for use as a background for the individual receptor and emission sources. It is recommended that the coordinate system (i.e., UTM zone) be established before receptors and sources are entered. Multiple raster data files can be added as tiles to form a larger background. These types of files contain large amounts of information that may cause some degradation in performance of the map display if several files are used.

E.4   Map Data

In the United States, background map data may be downloaded from The National Map (http://nationalmap.gov/). The raster and vector data are managed by the U.S. Geological Survey (USGS) National Geospatial Program. Table E-2 lists the product themes available. The National Map Viewer and download platform can be found online at http://viewer.nationalmap.gov/viewer/.

Other free background GIS data are available from other U.S. agencies, such as the U.S. Census Bureau (http://www.census.gov/geo/maps-data/data/tiger.html), U.S. Department of Transportation (http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/index.html), U.S. Department of Agriculture (http://datagateway.nrcs.usda.gov/), and DATA.GOV, a general government data clearinghouse (http://catalog.data.gov/dataset).

Table E-2 Product Themes Available from the National Map

Theme
U.S. Topo
Historical Topo Maps
Structures
Transportation
Boundaries
Geographic Names
USGS Map Indices
Hydrography
Contours
Land Cover
Elevation
Orthoimagery

See the following link for data selection and download process:
http://viewer.nationalmap.gov/help/9.0%20TNM%20Cart%20Tab.htm.

APPENDIX F   USER PARAMETER LISTING

This appendix provides a list of the user input parameters in MILDOS4. Their definitions and upper-limit and lower-limit values, if applicable, are provided.

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
220EMANATION_FRAC	0	1	0.15	Radon-220 emanation fraction (also known as the emanating power), defined as the fraction of the total radon generated by radium decay that escapes from the soil particles; observed values range from about 0.01 to 1.0; the emanating power depends on many factors, such as mineralogy, porosity, particle size distribution, and moisture content; for soils with a low moisture content, a typical value is around 0.15
222EMANATION_FRAC	0	1	0.25	Radon-222 emanation fraction (also known as the emanating power), defined as the fraction of the total radon generated by radium decay that escapes from the soil particles; observed values range from about 0.01 to 1.0; the emanating power depends on many factors, such as mineralogy, porosity, particle size distribution, and moisture content; for soils with a low moisture content, a typical value is around 0.25
ACTIVE_AREA	1	1000000000	100	Area of the ore zone that is being mined (m^2)
ADULT_VEG_FRAC	0	1	0	Fraction of vegetables consumed by an adult that is composed of a given vegetable type (unitless)
AGE_GROUP	—	—	Adult	One of four age groups used in MILDOS4 (adult, teenager, child, or infant)
ambientT	211	330	283	Ambient temperature (K)
anemHeight	0	200	10	Anemometer height (m)
AREA	1	1.00E+12	1	Total area of an area source (m^2)
CAKE_RATE	0	1000000	0	Average daily amount of yellowcake (U_3O_8) that is produced at the facility (kg/d)
caseInfo	—	—	More case information	Additional user-specified information for the case under study
caseTitle	—	—	User case	User-defined title for case under study
CHILD_VEG_FRAC	0	1	0	Fraction of vegetables consumed by a child that is composed of a given vegetable type (unitless)
CIRC_RAD	1	10000	100	Radius of a circular area source (m)
CIRC_VOL	1	1000000000	1000	Total volume of process water that is actively circulating between injection wells, extraction wells, and ion exchange columns (L)
COL_RATE	0.1	100	1	Average daily number of times the ion exchange columns are unloaded
COL_VOL	0	100000	1000	Volume of the space in the ion exchange columns occupied by resin (L)
CONTAM_DEPTH	0.01	100	0.15	Thickness of the soil over which the contaminants are distributed; a typical value may be 0.15 m (m)
cowIngestRate	1.00E-06	100	50	Ingestion rate (feed wet weight) of animals (beef cattle and milk cows) (kg/d)
cutoffHeight	10	100	50	Height above which to use Briggs urban dispersion coefficients (m)
decayPlants	1	35	14	Weathering decay half-life for loss of contamination from vegetation due to weathering processes (d)
DEP_VEL	1.00E-06	1	0.01	Particulate deposition velocity (m/s)
DISP_COEFF	—	—	Pasquill-Gifford	Dispersion coefficients: Effective release height, Pasquill-Gifford, Briggs Rural, or Briggs Urban
DISTRIB_COEFF	0	20000000	100	Also known as the soil/water partition coefficient (Kd); empirical parameter that estimates the distribution of radionuclides between the solid and liquid phases in soil (cm^3/g or L/kg)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
EXIT_VEL	0	20	2	Exit velocity from point source (m/s)
FRAC_POP	0	1	0	Fraction of the regional population that belongs to a specific age group
fracEdibleLeafAnimal	0	1	1	Fraction of radionuclides reaching the edible portion of animal-consumed vegetation
fracEdibleLeafHuman	0	1	1	Fraction of radionuclides reaching the edible portion of human-consumed leafy vegetables
fracEdibleRoot	0	1	0.1	Fraction of radionuclides reaching the edible portion of human-consumed root vegetables
fracHayInd	0	1	0.4	Fraction of livestock feed from stored hay for individual consumption
fracHayPop	0	1	0.4	Fraction of livestock feed from stored hay for consumption by the general population
fracMeatPrep	0	1	1	Fraction of radioactivity in meat remaining after food preparation
fracMilkPrep	0	1	1	Fraction of radioactivity in milk remaining after food preparation
fracPastureInd	0	1	0.6	Fraction of livestock feed from pasture grass for individual consumption
fracPasturePop	0	1	0.6	Fraction of livestock feed from pasture grass for consumption by the general population
fracRetain	0	1	0.2	Fraction of air-deposited radionuclides retained on vegetation
fracVegPrep	0	1	0.5	Fraction of radioactivity in vegetables remaining after food preparation
gridSize	1	1000	5	Size of grid blocks to use when calculating air concentrations (m)
HEAT_REL	0	10000000000	0	Heat release from stack (cal/s)
IN_OCCUPY	0	1	0.583	Fraction of time spent indoors at receptor location
IN_SHIELD	0	1	0.7	Shielding factor provided by indoor shelter at receptor location (unitless)
INFANT_VEG_FRAC	0	1	0	Fraction of vegetables consumed by an infant that is composed of a given vegetable type (unitless)
INFILTRATE	0	1	1	Indoor infiltration factor for particulates. Fraction of outdoor particulate concentration for use in indoor inhalation dose calculations at a given location (unitless)
isMomentum	0	0	1	Determines if plume rise calculations assume a momentum-driven or buoyancy-induced plume; true (1) if momentum-induced is assumed or false (0) if buoyancy-induced is assumed
isPopExposure	0	1	1	Option to perform population exposure calculations; true (1) or false (0)
isPopIngest	0	1	1	Option to perform population ingestion calculations; true (1) or false (0)
jfdNotes	—	—		Stores user notes as needed
LAND_AREA	0	1000000000	1000	Area of the land application (m^2)
Latitude	–90	90	—	A geographic coordinate that specifies a north-south position on the Earth (decimal degrees)
Longitude	–180	180	—	A geographic coordinate that specifies an east-west position on the Earth (decimal degrees)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
mapProj	—	—	Local Coordinates	Contains the current map projection being used for the map display; consists of a list of the UTM zone, the datum (WGS84 or NAD83), and the EPSG code for the projection (EPSG stands for what used to be the European Petroleum Survey Group)
mapState	—	—	—	String with serialized map state
maxDistCalcArea	0.5	10000	1500	Maximum distance between an area source and receptor where the area source model will be used; the source will be treated as a point source beyond the specified distance (m)
MEAT_INGEST	0	1	0	Consider the meat ingestion pathway for this receptor; true (1) or false (0)
MEAT_RATE	0	1000	110	Meat ingestion rate for individuals (kg/yr)
meatProd	0	1000000	0	Farmland meat productivity (kg/yr)
metFreq	0	1	0	Frequency of time wind is blowing in a specific direction, under a specific stability category, at a given wind speed
MILK_INGEST	0	0	0	Consider the milk ingestion pathway for this receptor; true (1) or false (0)
MILK_RATE	0	1200	310	Individual milk consumption rate (kg/yr)
milkProd	0	4200000	0	Farmland milk productivity (kg/yr)
N_PITS	0	1000	1	Number of mud pits in use at a well field (1/yr)
NAME	0	0	Default name	Name that identifies a specific receptor or source
nPeople	0	3000000		Number of people in sector segment (persons)
OP_DAYS	0	365	100	Number of days during the year when well field restoration activities are being performed
OPTION_AREA	CIRC	RECT	CIRC	Species; the type of area source under consideration (circular, rectangular, or polygon; CIRC, RECT, or POLY)
OPTION_EROSION	0	1	1	Option to use the erosion model in area source releases; do not use is false (0) or do use is true (1)
optOutTable	0	0	STD	Option that controls contents of the analysis output. STD - standard output only; STD_CUSTOM - standard and user specified custom output
optOutWho	0	0	0	Option that specifies what receptor type custom output to generate. 0 - individual receptors; 1 - population receptors; 2 - both individual and population receptors.
ORDER_ID	1	999999	1	Position (order) of source or receptor in their group
ORE_DENSITY	0.1	1000	2.65	Dry bulk density of the ore material (g/cm^3)
ORE_THICK	0	1000	1	Average thickness of the ore zone that is being mined (m)
OTHERS_FRAC	0	1	0	Fraction that represents the activity present in the yellowcake from other radionuclides divided by the activity of U-238 in the yellowcake; typical values range from 0.0015 to 0.005; the fraction released to stack is applied to the activity fraction to obtain the activity of each radionuclide that is released from the stack
OUT_OCCUPY	0	1	0.02	Fraction of time spent outdoors at receptor location
PART_ADJUST	0	1	1	Adjustment factor for particulate releases for a given source for a given time period (unitless)
PART_DENS	1	100000000	2400000	Density of particulates used in the erosion model (g/m^3)
PART_DISTRIB	1	3	1	Particle size distribution set (1, 2, or 3)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
PART_RATE	0	100	0	Particulate release rate from an area source (g/m^2-s)
PART_RATE_LAND	0	100	0	Particulate release rate from a land application source (g/(m^2-s))
PART_SIZE	0.1	200	1	Particle size (micrometers) [AMAD]
partFrac	0	1	0	Fraction of particle size distribution for a given average particle size
Pb	0	1	1	Transfer factor for lead from soil to a specific plant type or from animal feed to meat or milk [pCi/kg [wet] plant per pCi/kg [dry] soil) or (pCi/kg per pCi/d)
PIT_ORE	0	10000000000	0	Rate at which ore material is placed in the mud pit; the product of the number of mud pits generated in a year at the new well field and the average mass of ore that is deposited in a mud pit (g/yr)
PIT_TIME	0	365	0	Average number of days between the time the well cuttings are placed in the mud pit and the time at which these cuttings are disposed of
pmMix	1	5000	1600	Annual afternoon mixing height (m)
POP_ADJUST	0	100	1	Population adjustment factor for a given time period (unitless)
POP_VEG_FRAC	0	1	0	Fraction of vegetables consumed by the collective population that is composed of a given vegetable type (unitless)
Ra	0	1	1	Transfer factor for radium from soil to a specific plant type or from animal feed to meat or milk [pCi/kg [wet] plant per pCi/kg [dry] soil) or (pCi/kg per pCi/d)
RA_FRAC	0	1	0	Fraction that represents the activity present in the yellowcake from radium divided by the activity of U-238 in the yellowcake; typical values range from 0.0015 to 0.005; the fraction released to stack is applied to the activity fraction to obtain the activity of each radionuclide that is released from the stack
RA224_CONC	0	1000000	0	Concentration of the Ra-224 in the ore that is used to estimate the amount of Rn-220 generated by radioactive decay (pCi/g)
RA226_CONC	0	1000000	0	Concentration of the Ra-226 in the ore that is used to estimate the amount of Rn-222 generated by radioactive decay (pCi/g)
RADON_ADJUST	0	1	1	Adjustment factor for radon releases for a given source for a given time period (unitless)
rain	0	25	0	Rainfall rate (m/yr)
RATE_OR_CONC	0	1000000	1	Radionuclide concentration or release rate for a point source (Ci/yr), for an area source pCi/g), or for a land application source (pCi/L)
RECT_LENGTH	1	10000	100	Length of a rectangular area source (m)
RECT_ROT	0	90	0	Rotation of a rectangular area source (m)
RECT_WIDTH	1	10000	100	Width of a rectangular area source (m)
relRate	0	1000	1	Nuclide release rate (Ci/yr)
RESIN_POROSITY	0	1	0.1	Porosity of the ion exchange resin material; the fraction of the ion exchange resin volume that is occupied by process water (unitless)
RESTORE_AREA	1	1000000	100	Area of the ore zone that is being restored (m^2)
resuspDepVel	1.00E-05	1	0.01	Deposition velocity for particulates associated with the initial and final resuspension factors specified (m/s)
resuspFacFinal	1.00E-11	0.0001	1.00E-09	Final resuspension factor for determining resuspended air concentrations (1/m)
resuspFacInitial	1.00E-11	0.0001	1.00E-05	Initial resuspension factor for determining resuspended air concentrations (1/m)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
resuspHalfLife	1.00E-05	100	0.137	Resuspension factor decay half-life (yr)
RN_FRAC	0	1	0.8	Fraction of the radon that is carried by circulating water; the balance of the fraction of radon in the mined area that is not swept in the injection-extraction well loop and remains trapped in the ore zone
RN_VENT	0	1	0.01	Fractional daily rate of radon release due to occasional venting from wellheads, valves, and leaking transport piping during circulation
RN220_RATE	0	100000	0	Radon-220 release rate from an area source (pCi/m^2-s) or from a point source (Ci/yr)
RN222_IN_EQ	0	1	0.5	Rn-222 equilibrium fraction of radon daughters with radon in indoor air (unitless)
RN222_OUT_EQ	0	1	0.7	Rn-222 equilibrium fraction of radon daughters with radon in outdoor air (unitless)
RN222_OUT_EQ_CALC	0	1	0	(Option selection) If checked, the user input for Rn-222 equilibrium fraction of radon daughters with radon in outdoor air is used; otherwise, it is calculated by the program
RN222_RATE	0	100000	0	Radon-222 release rate from an area source (pCi/(m^2-s) or from a point source (Ci/yr)
SALT_DIAM	1.00E-06	0.1	0.0003	Average diameter of a saltating particle (m)
sensFactor	0.1	100	1.1	User-supplied sensitivity factor for use in sensitivity calculations (unitless)
SET_1	0	1	0	Fraction of particles of a given size for Particle Distribution Set 1 (unitless)
SET_2	0	1	0	Fraction of particles of a given size for Particle Distribution Set 2 (unitless)
SET_3	0	1	0	Fraction of particles of a given size for Particle Distribution Set 3 (unitless)
SET_1_DENSITY	0.1	1000	8.9	Density of particles of a given size for Particle Distribution Set 1 (g/cm^3)
SET_2_DENSITY	0.1	1000	2.4	Density of particles of a given size for Particle Distribution Set 2 (g/cm^3)
SET_3_DENSITY	0.1	1000	2.4	Density of particles of a given size for Particle Distribution Set 3 (g/cm^3)
SOIL_DENSITY	0.1	1000	2.65	Dry bulk density of the surface soil (g/cm^3)
soilArealDen	1.00E-05	10000	240	Areal surface density/effective surface soil density (kg/m^2)
soilConc	0	10000	0	Nuclide soil concentration for area sources (pCi/g)
soilHalfLife	0	135	50	Environmental soil loss half-life (yr)
SOLUBILITY_CLASS	—	—	Year	Solubility class selected for the specified radionuclide: "Day," "Week," or "Year"
SRC_TYPE	0	0	Point source	Definition of the source type to analyze, from predetermined list in GUI drop-down list
SRL	1.00E-06	100		Surface roughness length (cm)
STACK_DIAM	0.1	10	1.5	Point source stack diameter (m)
STACK_FRAC	0	1	0	Fraction of yellowcake produced that is released from the stack; a typical value ranges from 0.0005 to 0.001; this fraction is applied to the yellowcake production rate to estimate the activity of U-238 released from the stack (unitless)
SURF_ROUGH	1.00E-05	100	0.1	Surface roughness height used in the particulate erosion model (m)
TAIL_MASS	0	100	3	Percent of the tailing mass that has a diameter smaller than 20 micrometers
TEENAGER_VEG_FRAC	0	1	0	Fraction of vegetables consumed by a teenager that is composed of a given vegetable type (unitless)
Th	0	1	1	Transfer factor for thorium from soil to a specific plant type or from animal feed to meat or milk (pCi/kg [wet] plant per pCi/kg [dry] soil) or (pCi/kg per pCi/d)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
TH_FRAC	0	1	0	Fraction that represents the activity present in the yellowcake from thorium divided by the activity of U-238 in the yellowcake; typical values range from 0.0015 to 0.005; the fraction released to stack is applied to the activity fraction to obtain the activity of each radionuclide that is released from the stack (unitless)
TIME_INCREMENT	1	100	1	Length of time to be used for a given time segment to be analyzed (yr)
U	0	1	1	Transfer factor for uranium from soil to a specific plant type or from animal feed to meat or milk (pCi/kg [wet] plant per pCi/kg [dry] soil) or (pCi/kg per pCi/d)
USAF_ID	—	—	—	U.S. Air Force station identifier
UTCdiff	0	14	—	Time zone difference from UTC (hr)
VEG_INGEST	—	—	0	Consider the vegetable ingestion pathway for this receptor; true (1) or false (0)
VEG_RATE	0	1800	584	Vegetable ingestion rate for individuals (kg/yr)
VEG_TYPE	—	—	Above ground	Vegetable type under consideration: above ground vegetables (Above Ground), potatoes (Potatoes), or other below ground vegetables (Below Ground)
vegProd	0	18000000	0	Farmland vegetable productivity (kg/yr)
vGrow	0	180	60	Exposure time to radionuclides during the human-consumed vegetable growing season (d)
vGrowPasture	0	180	30	Exposure time to radionuclides during the animal-consumed vegetation growing season (d)
WATER_CONTENT	0	1	0	Volumetric water content of the soil; the fraction (dimensionless) of the total porosity of the soil material occupied by water; dry soil is represented by a value of 0, saturated soil is represented by a value of 1
WATER_RATE	0	100000	100	Water purge rate; rate at which treated water is purged from the system; the purge in the production well field is necessary to maintain a hydraulic cone of depression around each well field to prevent leakage of mining solutions outside the production zone (L/d)
WATER_VOL	0	1000000000	1000	Volume of treated water released onto the irrigated area over the duration of the land application (m^3)
WATER_WT	1.00E-06	100	0.1	Water content in weight by percent used in the erosion model
WBAN_ID	—	—	—	WBAN station identifier
X_VALUE	–1000000	1000000	0	Definition of x value for a node in a polygon table (m)
x_y_coord	-9999999	9999999	—	Used to check limits on user x,y coordinate input when recentering sources and receptors.
XLOC	-99999999	99999999	0	x coordinate for receptor or source location (m)
Y_VALUE	–1000000	1000000	0	Definition of y value for a node in a polygon table (m)
yieldMeat	0	50000	3070	Farmland production rate of meat for population ingestion calculations (kg/km^2-yr)
yieldMilk	0	100000	6710	Farmland production rate of milk for population ingestion calculations (kg/km^2-yr)
yieldVeg	0	400,000	55800	Farmland production rate of vegetation for population ingestion calculations (kg/km^2-yr)
YLOC	-99999999	99999999	0	y coordinate for receptor or source location (m)
yVeg	0	5	2	Yield density of human-consumed vegetation on farmland (kg/m^2)

Parameter	Lower Limit	Upper Limit	Default Value	Definition and Units
yVegPasture	0	5	0.7	Yield density of animal-consumed vegetation on farmland (kg/m^2)
ZLOC	-200	5000	0	z coordinate for receptor or source location (m)

APPENDIX G   VARIABLE DEFINITIONS

λ_{Rn220}	Rn-220 decay constant (1/d)
λ_{Rn222}	Rn-222 decay constant (1/d)
ρ_a	density of air (g/m^3)
ρ_o	bulk density of the ore material (g/cm^3)
ρ_p	particle density (g/m^3)
σ_z	vertical dispersion coefficient (m)
σ_{yb}	buoyancy-induced horizontal dispersion coefficient (m)
σ_{zb}	buoyancy-induced vertical dispersion coefficient (m)
A_o	active area of the ore zone (m^2)
C_a	local air concentration (Ci/m^3)
C_{oRa224}	concentration of Ra-224 in the ore (pCi/g)
C_{oRa226}	concentration of Ra-226 in the ore (pCi/g)
$\overline{C_{sec}}(i,x)$	sector-average air concentration of radionuclide i at distance x (Ci/m^3)
c_h	empirical constant to relate shear velocity to horizontal flux (1 × 10^2 g-s^2/m^4)
c_t	dimensionless coefficient equal to 0.1
c_v	coefficient of proportionality for vertical flux (2 × 10^{-6} g/m^2-s)
C_{wRn220}	Rn-220 concentration in process water (pCi/L)
C_{wRn222}	Rn-222 concentration in process water (pCi/L,
D_o	average thickness of the ore zone (m)
d	average diameter of saltating particle (m)
d_{op}	number of days of well field operation in one year (d)
d_p	particle diameter for particulate p (μm)
d_s	inside diameter of the emission stack (m)
E_p	release elevation, the reference point for the release height (m)
E_r	receptor elevation (m)
E_{Rn220}	emanating power for Rn-220 (unitless)
E_{Rn222}	emanating power for Rn-222 (unitless)
F_{ix}	water discharge rate from resin unloading of ion exchange columns (L/d)
f_{others}	fraction of Pb-210 relative to U-238 released through the drying/packaging facility stack (unitless)
F_p	"purge" rate of treated water (L/d)
f_{Ra}	fraction of Ra-226 relative to U-238 released through the drying/packaging facility stack (unitless)
f_{Rn}	fraction of radon source carried by circulating water (unitless)
f_s	fraction of production released through the drying/packaging facility stack (unitless)
f_{Th}	fraction of Th-230 relative to U-238 released through the drying/packaging facility stack (unitless)
g	gravitational acceleration (9.80665 m/s^2)
Δh	plume rise (m)
H	effective release height (m)
h	physical release height (m)
h_v	vertical (gravitational) settling of the plume (m),
L	mixing layer height, sometimes referred to as the lid height (m)
L_{am}	average mixing layer height in the morning (m)

L_{pm}	average mixing layer height in the afternoon (m)
l	normal adiabatic lapse rate of the atmosphere (0.0098 K/m)
M_{ore}	average mass of ore material in a mud pit (g)
N_{ix}	number of ion exchange unloadings per day
N_{pit}	number of mud pits generated per year
P_c	plume-path coefficient (unitless)
P_{ix}	porosity of the ion exchange resin (unitless)
p_{tm}	percent of tailing mass that has a diameter smaller than 20 μm (unitless)
$PB210_{dp}$	Pb-210 release rate from the drying / packaging facility stack (Ci/yr)
p	power for height ratio (unitless)
Q_{Oi}	initial amount of radionuclide i released (Ci/s)
Q_h	heat flux from radionuclide release area (cal/s)
Q_{xi}	depleted source strength of nuclide i at distance x (Ci)
q_h	horizontal flux of particulate material (g/m-s)
q_v	vertical flux (emission rate) of particulate material (g/m^2-s)
R	rainfall rate (mm/h)
$RA226_{dp}$	Ra-226 release rate from the drying/packaging facility stack (Ci/yr)
$Rn220_{nw}$	Rn-220 release rate from a new well field (Ci/yr)
$Rn222_{nw}$	Rn-222 release rate from a new well field (Ci/yr)
R_{yc}	daily production rate of yellowcake at the facility (kg U$_3$O$_8$/d)
s	stability parameter (unitless)
S_{in}	indoor external shielding factor (unitless)
S_{in_inh}	indoor inhalation shielding factor (unitless)
$TH230_{dp}$	Th-230 release rate from the drying / packaging facility stack (Ci/yr)
T_a	ambient air temperature (K)
t	time following release (s)
t_{pit}	storage time in a mud pit (d)
u_*	shear velocity (m/s)
u_{*t}	threshold shear velocity (m/s)
$U238_{dp}$	U-238 release rate from the drying/packaging facility stack (Ci/yr)
$U238_{sa}$	specific activity of U-238 (3.3 × 10^{-7} Ci/g)
u_a	wind speed at measurement height (m/s)
u_H	average wind speed at the effective release height (m/s)
u_z	wind velocity at height z (m/s)
V_c	volume of water in circulation (L)
V_{dp}	deposition velocity for particle size p (m/s)
V_{ix}	volume content of the ion exchange column (L)
V_s	settling velocity (m/s)
V_w	washout coefficient (1/s)
v_{Rn}	rate of radon venting from piping and valves during circulation (1/d)
v_s	exit velocity of effluent from emission stack (m/s)
W	water content expressed in weight by percent
W_c	washout coefficient (1/s)(mm/h)$^{-1}$
x	downwind receptor distance from release area (m)
y	crosswind distance from the plume centerline (m)
z	wind measurement height (m)
z_o	characteristic surface roughness height (g/m-s)
z_a	height of anemometer for wind speed measurement (m)
z_r	vertical distance above the release point (m)

2. TITLE AND SUBTITLE

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5. AUTHOR(S)

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11. ABSTRACT (200 words or less)

The MILDOS computer code is used to estimate the radiological impacts of airborne emissions from uranium mining and milling facilities. The code allows users to consider both conventional uranium ore operations and operations associated with *in situ* recovery (ISR) facilities. The code is used by license applicants and U.S. Nuclear Regulatory Commission staff to perform routine radiological impact and compliance evaluations for various uranium recovery operations. As part of a major code update, the following improvements and additions were made to the code: (a) revised ISR models, (b) support for ores containing thorium-232 (Th-232) and its daughter radionuclides in addition to the currently supported uranium-238 (U-238) and its daughter radionuclides, (c) a revised area source model, (d) the capability to perform sensitivity analysis on specific input parameters, (e) the capability to use current meteorological data provided by the National Centers for Environmental Information, and (f) an interactive results module.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

external dose
gaussian plume model
in situ recovery
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radon
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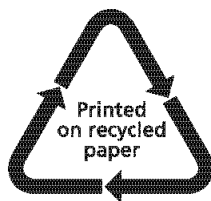
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